Proceedings of the 12th Meeting of the United States – Japan Cooperative Program in Natural Resources (UJNR)

Panel on Diving Physiology

Washington, DC, July 13-14, 1993

August 1995

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Undersea Research Program

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William S. Busch, U. S. Chairman
Shinichi Ishii, Japanese Chairman

Marcia R. Collie, Editor

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U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary
National Oceanic and Atmospheric Administration
D. James Baker
National Undersea Research Program
Henry R. Frey, Acting Director

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Preface

The 12th meeting of the Diving Physiology Panel was an unqualified success. This is especially significant because prior to this meeting Diving Physiology had been included with submersible science in the Diving Physiology and Technology Panel. Because of the overwhelming participation in the combined Panel, the 14th UJNR Administrative and Marine Resources and Engineering Coordination Committee (MRECC) agreed in July of 1993 to separating diving physiology and submersible science into two separate panels. This meeting demonstrated that the Diving Physiology Panel can easily stand on its own. The major share of the credit for this success goes to the participants on both the Japanese and United States sides. The genuine interest and willingness to take the time and make the effort to participate in the projects and meetings has made this panel the most active of all the UJNR panels.

Leadership also plays a role, and we did not know it at the time, but the 12th meeting was the last meeting in an official capacity for Dr. David Duane. As the U.S. chair of the MRECC and the champion of Diving Physiology and Submersible Science within NOAA, David provided leadership and support from the top and personal interest and participation from within. David's presence will be missed and on behalf of all his friends within UJNR, I have extended David a lifetime invitation to future Diving Physiology Panel meetings.

For the past 10 years the spirit, enthusiasm, and knowledge of the U.S. chairperson, Dr. William S. "Bill" Busch, has been a major factor in the panel's success. Bill has been the spirit and catalyst for the U.S. side, using his many organizational talents, countless hours of his personal time, and unlimited enthusiasm to bring together willing but extremely busy participants.

For this 12th meeting, Kathy Watson assisted with the preparations, and Marcia Collie spearheaded production of the proceedings. The demands of Bill's new position in NOAA have caused him to relinquish the reins but not the enthusiasm, and Bill will still participate in the meetings as time allows. I am honored to follow in Bill's footsteps and look forward to working with participants on both sides toward the continued success of the panel.

N. Eugene Smith
Incoming U.S. Chairperson

Dr. William S. Busch, U.S. Chairman

Mr. Shinichi Ishii, Japanese Chairman

Overview

William S. Busch

Solutions to today's global issues and concerns facing the world's populations require strong international partnerships. This is especially true in scientific and technology development disciplines involving interactions among governments, academia, and private sectors. World leaders, as well as the general public, are calling for better management and development of world ocean resources, an area where Japan has a wealth of experience and capability.

For the past 3 decades, UJNR has provided an invaluable forum for the close and important interactions, technology transfer, and collaborative programs benefitting both the United States and Japan, as well as other countries worldwide.

Within the eight MRECC panels that address marine issues, the Diving Physiology Panel -- being one of the oldest --is recognized as the most active and productive. Not only has it exchanged data, information, and researchers, but also has implemented strong and important collaborative programs and shared facilities benefitting both countries.

Because of man's increased dependence on ocean resources for sustainable development, the fields of diving physiology addressing hyperbaric research and technology development, safety, related medical issues, and new operational methods are more important today than ever before. The diving panel and its activities play a vital role in allowing researchers to address today's global problems facing the world's oceans that include:

- Environmental anthropogenic impact on the world's oceans
- Oceans' assimilative capabilities
- Sources of alternative energies from the sea
- Role of oceans in global change and greenhouse gas processes
- Oceanic resources as foodstock for both humans and livestock as well as sources for other byproducts such as chemicals and pharmaceuticals
- Marine recreation.

Each of these areas requires direct use of divers and their being able to work in-situ for long periods of time, in varying water quality and conditions, and at extended depths. These are all emphasized by activities of the diving panel.

The success of the panel is due to the dedicated and enthusiastic efforts by each of the panel members and advisors. The most important commodity that we have is the people involved and their close and candid interactions. As a past U.S. panel chairman and current member, I am proud to be a part of the panel and its activities and will cherish my involvement and the close friendships with my Japanese colleagues that have been made.

Thank you

Bill Busch

William S. Busch

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2nd August 1993

Dear Mr. G. Smith,

I should like to thank you for your warm hospitality toward the delegation from Japan. It was obvious from the response of the participants at the Diving Physiology & Technology Panel symposium that it was a great success.

We shall never forget our visit to your country. It was a wonderful experience. I have the greatest regard for the quality of research being done in the U.S.A.

I hope that we shall be able to meet again at the next UJNR joint meeting.

Yours sincerely,

Shinichi Ishii

Mr. Shinichi Ishii
Executive Director of JAMSTEC

1993 UJNR DIVING PHYSIOLOGY PANEL MEETING

July 13–14, 1993

DAY 1

AGENDA

8:00AM - 8:30AM	*REGISTRATION AND COFFEE*	
8:30AM - 9:00AM	*OPENING OF THE MEETING*	William S. Busch, Chairperson of U.S. Panel Shinichi Ishii, Chairperson of Japanese Panel 1. Election of Chairperson & Co-Chairperson 2. Adoption of the Agenda 3. Opening Remarks
9:00AM - 9:10AM	*WELCOME ADDRESS*	CAPT Robert G. Walter, Commanding Officer, NMRI
9:10AM - 9:20AM	*RESTRUCTURING OF THE UNDERSEA RESEARCH PANEL(S)*	William S. Busch
9:20AM - 9:40AM	*UNDERSEA RESEARCH ACTIVITIES IN THE MDSF UNDERSEA MEDICAL CENTER*	Hiromichi Oiwa
9:40AM - 10:00AM	*ACTUAL INVESTIGATION OF SPORTS DIVERS IN JAPAN*	Yoshihiro Mano
10:00AM - 10:20AM	*BREAK*	
10:20AM - 10:40AM	*SCIENTIFIC DIVING IN THE U.S. - UPDATE AND REVIEW*	Michael Lang
10:40AM - 11:00AM	*PATHOGENESIS* AND PREVENTION OF DYSBARIC OSTEONECROSIS	Mahito Kawashima, Hiroaki Tamura, Yoshihiro Noro, and Katsuhiro Takao
11:00AM - 11:20AM	*MICROBIOLOGICAL HAZARDS TO DIVERS*	Rita Colwell
11:20AM - 1:00PM	*LUNCH*	
1:00PM - 1:20PM	*MANNED DIVING AS A METHOD FOR COASTAL SEA RESEARCH*	Mineo Okamoto, Motohiko Mohri and Gentato Kai
1:20PM - 1:40PM	*DIVING SAFETY AND PHYSIOLOGY RESEARCH PROGRAM at NURP*	Eugene Smith

1:40PM - 2:00PM *MAINTENANCE AND MANAGEMENT TECHNOLOGY ON DURABILITY OF MID-LAYER FLOATING TYPE MARINE CULTIVATION FACILITY*
Naoyuki Takatsu, Mineo Okamoto, Osamu Nagahama, and Gentaro Kai

2:00PM - 2:20PM *NAVY UNDERSEA MEDICINE PROGRAM REVIEW*
Barbara Schibly

2:20PM - 2:40PM *BREAK*

2:40PM - 3:00PM *THE WAY AHEAD FOR U.S. NAVY DIVING*
Don Chandler

3:00PM - 3:20PM *U.S. RECREATIONAL DIVING ACCIDENTS AND MORTALITY ANAYLSIS*
Peter Bennett

3:20PM - 3:40PM *RELEVANCE OF IFEM HUMAN OXYGEN TOLERANCE RESEARCH PROGRAM*
Christian Lambertsen

3:40PM - 4:00PM *DISCUSSION PERIOD - FUTURE OF WET DIVING*

4:00PM *ADJOURN*

6:00PM - 8:00PM U.S.Sponsored Reception - Patio Room
Officer's Club

1993 UJNR DIVING PHYSIOLOGY PANEL MEETING

JULY 13–14, 1993

DAY 2

AGENDA

9:00AM - 9:30AM COFFEE

9:30AM - 9:40AM RECAP AND OVERVIEW
Eugene Smith

9:40AM - 10:00AM CHANGES IN ELECTROMYOGRAM POWER SPECTRA FOR STATIC EXERCISE DURING A SATURATION DIVE AT 31 ATA (NEW SEATOPIA-19)
Nobuo Naraki, F. Shidara, G. Tomizawa, and Motohiko Mohri

10:00AM - 10:20AM WHERE HAVE THE FUNDS GONE?
Leon Greenbaum

10:20AM - 10:40AM BREAK

10:40AM - 11:00AM AQUARIUS UNDERSEA RESEARCH LABORATORY
Dave Dinsmore

11:00AM -11:20AM EXPERIMENTAL TRIMIX CHAMBER DIVES FOR DEEP CAISSON WORK
Koh Kobayashi, Yoshiyuki Gotoh, Ichiro Nashimoto, and W. Sterk

11:20AM -11:40AM THE CIRCULATORY INDEX OF DECONDITIONING IS UNCHANGED DURING A 7-DAY AIR SATURATION DIVE AT 3 ATA
Yu-Chong Lin

11:40AM - 1:00PM LUNCH

1:00PM - 1:20PM RISK AND PREVENTION OF DYSBARIC OSTEONECROSIS IN COMMERCIAL, RECREATIONAL, AND SCIENTIFIC DIVING
Charles Lehner

1:20PM - 1:40 PM *THE POTENTIAL RISK OF DYSBARIC OSTEONECROSIS IN JAPANESE DIVING FISHERMEN*
Yasushi Taya, et. al.

1:40PM - 2:00PM *NURC/UNCW'S ENRICHED AIR NITROX DIVING PROGRAM*
Dave Dinsmore

2:00PM - 2:20PM *BREAK*

2:20PM - 2:40PM *MODIFICATION OF INERT GAS EXCHANGE BY MANIPULATION OF BLOOD CIRCULATION*
Claes E.G. Lundgren

2:40PM - 3:00PM *LOOK TO THE FUTURE OF UNDERWATER SCIENCE AND EXPLORATION*
Sylvia Earle

3:00PM - 4:00PM *DISCUSSION PERIOD*

WHAT IS REALLY NEEDED FOR TODAY AND THE FUTURE

OVERVIEW
David Duane

JAPANESE SUMMARY
Shinichi Ishii

U.S. SUMMARY
William S. Busch

4:00PM *ADJOURN*

6:00PM - 9:00PM Japanese Sponsored Reception - Bethesda Holiday Inn

Participants

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Gentaro Kai
Mahito Kawashima
Koh Kobayashi
Yoshihiro Mano
Nobuo Naraki
Hiromichi Oiwa
Mineo Okamoto
Naoyuki Takatsu
Yasushi Taya
Teruhiko Tsunosue

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William Busch, Chairman

Peter Bennett
Don Chandler
Rita Colwell
Dave Dinsmore
David Duane
Sylvia Earle
Ed Flynn
Leon Greenbaum
Nathaniel Howard
Regina Hunt
Christian Lambertsen
Michael Lang
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Shinichi Ishii, Japanese Chairman, and Eugene Smith, U.S. Incoming Chairman

The Way Ahead for U.S. Navy Diving

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Abstract

"The structure and mission of U.S. Navy diving has remained unchanged for decades. With the recent downsizing of our fleet many diving capable ships have been decommissioned or are scheduled for inactivation. This loss of diving billets has created a community which is significantly overmanned. Without some basic changes to the diving program there appears to be no long-term solution to this problem. Historically, Navy Diving has centered on Salvage, Submarine Rescue, and Underwater Ship Husbandry (UWSH). As underwater work tools and techniques have advanced, our capabilities to conduct waterborne maintenance and repairs on our ships have greatly improved.....the majority of Navy Diving today is in support of UWSH. With an effective UWSH program we are able to perform many repair and maintenance tasks without putting ships in drydocks. Each time we can avoid drydocking one of our ships we save approximately $850,000." (Quoted from a draft memorandum prepared by the Chief of Naval Operations for the Secretary of the Navy.)

In June 1993, a contingent of more than 70 leading experts in U.S. Navy diving met at the Navy Diving and Salvage Training Center, Panama City, Fla., and in 4 days changed Navy diving for the first time in 69 years. The delegation was made up of representatives from every community of Navy diving, the Chief of Naval Operations, Chief of Naval Personnel, Chief of Naval Technical Training, the Bureau of Medicine and Surgery, diving research organizations, and the Atlantic and Pacific Fleet Commanders. This paper discusses the changes that will have a profound affect on every aspect of U.S. Navy diving operations, including diving research and development.

Background

Since 1924, Navy divers have been using helium/oxygen gas mixtures as a breathing medium for dives where it was important to avoid the narcotic affect of nitrogen in air. Mixed-gas diving quickly became commonplace for Navy diving operations, and to achieve a mixed-gas certification has always been a matter of high achievement for Navy divers -- it proved their mettle, as it were.

The mission of the Navy diver has evolved away from deep mixed-gas diving, however, and today the typical Navy non-combatant diver performs most of his dives doing ship husbandry tasks. During the past 3 years, for example, Navy non-combatant divers performed 71,938 dives, and only 91 of those used mixed-gas as a breathing medium.

Because the mission of the typical U.S. Navy diver has shifted away from mixed-gas diving, over 70 experts from all communities of Navy diving gathered at the Naval Diving and Salvage Training Center in Panama City, Fla., in June 1993. Their mission was to change the structure of Navy diver training to reflect the current mission of a Navy non-combatant diver. After 4 days of hard discussion (by representatives from both the Atlantic and Pacific fleets, Chief of Naval Operations, Chief of Naval Personnel, Bureau of Medicine and Surgery, Chief of Naval Technical Training, and Diving Research and Development Organizations), the typical non-combatant Navy diver was redefined for the first time in 69 years.

The New Look of Non-Combatant Navy Diving

Some Programmatic Changes

Downsizing the U.S. Navy with its attendant budget reductions and shifting the Navy mission because of the end of the cold war have affected all of the Navy. Because of this, programmatic changes in the Navy Diving Policy have been implemented. Some of these changes are:

o The population of non-combatant Navy divers has been reduced from 1,800 to 1,100. This reduction of 700 divers will occur within the next few months and will be accomplished through attrition and transfers.

o Mixed-gas training has been eliminated from the regular curriculum at the Naval Diving and Salvage Training Center (NDSTC).

o All fleet-supported diving schools will be consolidated at NDSTC, Panama City, Fla.

o The basic diver training for enlisted divers is 24 weeks long and for officers is 16 weeks. Both courses have add-on modules in specialized areas that will be taught on an as-needed basis. These basic courses have heavy concentrations in ship husbandry tasks but, again, no mixed-gas training. Advanced specialized training for both enlisted and officer personnel is available. NDSTC will continue to offer 12 different diving courses of instruction to all uniformed services.

o For the foreseeable future, the Navy will draw upon its inventory of mixed-gas trained divers to supply fleet needs, if and when mixed-gas diving is needed in regions/situations where contracting the work with a commercial firm is not an option.

o All of the Navy's submarine rescue ships (ASR class) will be decommissioned soon. A submarine rescue capability will be maintained through the use of a "fly-away" saturation diving system; thus, a saturation diving capability will be maintained in the Navy. Only the divers selected for saturation diver training will receive mixed-gas training.

o Navy divers are no longer trained in underwater welding and cutting. (This will be contracted to a commercial firm.)

o The typical Navy diver is qualified to dive SCUBA and surface supplied air to 190 fsw.

o Non-combatant fleet diving lockers (groups) will be consolidated in three locations on the East Coast, two on the West Coast, and one in Hawaii. The only exceptions to this will be the Underwater Construction Teams with the Navy SEABEE units; these have such a specialized non-combatant mission that they cannot consolidate with the typical dive locker.

The Way Ahead

The way ahead for Navy diving will show that the mission for Special Warfare and Explosive Ordnance Disposal divers basically remains the same. The mission for the non-combatant diver, on the other hand, is changed, and future years will see the typical Navy diver performing long bottom-time shallow dives (less than 100 fsw) using air as a breathing medium. Indeed, some divers will spend the bulk of a 20-year Navy career as a diver and never do one mixed-gas dive.

The need to reduce expenses will be under continual scrutiny by Navy officials, and on-scene commanders will be forced into a frugal existence for Navy diving operations. One of the areas where significant savings is possible is in ship husbandry. It has been estimated that if Navy divers were to perform Underwater Ship Husbandry (UWSH) rather than performing these maintenance tasks in drydock, the Navy could save $850,000 per ship. The way ahead, then, will see Navy non-combatant divers making about 30,000 dives each year to perform the following tasks:

I. Underwater Ship Husbandry
- Install cofferdams/flanges/patches
- Shaft/rudder packing/seal replacement
- Propeller inspection/repair/replacement
- Sonar dome rubber window repair
- Underwater ultrasonic hull inspections/repair
- Interim hull cleaning
- Prairie Masker air relief valve replacement
- Prairie Masker belt cleaning/inspection an replacement
- APU inspection/replacement
- Borescope inspection
- Rodmeter/pitsword repair/replacement
- Bow thruster repair
- Underwater photography
- Underwater rigging
- Check docking blocks
- Underwater sacrificial zinc replacement
- Underwater painting
- Technical assistance for underwater repairs
- Enclosed space diving
- Gooseneck/radiation fitting installation/removal
- Sound head/hydrophone inspection/replacement
- Main ballast vent valves maintenance/repair

II. Salvage
- Flyaway salvage and recovery
- Underwater search, location, and recovery of lost objects
- Underwater salvage rigging
- Battle damage repair
- Underwater demolition
- Underwater damage assessment
- Submarine rescue chamber operations
- Ship and aircraft salvage/recovery
- Research and development support
- Use of remotely operated vehicles
- Operate side scan-sonar
- Debeaching stranded vessels
- Harbor clearance
- Dewatering
- Offship fire fighting
- Open ocean towing
- Oil spill recovery
- Recover exercise torpedoes
- Recover non-service mines
- Underwater search with hand-held sonar
- DSRV operation and support

III. Saturation Diving
- Saturation diving to 850 fsw
- Submarine rescue

IV. Underwater Construction
- Inspect/repair waterfront facilities
- Install/maintain/inspect underwater surveillance systems
- Install/maintain/recover offshore petroleum distribution system

Hydrographic/geotechnical services
Underwater construction
Install/maintain/inspect fleet moorings
Test and evaluate new underwater construction equipment
Arctic diving operations
Underwater dredging and jetting operations
Operate underwater hydraulic tools
Contaminated/hazardous environment diving
Placement of SEAFORM bags and SYMONS forms/concrete
Propellent Embedment Anchors (PEA)
ROV operation and maintenance

V. Miscellaneous

Recompression chamber operations
Aviation water survival training
Aircrew rescue
Research and development support
SCUBA diving instruction/qualification/supervision
Support for Swimmer Delivery Vehicle (SDV) Teams
Security swims
Maintain medicine support
Diver proficiency/requalification
Diver Life Support System (DLSS) certification

Impact on Navy Diving Medicine Research and Development

The changes that have been in effect since that historic June meeting in Panama City, Fla., will have a profound effect on diving medicine research and development. Historically, diving medicine R&D has been primarily focused on physiological problems associated with deep mixed-gas diving and saturation diving. This will change quickly. A restructuring of the Navy's diving medicine R&D plans is underway with a focus on the following mission priorities (in order of importance):

1. Special Warfare Swimmer
2. Explosive Ordnance Disposal
3. Ship Husbandry
4. Salvage
5. Saturation

Given the above mission priorities, Navy diving medicine research priorities have been prioritized as follows:

1. Increased time in cold water
2. Improved surface decompression procedures
3. Accelerated decompression (bounce dives)
4. Oxygen toxicity
5. Diver hearing conservation
6. Long-term health effects
7. Improve/ensure breathing gas purity
8. Recover SSBN crew from 1.5 - 2.5 ATA
9. Improved treatment of DCS/AGE
10. Improved work performance at depth
11. Saturation diving to maximum of 1,000 fsw
12. Hypercarbia recognition
13. Bounce dive to deeper than 400 fsw
14. Improved CO_2 absorbent and development of CO_2 sensor
15. Nutrition and hydration

While the Navy, as a whole, will be contracting out many diving services, they will maintain the following in-house medical capabilities:

1. World class DCS/AGE treatment/consult capability
2. DCS risk assessment
3. Oxygen toxicity risk assessment
4. Capability to address diver hearing/tool noise issues*
5. Gas purity/gas analysis*
6. Submarine escape/rescue issues
7. Conduct human experiments with Navy-unique risks
8. Maintain expertise in UBA test and evaluation

*Work could be contracted out but need in-house expertise to relate findings to Navy mission.

Summary

Navy diving has changed. For the first time in 69 years, the drive for deeper, longer dives is no longer in the forefront of the thoughts of Navy strategic planners for undersea operations. Just the opposite is true; shallow, long dives are now the vogue. This change has evolved over time, but one cannot dismiss the shrinking budget for armed forces operations and the end to the cold war as contributing factors.

Regardless of what gave genesis to the recent changes that have been implemented, those changes have caused a complete restructuring of diving research priorities. The future for diving medicine research will see an increase in oxygen toxicity work, decompression from multi-level dives, elevated PPO_2 decompression studies for both diving and submarine escape, in-water noise hazards, low frequency in-water transmissions, bounce diving deeper than 300 fsw for special interest groups, numerous thermal studies (both hot and cold), and the never-ending problems with atmosphere contaminants.

Bob Dillon once said, "Times they are a-changin.'" I'm here to say, "Times they have changed!"

Where Have the Funds Gone?

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As a permanent member of the Undersea and Hyperbaric Medical Society's Membership Committee, I have observed a steady decrease in diving physiologists applying for membership in the Society during the last 7 years. Most of the new member applicants are physicians working in or beginning to work in the clinical area of hyperbaric medicine. It is obvious then that in the years ahead when our present cadre of diving physiologists retire, there will be few, if any, well-trained scientists to take their places. As I see it from my position in the Society, this is not a phenomenon limited to the United States; it is a worldwide trend.

The most obvious answer to this trend is the unrelenting decline in research funds in federal agencies that in the past have supported diving research. Those federal departments or agencies in the Unites States have been the U.S. Navy and the National Oceanic and Atmospheric Administration (NOAA). Most of the support for diving research in the United States during the 1940's, 1950's, and 1960's originated in the Physiology Branch at the Office of Naval Research (ONR). Not only did it support the research, but it also supported the construction of chamber facilities. Following the establishment of NOAA as a new federal agency in 1970, an undersea research program was established later.

As the Office of Naval Research, and especially the biological sciences program began to shift its support to molecular research, the newly established U.S. Navy Medical Research and Development Command began to support diving research in the nation's universities and its in-house laboratories. However, the funds in the past that were awarded to universities began to decrease because of fiscal demands of expanding research capabilities in the Navy's laboratories, especially the new hyperbaric laboratory at the Naval Medical Research Institute, now renamed the Albert R. Behnke Diving Medicine Research Center.

The major weakness in NOAA's National Undersea Research Program was that it never had a specific allocation (non-budgeted) in the budget. It took a back seat to the Sea Grant Program that also was vulnerable to geographic or political tampering. In times of tightening federal budgets, a so-called non-funded or unbudgeted program as a line item was insecure with no guarantee of research continuity.

How can the Society help the diving research community reverse this downward trend of research funding? The U.S. Navy because of its history and operational needs has been the leader in diving research through its support of university research and its own laboratories. Therefore, it seemed most appropriate to begin with the U.S. Navy and, through the Navy, try to rectify a worsening funding situation.

Since most Congressional committees have become somewhat immune or insensitive to requests for increased biological research funds unless they are tied to a major illness or national security, we thought that focusing on a Navy personnel weakness might be the most productive approach.

Following conversations with a group of junior naval medical officers, it became obvious that many bright and highly motivated Navy physicians were not selecting diving and/or submarine medicine as naval careers. There was no career program to train them in diving medicine that also provided for career possibilities after life in the Navy, viz, occupational medicine.

This approach was pursued with the Senate's Armed Services Committee. They were at first surprised and secondly concerned that in the future the Navy would no longer have a cadre of well-trained submarine and diving medical officers because those physicians who were highly trained had retired or were retiring. We were asked by the Committee's staff to prepare a series of questions for use by the Committee for future discussions with naval staff. These questions were prepared by Society members who are retired U.S. Navy submarine and diving medical officers and who incidentally received postgraduate research training in university hyperbaric laboratories. Not only did the questions focus on the training of naval medical officers but also on the training of civilian scientists who could be employed by military laboratories or serve as future teachers and scientists in university laboratories. Support for these laboratories should be programmatic and receive facilities support. It is my understanding that some of these questions have already been responded

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to as a result of discussions with naval staff. Hopefully these discussions will eventually lead to renewed support of those university laboratories that in the past served as professional training grounds for future diving and submarine medical officers.

On the civilian side, we would like to take a similar approach to help with the funding of N0AA's National Undersea Research Program. As an effort to gain senior congressional support for NOAA's program, we contacted the Department of Fisheries in Maine to obtain income data on sea urchin, scallop, and fish farming, plus the estimated number of divers engaged in these occupations. This fisheries data, along with a letter emphasizing the importance of funding legislation that would support a diving research program to increase the safety and efficiency of professional divers, was forwarded to selected Congressmen and Senators. The state of Maine was selected specifically because a major source of its income is derived from the sea and also because of the senatorial seniority of one of its state's senators.

The Society will be arranging a diving symposium in collaboration with the Association of Diving Contractors for its annual meeting in 1994 to gain further insight into those areas of diving that require future research to make diving safer and more efficient. The commercial, military, scientific, and recreational diving communities will be invited to participate. The summary program derived from this symposium will be used later during discussions with Congress and the Chief Scientist at the Department of Commerce in an attempt to gain broad based and continued fiscal support for NOAA's National Undersea Research Program.

As was indicated earlier, the demise of support for diving is not limited to the United States; it is a worldwide phenomenon. Because of this international trend, the Society has contacted senior diving physicians and physiologists in most of those nations where diving has been a major commercial enterprise. Each of these leaders is having or will have national meetings to discuss and prioritize those major problems (technical and medical) related to diving.

An international meeting is scheduled for September 1994 in Marseille at which all or most of the national chairmen will attend to discuss and hopefully develop a listing of major diving problem areas. This will be published at a later date as an international diving research plan. We hope that these meetings along with the diving summaries will help to revitalize diving as a productive and safer occupation and a recreational activity.

Technical Diving: New Techniques for Untethered Diving in the Range of 40 to 100 msw

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Abstract

Technical diving consists of using special procedures, gas mixes, equipment, gas management, decompression, training, discipline, and much more to accomplish untethered diving in the range beyond traditional recreational diving. Technical diving is recreational in that people who do it do so for fun, but they do so well beyond the limits of traditional recreational diving. The main characteristic of technical diving is that it involves the use of more than one breathing gas mixture on a dive. Diving with oxygen-enriched air is not considered technical diving. This normally includes descent, time on the bottom, and ascent to the first decompression stop breathing a bottom mix with the appropriate oxygen level. Decompression calls for one or more intermediate breathing mixtures and usually ends with oxygen breathing at the shallow stops. Bottom mix is usually a "trimix" of oxygen, helium, and nitrogen, and intermediate mixes are usually oxygen-enriched air. Oxygen level is controlled to maintain efficient decompression yet avoid toxicity. A wide variety of special equipment and techniques are used, from filling the dry suit with argon for better insulation to taking decompression in an underwater station or "habitat." While a generally uniform set of procedures is taught and practiced, there is no general organization covering technical diving, and there are no accepted operational standards. Technical diving remains a high risk activity.

Introduction

Over the last 6 or 7 years, a new form of diving has developed. This is called "technical diving" by the media and many of the practitioners, as an analogy with technical mountain climbing. Technical diving is diving beyond the usual limits, made possible by the use of special techniques and equipment; it also requires a higher level of training and discipline, and a substantial investment in equipment and preparation. Since its original inception in the form of decompression and breathing gas management necessary for extensive cave exploration and penetration, the concept has reached something of a uniform set of practices in terms of what is done, how, and with what equipment. By no means is there yet a set of standards for safe performance of this special kind of diving.

Among the critical elements of technical diving are special gas mixes, custom decompression tables, means of carrying enough gas, adequate training, and a high order of discipline.

The practice customarily consists of descent with a bottom "trimix" comprising nitrogen, helium, and the appropriate oxygen fraction for the target depth, one or two "intermediate" decompression mixes of oxygen-enriched air, followed by inwater oxygen breathing at the shallow decompression stops. There are variations on this pattern depending on the mission or other factors; sometimes a "travel" mix is used when depth is great enough that bottom mix is not rich enough in oxygen to breathe at the surface. This form of untethered diving requires a lot of gas and special techniques to carry it, as well as thermal protection, sophisticated buoyancy control, and many other factors.

Deep Recreational Dives

Recreational diving is well recognized as being limited to the range to 130 fsw (fsw=feet of sea water, 1/33 atmosphere) or 40 msw (msw=meters of sea water; 1 msw=0.1 bar or 10 kPa), and it is further limited to dives with air as the breathing gas and not involving decompression stops. Realistically, these are not the limits within which all recreational divers operate, but they are the limits to which divers are trained by the recreational diving training agencies, particularly in the United States. "Deep" is a relative term that involves the diver's own skill and preparedness as much it does the water depth. Even within these limits, special "deep" training is needed to go even as deep as 130 fsw.

For some years now some scuba divers have exceeded the 40 msw (130 fsw) limit, using decompression stops when necessary, and under some conditions have even used oxygen for decompression (often with the otherwise unreliable USN Exceptional Exposure air decompression

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tables). These divers go well beyond the depth at which nitrogen narcosis can become seriously debilitating. As depth increases much beyond 60 msw (200 fsw), the PO_2 (partial pressure of oxygen) in air also becomes a risk factor due to CNS (central nervous system) toxicity. Because of the narcotic risk, in the late 1980's deep cave divers began to add some helium to their bottom mixtures (Hamilton 1990). This also allowed the oxygen fraction to be reduced, allowing lower PO_2's at bottom depth and making longer bottom times feasible from an oxygen toxicity viewpoint. The use of special mixtures made special decompression tables necessary, and these were developed. This technology quickly spread to deep wreck divers, who learned to do this same pattern with diver-carried gas (Mount and Gilliam 1993, Gentile 1992).

Definitions: Technical Diving and Nitrox

What is "technical diving"? By one definition, the minimal requirement of a technical dive, the characteristic that sets it off from recreational diving, is that on a technical dive the diver uses more than one breathing mixture. Just diving beyond the limits defined for recreational diving is not enough to qualify as technical diving, especially if air is the only breathing gas. However, deep air diving using other gas mixtures and oxygen for decompression, for example, would be regarded as technical diving.

One reason for this apparent pedantry is another new fad on the fringes of recreational diving, the use of breathing gas mixtures of air enriched with added oxygen, the so-called "nitrox" diving. The objective of enriching air with extra oxygen is to reduce the nitrogen component in the breathing gas (although the imprecise name "nitrox" might imply otherwise) and consequently to improve the decompression, either by allowing longer bottom time than an air dive at the same depth, or by reducing the decompression risk in comparison with the same dive on air. The practical depth limits of enriched air are actually less than the 40 msw (130 fsw) limit for recreational diving; but in the minds of some critics of "nitrox," it is technical diving. Diving with enriched air requires minimal extra knowledge or skill except for a better understanding of oxygen toxicity limits, but making and dispensing enriched air mixtures safely and with good quality control is another matter. This requires considerable knowledge and expensive equipment and can involve some risk. Whether "ordinary recreational divers" should dive with "nitrox" is still a mildly controversial issue, often clouded by substantial lack of understanding of what it is all about. Initial opposition was probably subconsciously based on a perceived loss of control by training agencies rather than safety. The technical diving community will generally agree that diving with enriched air or "nitrox" is not technical diving. While technical diving is special, risky, and has its own critics, it is so clearly outside the limits of recreational diving that there is not nearly so much controversy about it as there is about "nitrox." (For more on enriched air diving, see Hamilton et al. 1989, Hamilton 1992.)

Although the contrast with the recreational diving domain is clear enough, it is important to realize that most technical divers are in it for fun, so it is in fact "recreation." Some are photographers, treasure hunters, and scientists, but rarely are these divers "employees" in the traditional sense (as is usually the case with commercial divers). While there may be plenty of cause for concern, if technical diving methods result in fewer deep dives being done with air and consequently a reduced exposure to the risks of narcosis, it has to be of some benefit.

Technical Diving Practice

Technical divers penetrate to depths with diver-carried gas that are a moderate challenge to commercial diving contractors with surface-supplied gas. The commercial diver is tethered, under close supervision, has a tender and standby diver, wears a full-face mask or helmet, is in constant communication, and has a variety of other support functions such as surface-supplied hot water heating, medical backup, and a decompression chamber at the dive site. The technical diver, on the other hand, endeavors to be self-sufficient. Technical divers often work in teams of two or more, but the "buddy system" used by recreational divers is not usually regarded as an effective safety reserve in most technical diving situations. Tech divers do, however, use a variety of redundancies, including such things as extra regulators and gas. The surface often cannot be regarded as a haven, either because it cannot be reached (as from a cave or inside a shipwreck) or because the diver has a significant decompression obligation and cannot surface without stops.

Special Gas Mixes

A typical technical dive might be to explore a shipwreck at a depth of 75 msw (250 fsw). The diver might carry four scuba tanks of gas. Two of these would be large tanks in a backpack filled with bottom mix, enough to allow 20 or 30 min of time at near the bottom depth (allowing some as a reserve). The mix would most likely be a "trimix" of oxygen, helium, and nitrogen, with the oxygen level selected to give a favorable decompression but to stay out of the range of central nervous system oxygen toxicity at the maximum depth it is to be breathed (Nashimoto et al. 1991). The helium component in the trimix could range between 17 and 50%, for example; the helium portion is chosen to give an adequate reduction of nitrogen narcosis but also with a view to keeping the cost of the mixture down. Decompression time is generally a little shorter if the mix has less helium. Many divers make their own mixes, but they are available at some specialized dive shops. When available, a fill for a dive of the type under consideration costs on the order of $100. In any case, it is considered essential for the diver to check each mix with an oxygen analyzer before diving.

A small extra tank (a "pony" bottle) of bottom mix or one with slightly more oxygen (a "travel mix") might provide gas to breathe to the first decompression stop, possibly as a reserve if the bottom mix were suddenly lost from both tanks (unlikely, but not a happy thought). Another tank would contain an intermediate or "decompression" mixture. This would probably be an enriched air mixture, again chosen to optimize decompression, avoid oxygen toxicity, and be of sufficient quantity for the job. Sometimes two different intermediate decompression mixtures are used. Still another tank usually contains pure oxygen, to be used for the last part of the decompression. Each tank or tank manifold has its own regulator, of high quality and reliability.

Maintaining the right oxygen level is an ongoing problem in technical diving, mainly to ensure that CNS toxicity is avoided. The accepted guidelines for preventing CNS toxicity are those in the latest edition of the NOAA Diving Manual (1991). This allows an exposure to 1.6 atm PO_2 for as long as 45 min, but this limit is only appropriate for a diver not working hard and with no buildup of CO_2. Some divers wisely use a lower personal limit. A good algorithm for maintaining a high oxygen level for decompression efficiency and yet maintaining a low risk of toxicity is still lacking. Management of the slower acting "whole body" oxygen toxicity is only a consideration in an extreme exposure technical dive, such as some used in cave exploration.

Special Equipment

Since decompression from some of these dives can be quite long, up to several hours, the tech diver needs good thermal protection. He or she might wear a good quality dry suit and underwear as thick as necessary for passive thermal protection and might inflate the suit with argon instead of a mix containing helium because argon has lower thermal conductivity and thus greater insulating power (Barsky et al. 1992). For long exposures it is necessary to avoid urinating in the suit's insulation, because this renders it ineffective. Diapers and various "relief tube" devices are used.

To be able to carry enough gas is a challenge. A few years ago many divers overpressurized their tanks to just under 1.5 times the rated pressure (since that is presumably still within the tank's hydrostatic test pressure) in order to cram more gas in. No catastrophic events are known to have resulted from this practice, but it is risky; cracks have caused tanks to fail even without being overpressurized. Tanks with larger capacities without the need for overpressure are now available, including some of titanium. Cave divers in particular have worked out rather sophisticated methods for carrying and storing the necessary gas, but since the way out has to be carefully marked it is effective to "stage" extra tanks along the way. Staging is also done, but less confidently, by open water deep divers.

At present most technical divers use a standard scuba facemask (carrying a spare of course) and breathe from a demand regulator using a mouthpiece. Some are beginning to look at full-face masks and through-water voice communications, but these are not universal. One important benefit of a full-face mask is that it might enable a diver to survive a convulsion due to CNS oxygen toxicity. The risk of a convulsion increases as the oxygen content of the breathing mixture is increased, which is done in order to shorten decompression. The convulsion itself is not damaging, but drowning becomes almost inevitable when a convulsing diver spits out the mouthpiece; full-face masks greatly reduce this aspect of the risk. On the down side, full-face masks and especially those that allow conversation tend to require more gas, an item normally in short supply. Also, it is not so easy to share gas; this requires special connectors rather than just changing mouthpieces.

For long swims (as in a cave penetration) or swimming in a current, the tech diver might use a battery-powered "scooter," or diver propulsion vehicle. In open-water dives the diver has to be prepared for the eventuality that he/she cannot make it back to the boat for some reason, so signalling devices—flares and a strobe light—are standard gear. Open-water divers also may carry a line on a reel with a float that could be used to control decompression stages should the anchor line not be available. Another interesting twist is that sometimes divers use such a rig to allow them to decompress while drifting with the current. This "drift decompression" reduces diver exertion and greatly reduces the "wind chill" effect of the current, but it requires an alert boat captain and careful planning.

Technical divers use several methods of getting the diver out of the water during long decompression stops, especially when oxygen is being breathed. Examples are standard lift bags well anchored and configured with seats, or—in cave diving—a cattle watering trough may be inverted on the cave ceiling at the appropriate depth and filled with air. These stations are often supplied with oxygen by "hookah" hose from tanks at the surface.

Decompression Tables

As mentioned, there are no publicly available decompression tables for trimix diving of the sort that make air diving so accessible. In early technical diving, most decompression was done with special "custom" tables prepared for the particular exposure by a few specialists with the capability. In fact, these tables were the breakthrough that started the whole "technical diving" thing (Hamilton and Turner 1988). This method can work well as long as the computations have a good foundation. The outcome of these decompressions has been quite satisfactory considering the extent of the exposures; there have been relatively few cases of decompression sickness. A sample of the type of table used for a 250 fsw dive is given in figure 1. This dive uses an oxygen fraction of 17 percent in the bottom mix, giving a PO_2 of 1.46 atm at the bottom. Helium might vary between about 17 percent to as high as 50 percent. The fraction of helium selected is intended to be enough to give an acceptable narcosis level (to an "equivalent narcotic depth") based on air as a reference. At 110 fsw, the mix is switched to an enriched air intermediate mix of 36 percent oxygen, the balance being nitrogen. At 20 fsw, the diver goes on oxygen for the remainder of the dive and has the option of taking the 10 fsw stop at 20 fsw in case of a rough sea.

These dives are beyond the capacity of normal dive computers (DC's), and as of mid-1995, a diver-carried DC for trimix diving is not yet available. Some available DC's will log the time-pressure profile of dives of this type. Logging all profiles is highly recommended. A new decompression option has developed in the form of several PC-based computational programs that can be used by the diver to calculate his/her own decompressions (Hamilton and Crea 1993a, 1993b).

Treatment

One area not well under control in most technical diving practice is the matter of having a decompression chamber (some prefer to say "recompression" chamber) at the dive site. These are not presently available on most dive boats, nor are they usually accessible to cave diving sites. Two ways of partially dealing with this are available. One technique is inwater oxygen treatment. This has merit in some cases, has been known to work, but also has limitations (Edmonds 1993). A more decisive way of dealing with the need to recompress a diver with DCS is by means of a portable chamber. One notably well-engineered chamber made of Kevlar is available--the Hyperlite (SOS, London, 44(81)959-4517). It is small enough to be carried by one person and can be checked on an airline. Designed as an evacuation chamber rather than one to be used for remote treatment, it can offer great potential for survival following blowups and can make dealing with decompression illness following a properly done dive a great deal more effective and less disruptive. There is a high premium for beginning treatment promptly. Chambers should be on all dive boats, whether for recreational or technical diving.

Rebreathers Are Coming

For some conditions depending on depth, water temperature, and other factors, the limit to a dive is the diver's endurance or ability to maintain body temperature. For most technical dives, however, the limitation of what an untethered diver can do depends on how much gas he or she can carry using open-circuit gas supplies.

However, closed-circuit recirculating breathing apparatus offers new options. These have been used by the military for some years and are now on the civilian market. Basically, a rebreather consists of a breathing bag or counterlung, a canister for absorbing CO_2, an appropriate pressurized gas supply, and the necessary valves and hoses. The most sophisticated rebreathers are electronically controlled and are designed to maintain a constant oxygen partial pressure throughout the dive, at various depths and under different work loads and conditions. The constant oxygen partial pressure enables optimal decompression.

Simpler "semi-closed" rebreathers use a constant flow of an oxygen-rich mixture to maintain enough oxygen in the counterlung. These allow the oxygen level to vary with the exercise rate and hence oxygen consumption of the diver, making it more difficult to determine an efficient decompression. Some units link the oxygen inflow to the diver's breathing minute volume and thus maintain a more nearly constant oxygen level and permit a more efficient decompression.

Standards

Whereas commercial dives are virtually all handled as project operations with leadership and administrative structures, the pattern for technical diving may involve a buddy pair or trio, but it rarely involves a full team approach. Each diver has his or her own equipment, tables, and often procedures. This means that there are limitations in things like organization, communications, and topside support. Something else missing at this time is a set of guidelines or standards defining experience, training, equipment requirements, team structure, redundancy, and so on. Some training organizations have their

DCAP+ (c) 6.26-02 Run 92Dec06 16:50

KW-Demo TRIMIX DIVE

RWH	92Dec06	DEPTH	250 FSW
D159T0.HD3	MF11F6.DCP	BOTTOM TIME	25 MIN
		BOTTOM MIX	17TX50
		BOTTOM PO2	1.46 ATM
		Time in minutes	

DEPTH FSW	STOP TIME	DEC TIME	RUN TIM	MIX	HIPO2 ATM	COMMENTS
00	00	00	00	AIR	0.21	DESCEND TO BOTTOM AT COMFORTABLE RATE
	00	00	00	17TX50	0.17	BREATHE TRIMIX 17%O2, 50%HE FROM SURFACE
250	25	00	25	17TX50	1.46	ASCEND TO FIRST STOP AT -60 FSW/MIN
120	01	03	28	17TX50	0.79	RATE -30 FSW/MIN AFTER FIRST STOP
110	01	05	29	EANX36	1.56	SWITCH TO 36% EANx AT 110 FSW (OR 1STP)
100	01	06	31	EANX36	1.45	
90	02	08	33	EANX36	1.34	
80	01	10	34	EANX36	1.23	
70	02	12	37	EANX36	1.12	
60	05	17	42	EANX36	1.01	
50	05	23	47	EANX36	0.91	
40	10	33	58	EANX36	0.80	
30	18	51	76	EANX36	0.69	
20	15	67	90	OXYGEN	1.61	BREATHE 100% OXYGEN, 20 FSW TO SURFACE
10	26	91	118	OXYGEN	1.30	
00	00	93	118	OXYGEN	1.00	REACH SURFACE

Figure 1. Sample trimix decompression table.

own "standards," but there is no uniform, diver-driven consensus on the minimum requirements for a safe operation. Obvious practices are lacking, such as having a standby diver ready to aid a diver with extra gas or equipment if needed, and communications to tell when it is needed.

The best way for regulation to be done is by peer standards and peer pressure. This can best be done by a diver-run organization (as opposed to government). If the technical divers do not put their own houses in order, some other agency is likely to do it for them. There is as yet no widespread organization of technical divers. There is a growing "community" of diverse individuals with varying levels of training, experience, and sophistication who have a common goal to extend their diving capability beyond the traditional limits and to do this safely. The Catch 22 is that the same independence that motivates these divers to do these things makes it unlikely that they will organize themselves without a stronger incentive than they currently see.

If we cannot have standards, at least we can say, "Don't even **think** of doing it if you aren't going to do it right."

Literature Cited

Barsky S., D. Long, and B. Stinton, 1992. *Dry Suit Diving*. A guide to diving dry. San Diego: Watersport Publishing, Inc.

Edmonds C., 1993. In-water oxygen recompression: A potential field treatment option for technical divers. *aquaCorps* (N5; Bent):46-49.

Gentile G., 1992. *Ultimate wreck diving guide*. Philadelphia: Gary Gentile Productions.

Hamilton R.W., 1990 Feb-Mar. Call it "High Tech" diving. *AquaCorps* 1:6-9, 50.

Hamilton R.W., 1992 Jan. *Workshop findings: Evaluating enriched air ("nitrox") diving technology.* Boulder, CO: Scuba Diving Resource Group.

Hamilton R.W., and J.T. Crea, 1993a. Desktop decompression review. *aquaCorps J* (N6):11-17, Jun.

Hamilton R.W., and J.T. Crea 1993b. Desktop decompression review 2.0. *aquaCorps J* (N7):34-39, Dec.

Hamilton R.W., A.W. Hulbert, and D.J. Crosson (eds.), 1989. Workshop on enriched air nitrox diving. *NURP Research Report* 89-1, Sept., 152 pp. Silver Spring , MD: NOAA National Undersea Research Program.

Hamilton R.W., and P. Turner, 1988. Decompression techniques based on special gas mixes for deep cave exploration. *Undersea Biomed Res.* 15(Suppl):70.

Mount T., and B. Gilliam, 1993. *Mixed gas diving. The ultimate challenge for technical divers.* San Diego: Watersport Publishing, Inc.

Nashimoto I., K. Kobayashi, and Y. Gotoh, 1991. Trimix diving at moderately deep depth. In: G.D. Dennis (ed.), *Proceedings of the 10th United States-Japan Cooperative Program in Natural Resources (UJNR) Panel on Diving Physiology and Technology, June 4-7, 1989, Kauai, Hawaii*, pp. 137-142. Silver Spring, MD: NOAA's National Undersea Research Program.

NOAA, Office of Undersea Research, U.S. Department of Commerce, 1991. *NOAA Diving Manual*: Diving for Science and Technology. Silver Spring, MD.

Detection of Selected Pathogens in Divers and Diving Sites in the United States, Ukraine, and Russia: Analysis of Data from a 3-Year Study

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Abstract

A 3-year study, beginning August 1989 and ending May 1992, was carried out to investigate potential risk of divers working in polluted waters. Pre- and post-dive swabs were collected from the ears, nose, and throat of the divers and the mouthpiece/regulator of the diving gear. The specimens were analyzed for selected pathogens. A 20 ml blood sample was drawn from each diver before the dive and 30 days after the dive for immunological analyses. Surface water, bottom water, and sediment samples from each dive site were also collected for microbial and chemical analyses.

A total of 286 bacterial strains were isolated from divers and environmental samples. Toxigenic *Vibrio cholerae* 01 was isolated from the U.S., Ukraine, and Russian divers and dive sites. The frequency of isolation of specific pathogens was: *Pseudomonas* spp. (63.6%); *Aeromonas* spp. (28.7%); *V. cholerae* 01 and non 01 (6.3%); and others (1.4%), which include *V. vulnificus* and *Alteromonas putrefaciens*. Immunological analyses of the sera revealed that more than 70 percent of the divers were exposed to the specific pathogens that had been isolated. Results of the study provide a detailed understanding of the microbiological hazards associated with diving in polluted waters.

Introduction

Investigation on the microbial colonization of divers and their diving gear during diving operations was carried out in our laboratory (Colwell 1991, Joseph et al. 1991). A low incidence of infection of divers was successfully traced back to exposure to pathogens in the aquatic environment. The outcome of several studies during the past decade suggests the presence of risk of infection for divers, exemplified by an incident in New York City during the summer of 1982. Gastrointestinal symptoms were reported by 17 of 40 fire department scuba divers after the divers had undergone dive training in polluted coastal waters (Jones et al. 1985). In general, the most frequently reported infections associated with diving in polluted waters are ear infections and skin rashes, followed by mild to severe gastrointestinal disorders that may last from 2 to 10 days (Daily and Coolbaugh 1985). Wound and respiratory infections caused by waterborne pathogens have also been reported (Jones et al. 1985, Losonsky 1991). The study reported here was undertaken to define, more precisely, the risks to divers who must dive in microbiologically and/or chemically polluted waters. The major objectives of the study were to determine the effect of pathogens present at dive sites and the colonization of the divers with those organisms while diving. Although several microbial species have been implicated with infections incurred while diving in polluted waters, the pathogens that were targeted in this study included: *Vibrio cholerae* serotype 01 and non-01; *V. vulnificus; Pseudomonas aeruginosa;* and *Aeromonas* spp. It may be mentioned here that very often bacterial cells cannot be cultured using conventional culture methods when they exist in a viable but not culturable state. Results from the study reported by Huq et al. demonstrated that greater than 63 percent of plankton samples were positive for *V. cholerae* 01 by direct detection method when only 1 percent was culture positive (1990). Rapid detection kits developed and optimized for

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Table 1. Diving sites and number of volunteers who participated at each diving occasion

	Diving sites	Date	Number of volunteers
1.	Anacostia River, Washington, DC	08/09/89	5
2.	Potomac River, Washington, DC	08/16/89	5
3.	L. Bird Johnson Park, Washington, DC	08/23/89	5
4.	Loch Raven Reservoir, Bridge site, Baltimore, MD	09/20/89	9
		04/17/91	10
5.	Delta Dam, Pennsylvania	04/11/90	7
		04/18/90	9
6.	Frog Mortar Creek, Martin St. Airport site Baltimore, MD	05/09/90	5
		05/16/90	
7.	Seneca Creek, Martin St. Airport, Baltimore, MD	05/16/90	1
8.	Beaver Dam Quarry, Baltimore, MD	09/12/90	10
		11/21/90	6
9.	Oregon Ridge Lake, Cockeysville, MD	10/10/90	9
10.	Narrow River, Narragansett, RI	11/16/90	4
		10/18/91	5
11.	Washington Channel, Potomac River, Washington, DC	02/05/91	6
12.	Patapsco River, Baltimore, MD	05/15/91	8
		05/12/92	15
13.	Loch Raven Reservoir, Dam Site, Baltimore, MD	06/12/91	9
14.	Gelendzhik, Black Sea, Russia	07/15/91	5
15.	Odessa, Black Sea, Ukraine	07/18/91	5

V. cholerae are now available commercially (Colwell et al. 1992, Hasan et al. 1994a, Hasan et al. 1994b). Results on chemical pollution, however, are not presented here.

Diving Sites and Volunteer Divers

Several diving sites were included in the study such as lakes and/or rivers in Maryland, Pennsylvania, Rhode Island, and Washington, DC, and in the Black Sea, off the coasts of Russia and the Ukraine. Professional divers at these locations, who were doing diving exercises as part of their routine training, volunteered for the study. A total of 166 volunteer divers were included in the study, which took place during August 1989 to May 1992 (table 1). The divers were sampled during each 30-minute diving operation, and some of the divers were sampled more than once, which was appropriately recorded and taken into account when tabulating and interpreting the results.

Collection of Samples

Swabs were taken from the areas of direct contact with water, such as nose, ears, and throat of each diver and of their gear, i.e., regulators, before and after each dive. Each swab sample was incubated in alkaline peptone water (APW) for 6 h at 35°C. Water and sediment samples collected at the dive sites were also enriched in APW for 6 h at 30°C. Blood samples from the divers, collected before and 30-60 days after each dive, were analyzed for IgG and IgA titers against whole cell antigen of the isolates of *V. cholerae* 01.

Identification of Isolates

Swab samples were incubated in APW for 6 h and streaked onto thiosulphate citrate bilesalts sucrose (TCBS) agar (Oxoid, Hampshire, England) and trypticase soy agar (TSA [DIFCO Laboratories, Detroit, MI, USA]) plates. All plates were incubated at 35°C for 24-48 h. Suspected colonies of *V. cholerae* were identified, using conventional biochemical tests. Confirmation of *V. cholerae* 01 isolates was done by specific immunoassays, as follows. CholeraScreen™, a monoclonal antibody (COLTA™)-based coagglutination test (Colwell et al. 1992) (New Horizons Diagnostics [NHD] Corporation, Columbia, MD), was performed. Cholera SMART™, a colloidal gold-based colorimetric immunoassay, (Hasan et al. 1994a) (NHD) was also performed. Finally, a direct fluorescent antibody (DFA) staining test (Hasan et al. 1994b) was done, using Cholera DFA, fluorescein isothiocyanate labeled-COLTA monoclonal antibody to confirm identification. All tests involved in the study provided a broad range for detection of *V. cholerae,* minimizing the possibility of obtaining a false negative.

Other human pathogens were isolated and characterized following conventional microbiological methods (Farmer et al. 1985).

Table 2. Sources of *V. cholerae* 01 and non–01 strains isolated in this study

Serotype of *V. cholerae* (I.D. number)	Source	Date	Diving site	PCR and ELISA test
01 (TT-11)	Sediment	8-16-89	Potomac River Washington, DC	-
01 (36-a)	Post-dive right ear	5-9-90	Frog Mortar Creek Baltimore, MD	+
01 (TC-20)	Post-dive regulator	11-9-90 Narragansett, RI	Narrow River	+
01 (T-Surface 2)	Surface water	11-16-90	as above	-
non-01 (TC-40 PA)	Post-dive regulator	11-16-90	as above	-
non-01 (TC-water 1-sc)	Surface water	2-5-91	Chesapeake & Ohio Canal Potomac River	-
non-01 (TC-70-Cm)	Post-dive regulator	5-15-91	Patapsco River Baltimore, MD	-
non-01 (TC-37-Cn)	Post-dive left ear	6-12-91	Loch Raven Reservoir, MD	-
non-01 (TC-80-Cn)	Post-dive regulator	6-12-91	as above	-
non-01 (TC-water 1-Cn)	Surface water	6-12-91	as above	-
01 (26-T1)	Post-dive right ear	7-15-91	Gelendzhik Black Sea Russia	+
01 (SW-2 TT)	Surface water	7-15-91	as above	+
01 (36-TC 2)	Post-dive right ear	7-18-91	Odessa Black Sea Ukraine	+
01 (37-TC)	Post-dive left ear	7-18-91	as above	+
01 (SW-1 TC)water	Surface	7-18-91	as above	+
non-01 (TC-W1-Pb)	Surface water	7-18-91	Narrow River Narragansett, RI	-
non-01 (TC-20-Co)	Post-dive regulator	5-12-92	Patapsco River Baltimore, MD	-
non-01 (TC-W2-Co)	Bottom water	5-12-92	as above	-

+,-: presence of absence of cholera toxin gene and antigen, respectively. Reproduced from Huq et al. (1994). Colonization of professional divers by toxigenic *Vibrio cholerae* 01 and *V. cholerae* non 01 at dive sites in the United States, Ukraine, and Russia

Determination of Immunoglobulin Titers

For evaluation of acute immune responses (AIR), blood was collected from each diver, both before each dive and 30 to 60 days after. Additionally, sera collected over a period of 18 months were used for studies evaluating the duration of specific immune response.

Enzyme-linked immunosorbent assay (ELISA) was carried out using *V. cholerae* 01 whole cell preparations as antigens, while IgG or IgA from the sera served as the antibody, to detect the immune responses. Three categories of isolates were used in this study:

1. Isolates recovered from divers from whom blood was drawn;
2. Isolates recovered from divers from whom blood was not drawn, but the diver belonged to a diving team from which at least one blood sample was drawn; and
3. Isolates recovered from water or sediment samples collected at the diving sites.

Each whole cell antigen preparation that was made in this study, following methods described elsewhere (Levine et al. 1988), was allowed to react with all sera available from one diving team, if it was isolated during that

Table 3. Recovery of targeted bacterial species from dive site water, sediment, diving gear, and respiratory tract of divers before and after 30 min of dive.

Source of isolation	No. samples positive/total no. of samples (%)			
	Pseudomonas spp.	*Aeromonas* spp.	*V. cholerae* 01 & non-01	Others
Water	7/42 (16.7)	15/42 (35.7)	7/42 (16.7)	0
Sediment	3/20 (15.0)	8/20 (40.0)	1/20 (5.0)	0
Divers (pre-dive)				
Nose	4/142 (2.8)	0	0	0
Ears	14/284 (4.9)	0	0	0
Throat	2/142 (1.4)	1/142 (0.7)	0	1/142 (0.7)
Gear	9/142 (6.3)	0	0	0
Divers (post-dive)				
Nose	32/142 (22.5)	13/142 (9.2)	0	2/142 (1.4)
Ears	74/284 (26.0)	24/284 (8.4)	5/284 (1.7)	0
Throat	14/142 (9.8)	3/142 (2.1)	0	0
Gear	23/142 (16.2)	18/142 (12.7)	5/142 (3.5)	1/142 (0.7)

training dive. Immune responses to cell surface antigens were determined by a modification of a whole-cell extract assay (Cryz et al. 1993). A fourfold rise in IgG titer in postdive compared to predive samples was considered a seroresponse.

A total of nine strains of *V. cholerae* 01 and nine strains of *V. cholerae* non-01 were isolated and are listed in table 2. Seven of the 9 strains of *V. cholerae* 01, when tested for toxigenicity by PCR and ELISA, were positive (table 2). All of these strains were identified as *V. cholerae* 01 using conventional biochemical tests and the identifications were confirmed by CholeraScreen™, CholeraSMART™, and Cholera DFA (NHD).

The *V. cholerae* non-01 isolates obtained in this study were non-toxigenic. However, recent outbreaks of cholera in Bangladesh (Albert et al. 1993) and in India (Ramamurthy et al. 1993) caused by a novel *V. cholerae* non-01 strain (serogroup 0139) clearly demonstrate the virulence capability of such organisms. Waldor and Mekalanos have suggested that 0139 strains are very closely related to El Tor strains of *V. cholerae* (Waldor and Mekalanos 1994). Very recently, co-existence of *V. cholerae* 01 and 0139 has been reported in plankton samples collected in Bangladesh (Huq et al. 1995). We also observed that the cells of non-01 may convert to 01 in broth culture as detected by fluorescent antibody technique (Colwell et al. 1995) at a particular concentration. The mechanisms for modification of virulence and toxigenicity are possible means of adaptation of *V. cholerae* in nature directly or indirectly dependent on environmental parameters, an interesting area of research that needs to be addressed in future studies. Huq et al. (1993) reported little or no difference in major outer membrane proteins in the isolates of *V. cholerae* 01 from clinical and environmental sources, determined by SDS polyacrylamide gel electrophoresis. This may be interpreted as clinical and environmental stains having the same or similar properties. Thus, the presence of *V. cholerae* 01 and non-01 in water samples is potentially hazardous, i.e., able to cause disease, especially in professional divers who are required to dive in polluted waters to carry out their jobs such as repairing sewer outfalls.

Table 4. Pathogens isolated in the study[a]

Pseudomonas spp.	182 (63.6%)
Aeromonas spp.	82 (28.7%)
Vibrio cholerae 01 & non 01	18 (96.3%)
Others	4 (1.4%)

[a]Total number of isolates is 286.

A total of 286 bacterial strains belonging to genera *Pseudomonas, Aeromonas* and including *V. cholerae* 01 and non-01 were isolated from 142 volunteers at 21 diving occasions (table 3). The rate of isolation of all the bacterial species was significantly higher in postdive specimens when compared to that of predive specimens. Among the organisms studied, *Pseudomonas* spp was the most pre-

Table 5. Acute (within 2 months) and delayed (2–6 months) immune responses to whole–cell antigens of the *Pseudomonas* and *Aeromonas* isolates recovered from divers.

Isolate recovery site	No. of positive immune responses[a]/total no. of samples tested (%)					
	Experienced divers		Inexperienced divers			
	Acute	IgG titer of 100[b]	Acute	IgG titer of 100[b]	Delayed	IgG titer of 100[b]
Water[c]	1/29 (3)	18/29 (62)	1/9 (11)	4/9 (44)	2/4 (60)	3/4 (75)
Diver[d]	3/22 (14)	17/22 (77)	1/19 (5)	0/19	4/6 (66)	4/6 (66)
Other Diver[e]	18/146 (12)	129/146 (88)	8/56 (14)	23/56 (41)	8/34 (24)	20/34 (59)
Total	22/197 (11)	169/204 (83)[fg]	10/84 (12)[h]	27/84 (32)[fg]	14/44 (32)[h]	27/44 (61)[g]

[a]Number of serologic assays with a fourfold rise in titer. Data show combined responses to both *Pseudomonas* and *Aeromonas* spp.
[b]Presence in predive-serum of a specific IgG titer of 1:100.
[c]Strains isolated form water and sediment.
[d]Isolates recovered from the diver's own body.
[e]Isolates recovered from other divers.
[f]$P < 10^{-8}$ (chi-square).
[g]$P < 0.003$ (chi-square).
[h]$P < 0.004$ (chi-square).

Table 6. Duration of specific immunologic reactivity in six experienced divers.

Isolate recovery site	No. of positive samples/total no. tested (%)		
	Predictive specific IgG titer of 100 in September 1989	Rise (4-fold) in titer by June 1991	Drop (4-fold) in titer by June 1991
Sediment	5/6 (83)	1/6 (17)	3/6 (50)
Diver	2/2 (100)	1/2 (50)	0/2
Other divers	25/28 (89)	5/28 (18)	6/28 (21)

dominant followed by *Aeromonas* and *V. cholerae*, respectively (table 4).

From the first 8 diving occasions (49 divers), a total of 197 immunological tests were performed, of which 22 (11%) AIR of experienced divers showed evidence of a new immune response to organisms recovered immediately after a dive (table 5). Specific IgG antibody levels in six divers were evaluated to assess the persistence of immunologic responses over time. Forty-six percent of the specific responses remained unchanged for at least 18 months (table 6). Divers who work in the Chesapeake Bay have an increased antibody titer to autochthonous enteric pathogens, such as *V. cholerae* 01, compared with individuals not routinely exposed to Chesapeake Bay water. Our findings suggest that divers undergo seroconversion as a result of exposure to both the autochthonous and allochthonous microbial flora of waters where they carry out diving activities.

The majority of the experienced divers examined in this study carried antibodies to the pathogens present in the water in which they did their diving (Losonsky et al. 1993, Huq et al. 1994). The generation of specific seroresponses to waterborne pathogens is probably dependent, in large part, on the degree of exposure; that is, the number of dives a diver makes at a particular site. The majority of experienced divers had previous exposure to the pathogens, which was evidenced by preexisting specific IgG antibody of 62 to 88 percent of the isolates recovered. Diving influenced the seroreactivity specifically of the new diving recruits and showed a dramatic increase in specific seropositivity rate. The importance of systemic antibody in protection against the pathogens isolated from divers is not known. Therefore, the susceptibility to risk in case of both naive and experienced divers needs to be elucidated by further studies.

It is concluded that naive divers are at greater risk of acquiring waterborne infection, and more attention should be devoted to those divers who must dive in microbiologically polluted waters. It may be suggested that waters could be tested for bacteriological pollution with easy-to-use field test kits once they are available to the general public.

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Literature Cited

Albert, M.S., A.K. Siddique, M.S. Islam, A.S. Faruque, M. Ansaruzzaman, S.M. Faruque, and R.B. Sack, 1993. Large outbreak of clinical cholera due to *Vibrio cholerae* non-01 in Bangladesh. *The Lancet* 341:704.

Colwell R.R., 1991. Microbiological Hazards: background and current perspectives. *Undersea Biomed. Res.* 18:177-179

Colwell, R.R., J.A.K. Hasan, A. Huq, L. Loomis, R.J. Siebling, M. Torres, S. Galvez, S. Islam, M.L. Tamplin, and D. Berstein, 1992. Development and evaluation of a rapid, simple, sensitive, monoclonal antibody-based co-agglutination test for direct detection of *Vibrio cholerae* 01. *FEMS Microbiol. Lett.* 97:215-220.

Colwell, R.R., A. Huq, M.A.R. Chowdhury, P.R. Brayton, and B. Xu, 1995. Serogroup conversion of *Vibrio cholerae*. *Can. J. Microbiol.* 41:in press.

Cryz, S.J., Jr., E. Furer, and R. Germanier, 1993. Development of an enzyme-linked immunosorbent assay for studying *Vibrio cholerae* cell surface antigens. *J. Clin. Microbiol.* 16:41-45.

Daily, O.P., and J.C. Coolbaugh, 1985. Infectious disease hazards associated with polluted waters. *Oceans.* 85:942-944.

Farmer, J.J., III, F.W. Hickman-Brenner, and M.T. Kelly, 1985. *Vibrio*, pp. 282-301. *In*: E.H. Lennette (ed.), *Manual of Clinical Microbiology.* 4th ed., Washington, DC, American Society for Microbiology.

Hasan, J.A.K., A. Huq, M.L. Tamplin, R.J. Siebeling, and R.R. Colwell, 1994a. A novel kit for rapid detection of *Vibrio cholerae* 01. *J. Clin. Microbiol.* 32:249-252.

Hasan, J.A.K., D. Bernstein, A. Huq, L. Loomis, M.L. Tamplin, and R.R. Colwell, 1994b. Cholera DFA: an improved direct fluorescent monoclonal antibody straining kit for rapid detection and enumeration of *Vibrio cholerae* 01. *FEMS Microbiol. Lett.* 120:143-148.

Huq, A., R.R. Colwell, R. Rahaman, A. Ali, M.A.R. Chowdhury, S. Parveen, D.A. Sack, and E. Russek-Cohen, 1990. Occurrence of *Vibrio cholerae* in the aquatic environment measured by fluorescent antibody and culture method. *Appl. Environ. Microbiol.* 56:2370-2373.

Huq, A., S. Parveen, F. Qadri, and R.R. Colwell, 1993. Comparison of *Vibrio cholerae* serotype 01 isolated from patient and aquatic environment. *J. Trop. Med. and Hyg.* 96:86-92.

Huq, A., J.A.K. Hasan, G. Losonsky, and R.R. Colwell, 1994. Occurrence of toxigenic *Vibrio cholerae* 01 and non 01 in professional divers and dive sites in the United States, Ukraine, and Russia. *FEMS Microbiol. Lett.* 120:137-142.

Huq, A., R.R. Colwell, M.A.R. Chowdbury, B. Xu, S.M. Moniruzzaman, M.S. Islam, M. Yunus, and M.J. Albert, 1995. Co-existence of *V. cholerae* 01 and 0139 Bengal in Plankton in Bangladesh. *The Lancet* 345:1249.

Jones, C.J., A. Goodman, T. Cox, S. Friedman, and S. Schultz, 1985. Scuba diving in polluted coastal waters. *Oceans* 85:950-961.

Joseph, S.W., A.M. Carnahan, P.R. Brayton, G.A. Fanning, R. Almazan, C. Drabick, E.W. Trudo, Jr., and R.R. Colwell, 1991. *Aeromonas jandaei* and *Aeromonas veronii* dual infection of a human wound following aquatic exposure. *J. Clin. Microbiol.* 29:565-569.

Levine, M.M., J.B. Kaper, D. Harrington, G.A. Losonsky, J.G. Morris, M.L. Clements, R.E. Black, B. Tall, and R. Hall, 1988. Volunteer studies of deletion mutants of *Vibrio cholerae* 01 prepared by recombinant techniques. *Infect. Immun.* 56:161-167.

Losonsky, G., 1991. Infections associated with swimming and diving. *Undersea Med. Res.* 18:181-185.

Losonsky, G.A., J.A.K. Hasan, A. Huq, S. Kaintuck, and R.R. Colwell, 1993. Serum antibody responses to divers to waterborne pathogens. *Clin. Diagn. Lab. Immun.* 1:182-185.

Ramamurthy, T., S. Garg, R. Sharmi, S.K. Bhattacharya, B. Nair, T. Shimada, T. Takeda, T. Karasawa, H. Kurazano, A. Pal, and Y. Takeda, 1993. Emergence of novel strains of *Vibrio cholerae* with epidemic potential in southern and eastern India. *The Lancet* 341:703.

Waldor, M.K., and J.J. Mekalanos, 1994. ToxR regulates virulence gene expression in non 01 strains of *Vibrio cholerae* that cause epidemic cholera. *Infect. Immun.* 62:72-78.

Pathogenesis and Prevention of Dysbaric Osteonecrosis

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Abstract

Japanese diving fishermen are known to have a high incidence of dysbaric osteonecrosis. Their typical dive practices are characterized by long exposure to high pressure and by repetitive diving. The etiology of dysbaric osteonecrosis still remains controversial. Because the development of dysbaric osteonecrosis may occur silently, the diver may be unaware of the actual ischemic event. Moreover, key etiologic evidence is often lost before the diver is examined. The early stage of dysbaric osteonecrosis was evaluated in four autopsy cases of divers who died of acute decompression sickness. Hypercoagulability was present in all these cases. Hypercoagulability of blood has also been observed in rats after decompression. Dysbaric osteonecrosis has been experimentally induced in six sheep at the University of Wisconsin-Madison. These findings are reviewed by comparing dysbaric osteonecrosis in both divers and animals. In conclusion, a bone compartment syndrome and hypercoagulability appear to be pathogenetic factors in dysbaric osteonecrosis.

Introduction

The first case of dysbaric osteonecrosis in divers was reported by Crutzmacher in 1941. The prevalence of dysbaric osteonecrosis is highest among Japanese diving fishermen. In our recent surveys of the Kyushu area, radiological investigation of 905 divers revealed 467 cases (51.6%) of osteonecrosis. As we already reported in past UJNR meetings, a characteristic of their diving profile is prolonged hyperbaric exposure and a rapid decompression.

As Elliot and Kindwall (1982) described, prolonged hyperbaric exposure and rapid decompression can provoke a high incidence of limb bends. As we already reported, there appears to be a strong association between limb bends and dysbaric osteonecrosis. The University of Wisconsin findings of bone necrosis in sheep long bones after hyperbaric exposure provide the basis for a proposed etiological and pathogenic model of dysbaric osteonecrosis.

Our hematological experiments in rats and autopsies in four divers also provide a basis for a etiological and pathogenic model of dysbaric osteonecrosis.

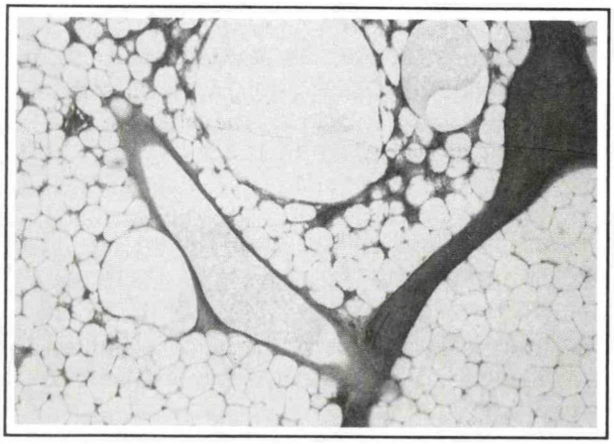

Figure 1. Platelet aggregation in the vicinity of the femoral bubbles.

Histopathology of Early Stage Osteonecrosis

This investigation was based on the histopathological examination of femoral heads taken from four divers who died of decompression sickness.

Proceedings of the 12th Meeting of the United States-Japan Cooperative Program in Natural Resources (UJNR) Panel on Diving Physiology, Washington, DC, July 13-14, 1993. National Undersea Research Program, Silver Spring, MD

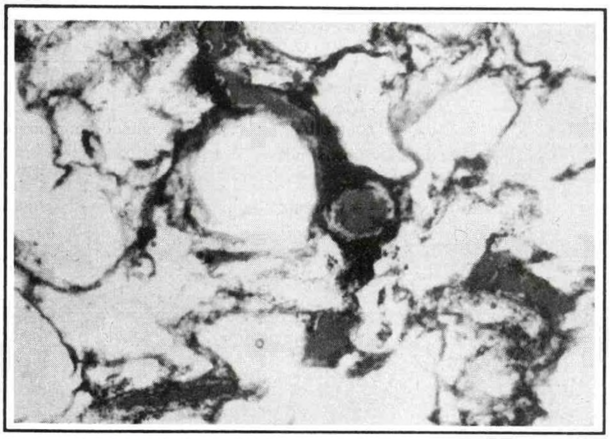

Figure 2. Fat emboli in the lung vessels.

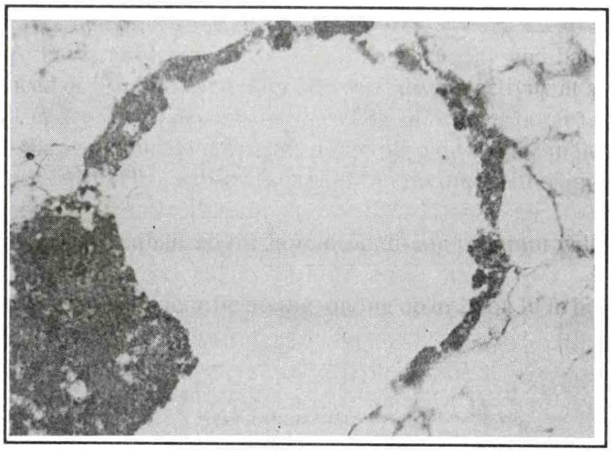

Figure 4. Platelet aggregation and thrombosis in the sinusoids.

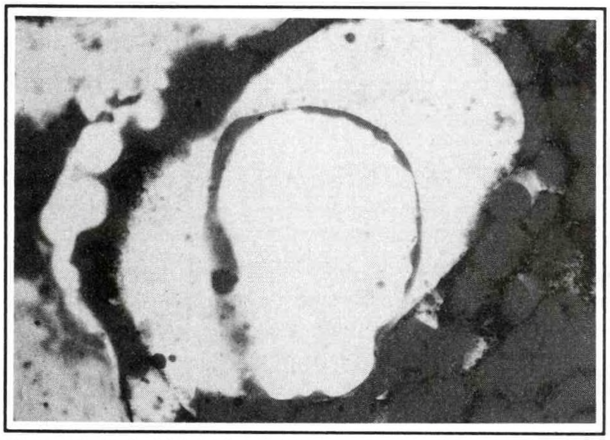

Figure 3. Air bubbles, platelet aggregation, and accumulation in the dilated sinusoids.

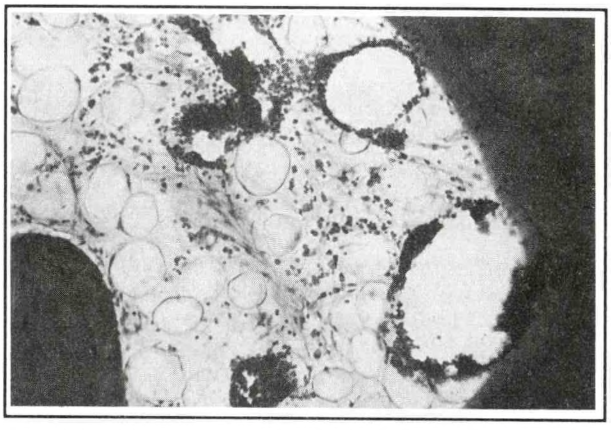

Figure 5. Slight hemorrhage, migration of phagocytes, and fibrosis around the femoral sinusoids.

Case 1 presented the most acute clinical course, with fatal chokes. Multiple air bubbles were found in the femoral sinusoids. A characteristic finding was platelet aggregation in the vicinity of the femoral bubbles (fig. 1).

The clinical course of case 2 was also acute, with chokes and spinal cord paralysis. Fat emboli were seen in the lung vessels (fig. 2). Air bubbles, platelet aggregation, and an accumulation of fat was seen in the dilated sinusoids (fig. 3).

The diver of case 3 died 5 days after the onset of spinal cord paralysis. An extensive necrosis was noted around the dilated sinusoids. Platelet aggregation and thrombosis was seen in the sinusoids (fig. 4).

The diver of case 4 died 14 days after the onset of spinal cord paralysis. Slight hemorrhage, migration of phagocytes, and fibrosis were found around the femoral sinusoids (fig. 5).

Experimental Hypercoagulability in DCS

Kitano and Kawashima (1978) succeeded in producing DCS in rats. Ten male rats were subjected to a hyperbaric exposure of 2 hours at 6 atm abs and were quickly decompressed to ambient pressure in 5 minutes. Platelets were counted before compression and after decompression. Thromboelastographical examination was performed on three rabbits that were subjected to a hyperbaric exposure of 1 hour at 6 atm abs and decompressed in 5 minutes to ambient pressure.

Before compression,the average number of platelets was 569,700/mm^3. After decompression, the average number of platelets was 491,300/mm^3. A significant reduction of the number of platelets was seen (fig. 6).

Thromboelastographs of the rabbits showed the shortening of k and r and the widening of ma after decompression; this finding indicates the breakdown of platelets (fig. 7).

Dysbaric Osteonecrosis in Sheep

Lehner and Lanphier at the University of Wisconsin had succeeded in producing dysbaric osteonecrosis in sheep long bone. Kitano and others performed a histopathological

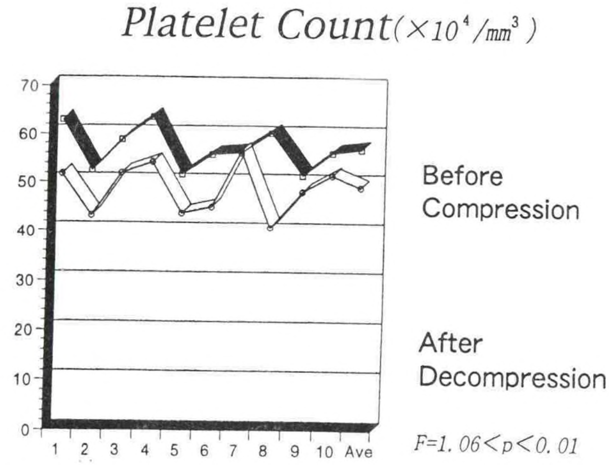

Figure 6. A significant reduction of the number of platelets after decompression (Kitano and Kawashima 1978).

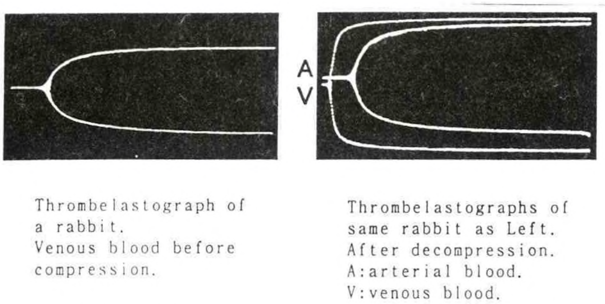

Figure 7. Thromboelastographs; left: thromboelastograph of a rabbit; venous blood before compression; right: thromboelastographs of same rabbit after decompression. A is arterial blood; V is venous blood (Kitano and Kawashima 1978).

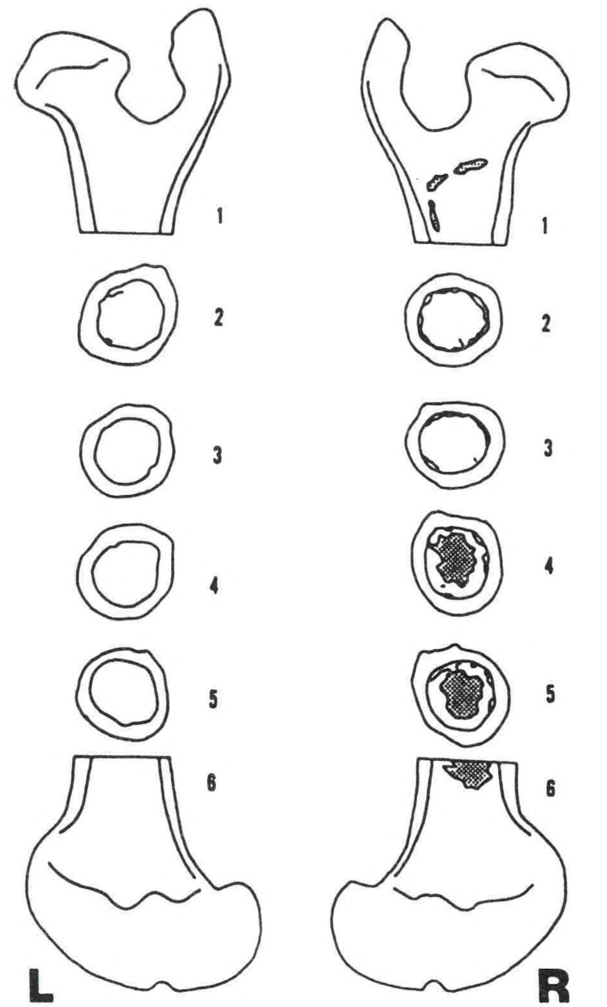

Figure 8. Schematic drawing of the distribution of necrotic foci in both the right (R) and left (L) femurs of Sheep #227. Dotted areas indicate the necrotic foci. Note the almost normal left femur except for a slight, irregular endosteal thickening of the cortical bone.

evaluation of the dysbaric osteonecrosis in sheep as the part of UJNR cooperative research.

Six, 2-year-old crossbred female sheep underwent a series of 29-30 hyperbaric exposures of 0.5 to 4 hours duration over a 2.5-year period. The maximum pressure of the hyperbaric exposures reached 2.68 atm abs in the 4 hour exposures and 4.31 atm abs in the 0.5 hour exposures.

Macroscopic Findings: Sectioned bone specimens from the sheep femora contained fatty marrow necrosis that is a common finding in dysbaric osteonecrosis. Fatty marrow necrosis appeared as opaque, shiny, yellow-white inclusions in the marrow cavity (figs. 8, 9, 10).

Histological Findings: Focal liquefaction of fat occurred in the necrotic lesion. Endosteal new bone formation was present in the cortical bone (fig. 11). Necrotic fatty marrow is surrounded by a fibro-osseous layer. Individual necrotic fat cells were enveloped by basophilic material of calcified tissue (figs. 12, 13). Articular cartilage appeared intact. The histological findings were also essentially identical to those found in dysbaric osteonecrosis Japanese divers that was reported by Kawashima (1976) and Kitano et al. (1976). However, in divers, the prevalence of necrotic foci appeared to be almost as high in the femoral heads as in the distal femoral shafts.

Discussion

The etiology of dysbaric osteonecrosis still remains controversial. Osteonecrosis associated with fat embolism of bone was first demonstrated clinically by Jones in 1965 and first confirmed experimentally by Jones in 1966. In our case 2, an accumulation of fat and aggregation of platelets was noted in the vicinity of air bubbles, and fat emboli were seen in the lung vessels. Jones proposed three mechanisms that would be potentially capable of producing interosseous fat embolism and triggering a process

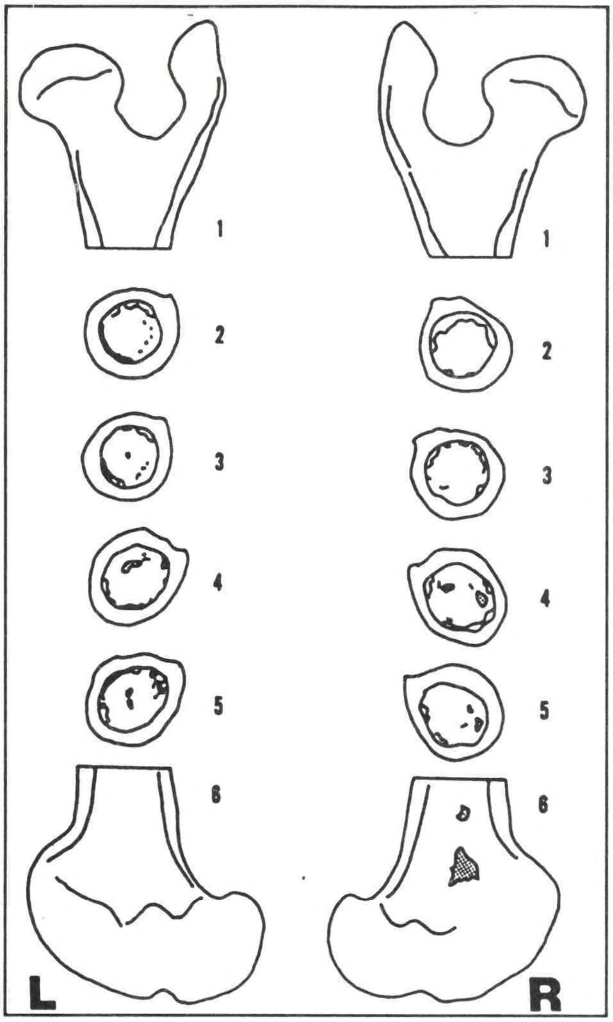

Figure 9. Distribution of necrotic foci (dotted areas) in both the right (R) and left (L) femurs of Sheep #249.

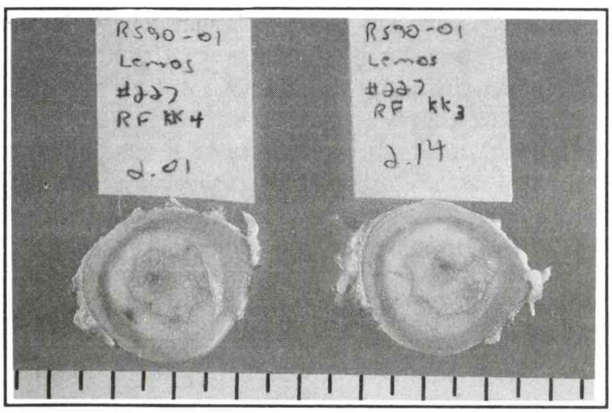

Figure 10. Transverse section of the distal shaft from the right femur of Sheep #227.

leading to focal intravascular coagulation and osteonecrosis (fig. 14).

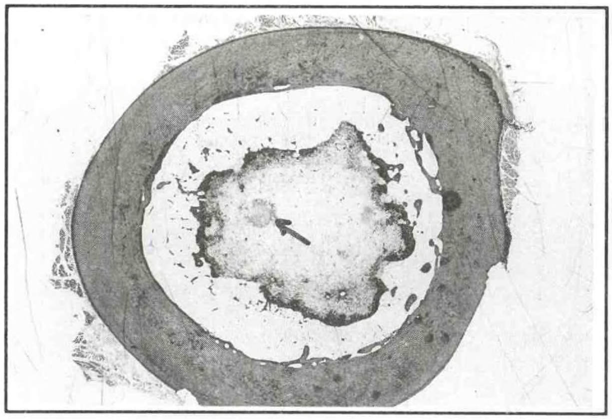

Figure 11. Focal liquefaction of fat (arrow) occurred in the necrotic focus.

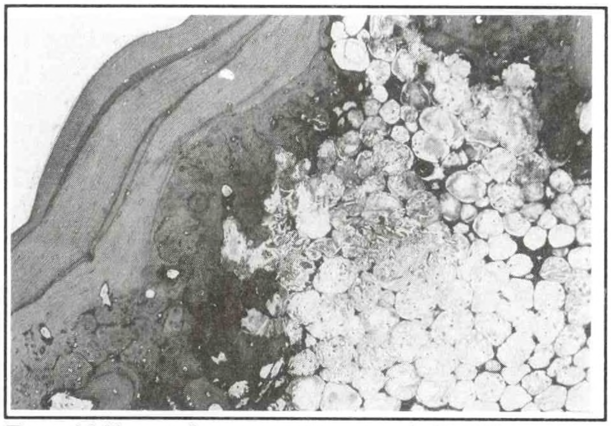

Figure 12. Necrotic fatty marrow is surrounded by a fibro-osseous layer .x750.

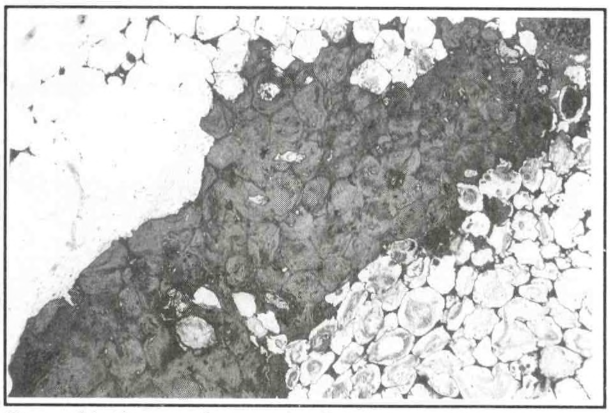

Figure 13. Necrotic focus in the distal shaft of the left femur of Sheep #249 .x375.

In our experimental DCS in rats, a marked reduction of the number of circulating platelets after decompression was observed. Intraosseous hypercoagulation and fat emboli also appeared to be important factors in the pathogenesis of dysbaric osteonecrosis.

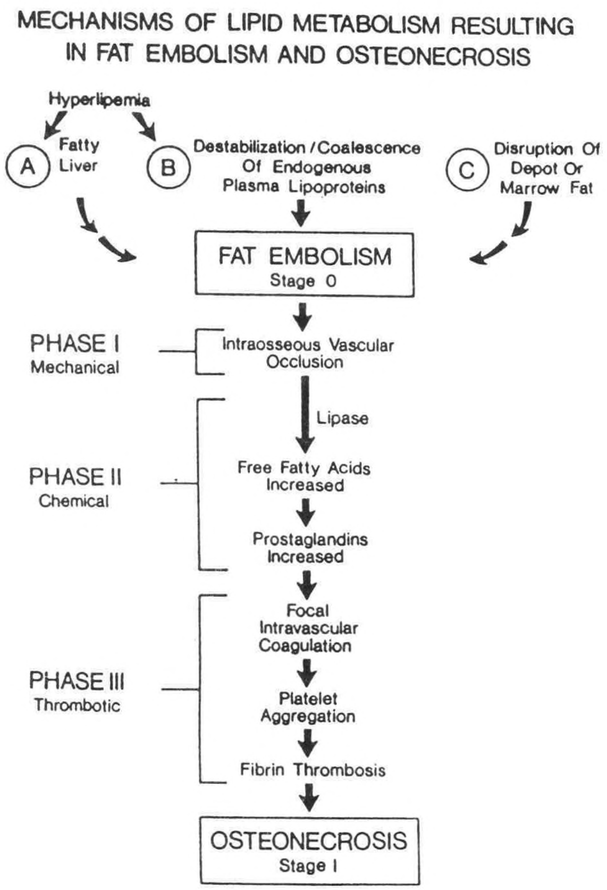

Figure 14. Fat embolism and osteonecrosis (Jones 1992).

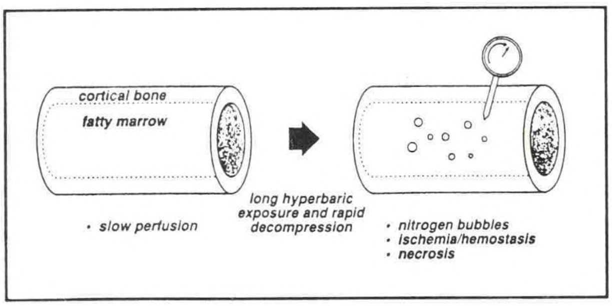

Figure 15. Decompression from prolonged hyperbaric exposure triggers bubble formation that initiates a bone compartment syndrome (Lehner 1992).

Lehner and Lanphier have proposed a bone compartment syndrome as the primary mechanism in the early pathogenesis of dysbaric osteonecrosis (fig. 15). Nitrogen is about five times more soluble in fat than in water. As Behnke observed (Behnke 1945), the cortical bone surrounding fatty marrow establishes a semiclosed compartment with a complex vasculature potentially vulnerable to vascular obstruction because of bubble formation.

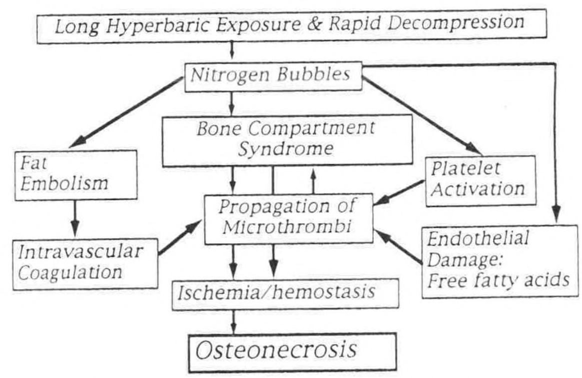

Figure 16. Pathomechanism of dysbaric osteonecrosis.

Hypercoagulation and thrombosis in long bone sinusoids would increase bone marrow pressure and promote a bone compartment syndrome (fig. 16). Lehner proposed prompt recompression therapy to prevent or block the development of dysbaric osteonecrosis. Increased ambient pressure in recompression will reduce the volume of any bubbles within the marrow cavity and thereby decrease tissue pressure within the long bones. Another proposed therapy to prevent or block the development of dysbaric osteonecrosis involves anticoagulants. Anticoagulants might prevent dysbaric osteonecrosis if they are administered at the time of prompt recompression therapy for limb bends.

Conclusions

1) Prolonged hyperbaric exposures permit substantial accumulation of dissolved nitrogen in the fatty marrow of the long bones.

2) Decompression may form bubbles i n the semiclosed compartment of the long bone. If significant numbers of bubbles form, tissue pressures can rise and ischemia may result. Persistent limb bends may reflect elevated bone marrow pressure and ischemia in the long bones. If the ischemia is sustained, dysbaric osteonecrosis may result.

3) Persistent ischemia may occur by the proposed mechanism of a bone compartment syndrome in dysbaric osteonecrosis development.

4) A bone compartment syndrome may be promoted by intraosseous hypercoagulation and fat embolism. These factors appear to be the pathogenetic mechanisms most likely responsible for dysbaric osteonecrosis.

5) Early recompression therapy, together with anticoagulant therapy, may prevent the development of dysbaric osteonecrosis.

Literature Cited

Amako, T., and M. Kawashima, 1974. Bone and joint lesions in decompression sickness. *Seminars Arthr. Rheum.* 4:151-190.

Behnke, A.R., 1945. Decompression sickness incident to deepsea diving and high altitude ascent. *Medicine* 24:381-402.

Elliot, D.H., and E.P. Kindwall, 1982. Manifestations of decompression disorders, In: P.B. Bennett and D.H. Elliot (eds.), *The Physiology and Medicine of Diving*, pp. 461-472. London, Bailliere Tindall.

Jones, J.P., Jr., 1985. Fat embolism and osteonecrosis. *Orthop. Clin. North Am.* 16:595-633.

Jones, J.P., Jr., 1992. Intravascular coagulation and osteonecrosis. *Clin. Orthop.* 277:41-53.

Kawashima, M., 1976. Aseptic bone necrosis in Japanese divers. *Bull. of Tokyo Medical and Dental University*, 23:71-92.

Kawashima, M., and M. Kitano, 1978. Pathological review of osteo- necrosis in divers. *Clin. Orthop.* 130:107-117.

Kawashima, M., and M. Kitano, 1977. Histopathology of the early stage of osteonecrosis in divers. *Undersea Biomedical Research* 4:409-417.

Kitano, M., M. Kawashima, T. Torisu, and K. Hayashi, 1976. Pathological review of osteonecrosis in divers. *Clinical Orthopedic* 11:1092-1099.

Kitano, M., M. Kawashima, and K. Hayashi, 1978. Experimental studies on decompression sickness. *Orthopedic and Traumatology* 27:653-658.

Kitano, M., 1981. Acute decompression sickness. *Acta Pathol. Jpn.* 31: 269-276.

Kitano, M., and M. Kawashima, 1978. Experimental Studies on Decompression Sickness. *Orthopedics and Traumatology* 27:653-658.

Kitano, M., C.E. Lehner, M. Kawashima, Y. Taya, and E.H. Lanphier, 1993. Experimentally induced dysbaric osteonecrosis in sheep, a histopathological analysis. *South Pacific Study* 13:173-182.

Lehner, C.E., 1992. Dive profiles and adaptation: pressure profiles target specific tissues for decompression injury. In: M.A. Lang and R.D. Vann (eds.), *Repetitive Diving Workshop*, pp. 203-217. American Academy of Underwater Sciences, Costa Mesa, California.

Histopathological Study of Femoral Bone Marrow of Rabbits With Acute Decompression Sickness --with consideration about pathogenesis of dysbaric osteonecrosis in divers--

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Abstract

Experimental data showing an acute stage of decompression sickness (DCS) marked by extensive formation of gaseous bubbles in the sinusoid and extravascular spaces with frequent arterial and arteriolar collapse in the bone marrow of the femurs in rabbits is presented. Discussing the related evidence linking these observations with dysbaric osteonecrosis (DON) in divers and caisson workers, intravascular and extravascular bubble formation may cause marked elevation of intraosseous pressure resulting in arterial collapse especially of the "watershed zones."** These zones include the weight-bearing juxta-articular area and distal shaft area of the femoral bone marrow. Disturbances in the venous return from the bone marrow because of extensive bubble embolization of the sinusoid should accentuate the elevation of the intraosseous pressure.

Introduction

Depending on the autopsy findings of Japanese divers with acute DCS, Kawashima et al. (1977) and Kitano and Hayashi (1977) described the formation of intravascular gaseous bubbles associated with activation of the thrombogenesis especially on the venous side. These bubbles were marked and extensive in the bone marrow of the autopsied cadavers. A hypothesis "venous return disturbance theory" was proposed in which circulatory disturbance on the venous side is a very important pathogenetic factor for bone marrow necrosis, which is considered to precede DON.

Recently, Lehner et al. (1990) and Lanphier et al. (1990) conducting DCS experiments on sheep have been concentrating on the "bone compartment syndrome theory" preceding DON. When bubble formation from the dissolved nitrogen gas occurs rapidly in fat cells within a compartment, as in the marrow cavity of long bones, tissue pressure elevation should occur. They thought that marked acute elevation of tissue pressure may result in bone marrow necrosis.

This paper is based on the histopathological findings in the femurs of 12 rabbits with experimental acute DCS. The purposes of this study are to clarify the precise pathogenesis of DON and to attempt to compromise the correlation between the two theories, "venous return disturbance theory" and "bone compartment syndrome theory."

Materials and Methods

Production of DCS in experimental animals

Six male rabbits, 3.5-4.0 kg in body weight, were compressed for 6 hours at 6 atm. abs. in the experimental hyperbaric chamber (Nakamura-Seisakujo Co., Ltd.) and then were decompressed quickly to ambient pressure in 5 minutes. All of them fell into dyspneic condition about 5 minutes after returning to ambient pressure. They all expired 5 to 10 minutes after the decompression under shock states.

An additional six male rabbits, 3.5-4.0 kg in body weight, were compressed for 1 hour at the same pressure and were decompressed in 5 minutes to ambient pressure. They showed some dyspneic conditions and paralysis in the posterior limbs. They all expired 15 to 60 minutes after the decompression.

Three male rabbits, weighing 3.5-4.0 kg, were used as control animals without compression-decompression procedures.

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**In this paper we use the term "watershed zone," which is often used in the field of Neuropathology, for the border or boundary zone between the territories of two or more major arteries.

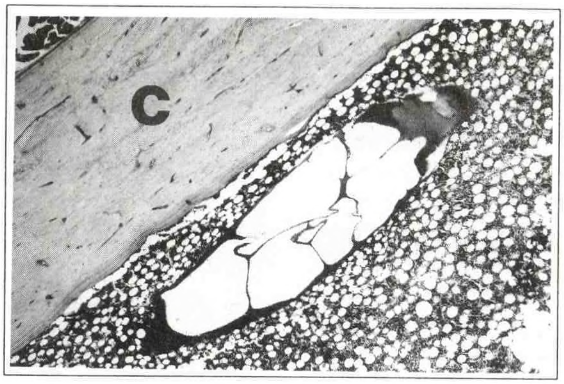

Figure 1. A longitudinally and laterally dilated sinusoid of the femoral bone marrow of an experimental rabbit possessing many gaseous bubbles entrapped in a fibrinous thrombus (C: Cortical bone of the femoral shaft. Hematoxylin-eosin, x40).

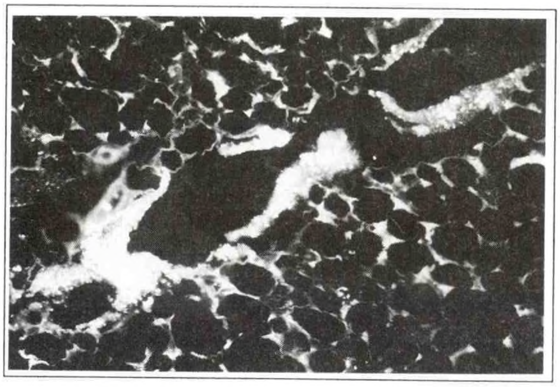

Figure 3. Accumulation of fibrinogen substance around the gaseous bubbles. (Immunostaining with FITC-conjugated antirabbit fibrinogen goat IgG, x100).

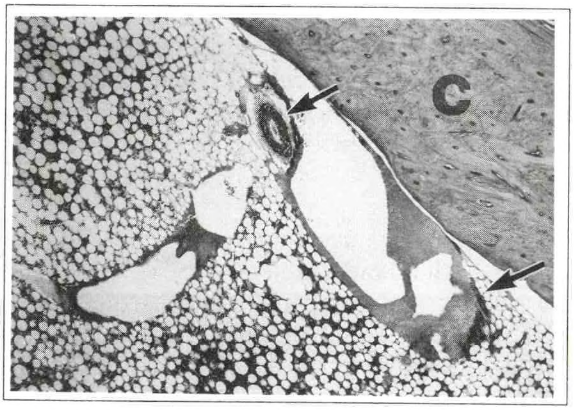

Figure 2. Dilated sinusoid with gaseous bubbles surrounded by thrombi. Small arteries and arterioles (arrows) in the bone marrow nearby the dilated sinusoid are collapsed (C: Cortical bone of the femoral shaft. Hematoxylin-eosin, x40).

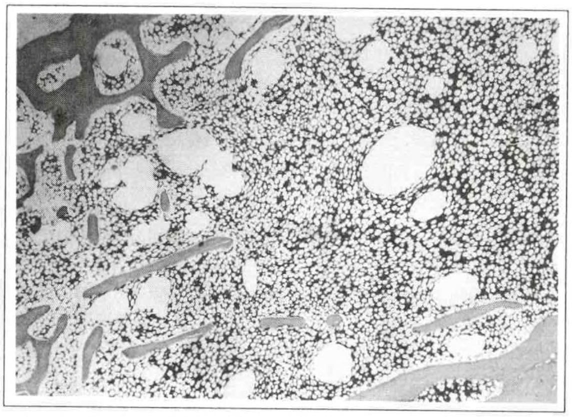

Figure 4. Many spherical spaces in the bone marrow suggesting gaseous bubbles. Many of them are devoid of apparent endothelial lining (Hematoxylin-eosin, x20).

Histopathological analyses

All of the experimental animals were necropsied for the subsequent histopathological evaluations on various organs, including the femurs. Of the 1-hour-compressed rabbits, three were examined for distribution of thrombi in the femoral bone marrows using a fluorescein isothiocyanate (FITC)-conjugated anti-rabbit-fibrinogen sheep-IgG.

Results

Numerous large or small, up to 2000 microns in diameter, gaseous bubbles were present in the blood vessels, especially in the sinusoid of the bone marrows of the femora. Histopathological findings were essentially the same in all the experimental animals. Platelet aggregation was noted in the vicinity of some bubbles, while thrombus formation was apparent around many of the bubbles (figs. 1, 2). Accumulation of fibrinogen substances around the bubbles in the sinusoid was demonstrated by application of the FITC-conjugated IgG (fig. 3).

The above-mentioned changes were more predominant in the shaft than in the head. In general, hemorrhage is rather mild and focal in the bone marrow. Moreover, numerous spherical bubbles up to 500 microns in diameter around which no definitive endothelial lining was evident in the bone marrow tissue suggested development of extravascular gaseous bubbles (fig. 4).

Another main event in the bone marrow of the femurs was that marked collapse of the small arteries and arterioles was seen frequently. This change was prominent near the dilated sinusoid possessing bubbles (figs. 2, 5).

Numerous gaseous bubbles were seen in the blood of the venae cavae and in the right atrium and ventricle of the

Figure 5. Markedly collapsed arterioles (arrow heads) in the vicinity of dilated sinusoid possessing gaseous bubble (Hematoxylin-eosin, x100).

heart. The synovial fluid of the knee joints was bubbled. The visceral organs were markedly congested.

Discussion and Conclusions

The epidemiological and clinical relationship between aseptic bone necrosis and DCS has been well established, and now we call it dysbaric osteonecrosis (DON). However, the precise etiology of DON remains a controversial subject. Until quite recently, it was generally accepted that DCS which included DON was caused by an arterial bubble with a common physiological mediation of the basic insult. Previously, Kawashima et al. (1977) and Kitano and Hayashi (1977) proposed the "venous return disturbance theory" for the etiology of DON because there were numerous gaseous bubbles associated with thrombus formation in the sinusoids of the femoral bone marrow of the divers who died of acute DCS.

Lehner et al. (1990) and Lanphier et al. (1990), on the other hand, employed another etiology of DON; that is, "bone compartment syndrome theory." The simple mechanical, compression-decompression procedures undertaken in this study leave little doubt that the volume of gas that was separated from blood, tissue, and fat cells in the bone marrow after the procedures could not be dissipated by tissue compliance in the bone marrow. For "encased" gaseous bubbles to cause actual arterial and/or arteriolar collapse with subsequent impairment of local circulation, the extravascular pressure must exceed the pressure of the blood within.

It is particularly difficult to measure or to find published values for the perfusion of these arteries and arterioles (Lanphier et al. 1990). This is complicated further by the known sympathetic vasomotor reflex in elevating local perfusion pressure to balance the potential collapsing pressure. The corresponding values in the bone marrow are likely to be appreciably lower, especially in the poorly perfused watershed zones, which are those most prone to decompression injury of the spinal cord (Hills and James 1982) and cerebrum (Kitano et al. 1991). Thus, encasing pressure has the potential to exceed the perfusion pressure with subsequent vascular collapse resulting in tissue anoxia. This is more likely in long bones where flow in collapsible blood vessels can be determined more by the transmural arterial pressure than by the arteriovenous pressure difference. The model depicted in figure 6 is drawn for probable areas of lowered perfusion pressure in "watershed zones" of the adult human femur.

This model is consistent with two relevant observations. First, there is a clinical finding that incidence of DON in divers and caisson workers are higher in the load-bearing area of the juxta-articular region of the head and distal shaft area of the femurs (Davidson 1976, Kawashima 1976) because these are areas with the lowest perfusion pressure and highest nitrogen content resulting from the highest lipid content (Davidson 1976). Second, anatomical analysis of the arterial circulation can easily induce a concept that these are the areas in which arterial branches become thinner and arterial flow decreases (Trueta and Harrison 1953, Okeda 1967, Longia et al. 1980, Laing 1953).

It was easy to envisage how large amounts of gas could cut off blood flow from all arterioles, resulting in the total bone marrow necrosis sometimes seen (Kitano and Hayashi 1977). For lesser amounts of gas, however, the closure of small arteries and arterioles could be localized, depending on whether the gas had been created enough to produce the bone marrow necrosis.

The reasons that dysfunction often does not occur equally in whole bone marrow of the femur as a total necrosis may be 1) not all gas is formed equally in various sites of the bone marrow in order of ratio of distribution of fat cells and hematopoietic cells or 2) when the blood perfusion pressure decreases, as depicted in the "watershed zones," it could generate enough differential to cease blood flow.

It was most interesting to study the femurs of the experimental rabbits to see how extensively and markedly dilated, either longitudinally or laterally, are sinusoid possessing large amounts of gaseous bubbles. Histopathological analyses often revealed tracking of gas, sometimes extending vertically along the long axis of the femurs. Aggregation of platelets and thrombus formation around the intravascular gaseous bubbles were observed frequently. However, it is not now feasible that bone marrow necrosis can be introduced only from the impairment of sinusoidal circulation. If this were correct, hemorrhagic changes that are one of the most prominent features of venous circulatory disturbance would be more extensive and marked in the bone marrow. Actually, hemorrhage was rather mild and focal in the rabbit femurs

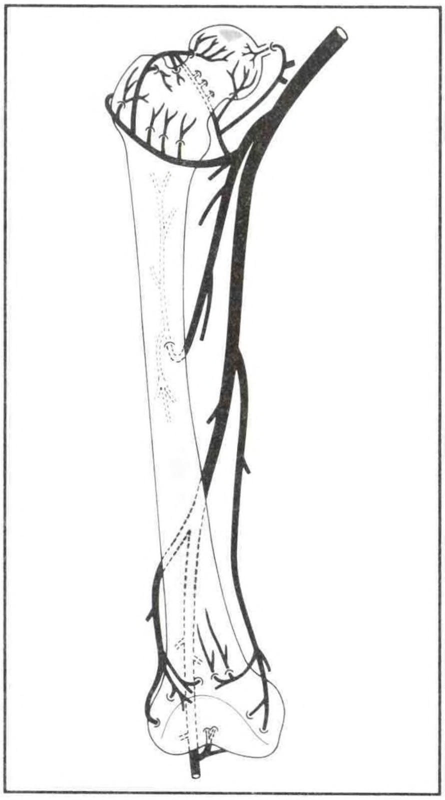

Figure 6. Schematic drawing of the arterial supply to the bone marrow of a human adult. The dotted areas are presumed as "watershed zones" of the bone marrow.

of this experiment and those of the divers reported by Kawashima et al. (1977).

It is appropriate to consider that the main pathway of dissipation of the elevated intraosseous pressure should be the blood vessels, especially of the venous system, until the perfusion pressure becomes equivalent to the surrounding soft tissue and organs. Thus, tending to retain gas emboli widely within the venous side does not allow the intraosseous pressure traveling through the small arteries and arterioles to reduce.

In conclusion, the detailed aspects of bone marrow necrosis and subsequent DON in DCS are too numerous to discuss here. The salient features would not seem explainable from either the simple "bone compartment syndrome theory" or the simple "venous return disturbance theory" from the basic mechanical experiments including the present study. Its primary attribute, however, is its compatibility with both the pathological evidence for compromises of arterial blood flow and its ability to explain the high-site predisposition of DON in the femur on multiple changes of pressure and their consistency on "watershed zones." Anyway, the importance of the venous return impairment should be emphasized.

Acknowledgments

We are grateful to Prof. R. Okeda (Department of Neuropathology, Institute of Medical Research, Tokyo Medical and Dental University) and Prof. T. Ogata (2nd Department of Oral Anatomy, Kagoshima University Dental School) for their useful guidance and advice on bone anatomy.

Literature Cited

Davidson, J.K., 1976. Dysbaric osteonecrosis. In: J.K. Davidson (ed.), *Aseptic Necrosis of Bone*, pp. 147-212. Oxford and New York, Excerpta Medica/American Elsevier.

Hills, B.A., and P.B. James, 1982. Spinal decompression sickness--mechanical studies and a model. *Undersea Biomed. Res.* 9:185-201.

Kawashima, M., 1976. Aseptic bone necrosis in Japanese divers. *Bull. Tokyo Med. Dent. Univ.* 23:71-92.

Kawashima, M., K. Hayashi, T. Torisu, and M. Kitano, 1977: Histopathology of the early stage of osteonecrosis in divers. *Undersea Biomed. Res.* 4:409-417.

Kitano, M., and K. Hayashi, 1977. Acute decompression sickness--Report of an autopsy case with withspread fat embolism. *Acta Pathol. Jpn.* 31:269-276.

Kitano, M., K. Hayashi, M. Kawashima, S. Tokufuji, and A. Urago, 1991. Histopathological analysis of the brain of acute decompression sickness (DCS) victim. *South Pacific Study* 11:93-103.

Laing, P.G., 1953. The blood supply of the femoral shaft--An anatomical study. *J. Bone Joint Surg.* 35B:462-466.

Lanphier, E.H., C.E. Lehner, T. Kanikula-Ives, L.C. Anderson, and S.E. Lemos, 1990. Measurement and modification of bone marrow cavity pressure in sheep. *Undersea Biomed. Res.* 17 (Supplement):58.

Lehner, C.E., E.H. Lanphier, S.E. Lemos, and W.M. Adams, 1990. Dysbaric osteonecrosis and elevated marrow pressure: A proposed etiological and pathogenic model. *Undersea Biomed. Res.* 17 (Supplement):29.

Longia, G.S., M.L. Ajmani, S.K. Saxena, and R.J. Thomas, 1980. Study of diaphyseal nutrient foramina in human bones. *Acta Anat.* 107:399-406.

Okeda, R., 1967. Histometrical investigation of arteries in the femoral bone marrow of autopsy cases. *Acta Heam Jpn.* 30:452-462 (in Japanese).

Trueta, J. and M.H.M. Harrison, 1953. The normal vascular anatomy of the femoral head in adult man. *J. Bone Joint Surg.* 35B:442-461.

Experimental Trimix Chamber Dives for Deep Caisson Work

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Abstract

It is difficult for divers to work in a compressed air environment at pressures greater than approximately 4 bars because of the increased influence of nitrogen narcosis. Experimental chamber dives breathing trimix ($N_2/O_2/He$), which is less narcotic than air at depths, were conducted to evaluate its applicability to deep caisson work. Five subjects were compressed with air to 5 bars for 60 minutes, while breathing a 50% N_2-25% O_2-He balance trimix via full-face band masks. After completing 60 minutes of hyperbaric air exposure, divers were decompressed using oxygen, according to Sterk's decompression procedure. The total decompression time was 92 minutes, and the accumulated Unit Pulmonary Toxic Dose (UPTD) was 230 units for the exposure and decompression. During the exposure and decompression, there were no symptoms of nitrogen narcosis or oxygen toxicity. In the course of decompression and during the 2-hour observation period thereafter, no signs of decompression sickness were observed, nor were there any later reports about such events. To further evaluate decompression risks in the procedure, bubble detection was performed by ultrasound Doppler and echogram methods three times during the 2-hour observation period after surfacing. No bubbles were detected in any of the five subjects. Based on our observation, it is suggested that the trimix gas is effective as a breathing medium for deep caisson work, and our approach on the composition of the trimix gas and decompression procedure seems reliable.

Introduction

At a site where underground water is abundant, the construction of a bridge foundation or shafts can be performed reliably using a pneumatic caisson method. This method has often been used in soft ground delta areas like the waterfront of Tokyo in Japan. It imposes a potential health hazard on workers who are exposed to the hyperbaric air environment. To minimize the health hazards related to compressed air work as well as to overcome the increasing shortage of skilled caisson workers, one of the constructors has developed a remotely controlled caisson system that excavates and conveys the removed mud without manpower (Hirata et al. 1992). This system has already been used successfully in a couple of caisson construction sites since 1991. It also promises to be a very useful tool for underground development at greater depths (more than 50 meters). Although the excavation system is remotely controlled, it is inevitable that technicians and/or engineers have to enter the caisson occasionally for maintenance or repair of machinery. Beyond 4 bars of air, however, there are increased risks of suffering from nitrogen narcosis, as well as difficulty in breathing due to increased air density. To minimize these risks, we have developed a nitrogen-helium-oxygen gas mixture (trimix gas) as a breathing medium for workers who have to enter the deep caisson that is filled with hyperbaric air (Kobayashi et al. 1993).

Experimental Procedures

Subjects

Five healthy male professional divers served as subjects for the trimix chamber dives (table 1). They were informed of the potential risks involved in the dive and participated in the experiment voluntarily.

Mixed Breathing Gas

For caisson work at pressures greater than 4 bars, breathing as mixtures containing less nitrogen than air are very important to reduce the effect of nitrogen narcosis. In choosing the composition of trimix, the nitrogen partial pressure should be lower than about 3 bars, which is equivalent to compressed air of 4 bars, to avoid nitrogen narcosis. The oxygen partial pressure should be lower than 1.6 bars to avoid central nervous system oxygen toxicity. For a given ambient pressure greater than 4.8 bars absolute, the remainder of the mixture could then be helium. We used a 50% N_2-25% O_2-He balance trimix to

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Table 1. Physical status of the subjects

Subject	Age	Height (cm)	Weight (kg)
A	23	180	75
B	23	168	68
C	21	168	54
D	29	169	76
E	20	169	59

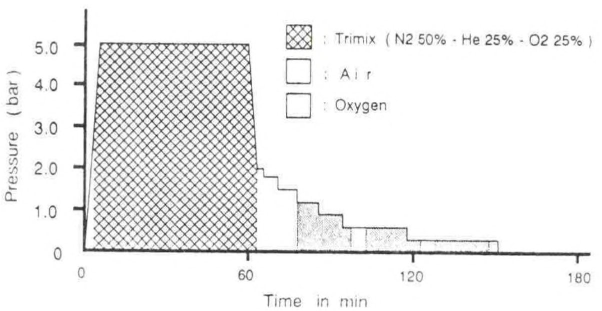

Figure 1. Dive profile of trimix chamber dives for the caisson work.

breathe through a full-face band mask equipped with a demand-type regulator in the hyperbaric air environment.

Dives

We adopted Sterk's method for decompression procedures from trimix breathing at a depth of 5 bars. During decompression, pure oxygen breathing was employed within the established limits to reduce decompression time and decrease risks of decompression sickness. Figure 1 shows the compression and decompression profile for the experimental chamber dives. We conducted 5-bar exposure for 60 minutes, breathing trimix several times, to evaluate the practicality of Sterk's method for use in hyperbaric caisson work. The total decompression time was 92 minutes, and the oxygen dose that is described as CPTD (Cumulative Pulmonary Toxicity Dose) was 230 units for the exposure and decompression. All five subjects completed the planned exposures.

Bubble Monitoring

After surfacing, we regularly monitored bubbles in all subjects for 2 hours using the continuous-wave Doppler ultrasound bubble detector devices (4 & 2.5 MHz, IAPM Seattle, USA) and an echocardio-camera (SSD-500, Aloka Japan). Measurements were made over the right side of the heart, the pulmonary artery, and the subclavian veins, with the subjects at rest and right after vigorous movement of the upper extremities for a short period.

Results

Throughout all exposures, there were no signs of nitrogen narcosis or oxygen toxicity. No bubbles were detected nor were there any signs of decompression sickness afterward. The subjects found the trimix breathing using full-face band masks quite comfortable at 5 bars. From our observations and the subjects' comments, we concluded that trimix gas is an effective breathing medium for workers entering deep caisson work to perform maintenance and repair of machinery and that our approach to the composition of the trimix gas and decompression procedure seems to work reliably. As a result, no major obstacles would be expected in using the remotely controlled caisson system at greater depths as planned.

Acknowledgment

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Literature Cited

Hirata, T., K. Takano, Y. Gotoh, I. Nashimoto, and W. Sterk, 1992. Remotely controlled caisson method and its maintenance. In: Engineering and Health in Compressed Air Work. In: Jardine, F.M. and R.L. McCallum (eds.), *Proceedings of the Construction Industry Research and Information Association (CIRIA) Conference, September 28-30, 1992, Oxford, UK,* pp. 375-381.

Kobayashi, K., Y. Gotoh, I. Nashimoto, and W. Sterk, 1993. Trimix chamber dives at 6 bar / 60 minutes. *J. Undersea and Hyperbaric Medicine*, Vol. 20, Supplement, p. 52.

Risk and Prevention of Dysbaric Osteonecrosis in Commercial, Recreational, and Scientific Diving

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Abstract

Dysbaric osteonecrosis (DON) is a form of aseptic bone necrosis that can cause the painful collapse of bone in weight-bearing joints leading to permanent disability. DON is associated with prolonged hyperbaric exposures, either in tunnel work or diving with compressed air. Recent diving practices of scallop divers in Maine and abalone divers in California closely match those of Japanese shellfish divers, most of whom have DON. This suggests that some American divers are at high risk of developing DON. Prolonged dives and lengthy repetitive diving can promote significant accumulations of dissolved tissue N_2 so that bubbles form upon abrupt decompression. Bubbles cause limb bends and presumably DON. Persistent limb bends may warn the diver and clinician of a bone compartment syndrome and the high likelihood of impending DON. Early recompression treatment of experimental limb bends cases in sheep prevented the later development of DON. This finding points to the clinical importance of prompt recompression therapy in limb bends cases. We propose that DON can be prevented in patients with limb bends by prompt recompression treatment. These findings contain important long-term health implications for reducing DON risk in populations of commercial, scientific, and recreational divers, especially for the 2 million recreational divers in the United States and the 300,000 recreational divers in Japan.

Introduction

Dysbaric osteonecrosis (DON) is a disabling form of aseptic bone necrosis usually associated with prolonged hyperbaric exposure of divers and tunnel workers (Davidson 1976 and 1989, Jones 1993, McCallum and Harrison 1993). Although the pathophysiological mechanisms that lead to DON remain uncertain, bubble formation in the long bones may be as important in DON pathogenesis as bubbles are in other forms of decompression disorders in diving and tunnel work (Elliott and Moon 1993). Bubble formation in the fatty marrow probably causes ischemia and necrosis of the long bones in the DON-affected diver and tunnel worker (Lanphier et al. 1994).

Dysbaric osteonecrosis can lead to painful joint collapse and permanent disability secondary to involvement of bone in the joint region (Davidson 1976, McCallum and Harrison 1993). Clinical manifestations in the DON patient may remain occult or silent for years before an acute collapse of the joint occurs (McCallum and Harrison 1993). As a consequence, it is often difficult to assign a specific hyperbaric insult or dive as the cause of a specific bone or joint lesion. Although DON is uncommon in most diver populations, the potentially severe disability associated with DON should raise important long-term health concerns for the diver.

Dysbaric osteonecrosis has been investigated in the Diving Physiology Laboratory of University of Wisconsin with animal studies using sheep (Lanphier and Lehner 1990), and in Japan with the evaluation of Japanese diving practices and x-ray examination of affected shellfish divers. This paper reviews our current understanding of the factors responsible for DON, its development, its risk, and methods for preventing DON in commercial, recreational, and scientific divers.

Dysbaric Osteonecrosis Epidemiology

Our understanding of DON in humans is largely derived from clinically disabled patients with DON. The prevalence of DON is greatest among those humans with a long history of prolonged hyperbaric exposure, typically after many months or years of repeated hyperbaric exposures, each often lasting for more than 4 hours (Lehner et al.

1994). Yet, a single hyperbaric exposure can induce DON in humans (James 1945).

Diving fishermen in Japan and coral divers in Hawaii represent populations with some of the highest occupational risks of DON. DON prevalences greater than 50% have been reported in these divers (Amako et al. 1974, Kawashima et al. 1978, Wade et al. 1978), based on plain radiographic examinations. Scallop divers of Maine and abalone divers of California presumably carry a potentially high risk of DON, given their current diving practices. This troubling assessment is suggested by their reported diving practices and by the lack of routine recompression for their limb bends. To our knowledge, these American shellfish divers have never undergone systematic radiographic evaluation to investigate the presence of DON lesions.

Tunnel and caisson workers exposed to hyperbaric conditions are known to represent an occupational group with a high risk of DON. Occupational exposures with an increased risk of DON accompany long work shifts, frequently more than 4 hours. Comparatively high pressures, those greater than 2.5 atm abs, equivalent to 50 feet of seawater depth, also appear to be implicated. Careful management of pressure profiles, particularly exposure times spent at maximum pressure and adequate decompression schedules, can decrease the risk of DON (Jones and Behnke 1978, Kindwall 1994, Kindwall et al. 1982).

The prevalence of DON in commercial, recreational, and scientific divers is not well-documented. Overall, the prevalence of DON in these groups must be comparatively low, especially among recreational divers, since relatively few cases have been reported. Yet, with approximately 2 million recreational divers in the United States and about 300,000 in Japan, even a low risk of DON can have far-reaching implications, because the acceptable risk of DON for most divers is very low.

A factor that can lead to substantially underestimating DON prevalence is the notoriously long clinical latency known to occur in many DON cases (Davidson 1976). Many years can elapse before the DON victim becomes symptomatic with a painful joint collapse. Lengthy clinical latencies in DON should be expected to lead to erroneously low estimates of DON if recent diving practices induce more DON cases than previous practices.

Fortunately, few DON cases have been associated with recreational diving. Before the use of dive computers, recreational diving characteristically involved no more than a few, comparatively brief dives each day. With dive computers, four to six dives per day became fairly routine (Lang and Vann 1992). Divers choose repetitive dives to gain additional bottom time. Repetitive dives lead to longer hyperbaric exposures and a greater DON risk. However, little is known about the overall risk of decompression sickness (DCS) in repetitive diving, and less is known about its DON risk.

Etiology and Pathogenesis of Dysbaric Osteonecrosis

While the etiological factors of DON, prolonged hyperbaric exposure and rapid decompression, are now better understood, the pathogenetic mechanisms of DON still remain uncertain and controversial (McCallum and Harrison 1993).

Sheep Experiments and DON Etiology

We discovered that DON could be reliably induced in sheep with prolonged hyperbaric exposure and rapid decompression (Lanphier and Lehner 1990). In the University of Wisconsin's Biotron laboratory, 24-hour hyperbaric exposures induced both persistent limb bends and DON in sheep. Such hyperbaric exposures are not unlike those experienced by tunnel workers during the early 1900's. It is widely accepted that prolonged hyperbaric exposures carry the greatest risk of DON, yet we discovered that hyperbaric exposures of 4 hours or less could also induce DON in sheep (Lehner et al. 1991).

Bubbles, Limb Bends, and a Proposed Bone Compartment Syndrome

Decompression forms bubbles that can cause DCS. Recompression therapy of the symptomatic DCS patient is effective, presumably because recompression quickly reduces bubble size and concomitant tissue pressures and, therefore, minimizes the mechanical and ischemic tissue injury. The prompt cessation of limb bends pain with recompression treatment supports the bubble mechanism theory for limb bends. In our observations, persistent limb bends have always preceded the development of DON in sheep, and we reasoned that bubbles could be the primary cause of DON as hypothesized by Behnke (1945).

We proposed that DON pathogenesis involves a bone compartment syndrome (Lanphier et al. 1994, Lehner et al. 1994, Zizic and Hungerford 1985). Each adult long bone represents a semi-closed, anatomical compartment in which compact bone surrounds mostly fatty marrow. Blood flow rates in fatty marrow are comparatively slow, and thus the rates of tissue gas uptake and elimination also tend to be slow. Fatty marrow has a high affinity for dissolved N_2, and N_2 is about five times more soluble in fatty than in non-fatty tissues. As a result, significant quantities of dissolved N_2 can accumulate in the fatty marrow during lengthy hyperbaric exposure. Rapid decompression causes N_2 supersaturation, and bubbles, mostly N_2, can form. Bubbles may obstruct or occlude blood flow in the complicated architecture of the venous vasculature. A tamponade or blockade of the venous outflow will raise tissue pressure in the marrow and bone. Arterial blood flow decreases, and tissue ischemia and hemostasis ensue, exacerbated by the swelling of fat cells, followed by bone and fatty marrow necrosis.

Later, the weakened, diseased bone that has undergone remodelling can collapse during weight-bearing. Progressive structural failure can involve a vicious cycle of successive remodelling and fracture, with a symptomatic collapse of the joint cartilage surface. Bone collapse can permanently disable the diver.

UW Sheep Model of Dysbaric Osteonecrosis

At the University of Wisconsin (UW), we found that repeated 24-hour hyperbaric exposures induced DON in sheep long bones (Lanphier and Lehner 1990). Twenty-four-hour hyperbaric exposures induced persistent limb bends in those limbs that later developed DON. Recently, severe to moderate DON lesions were induced in sheep long bones with single 24-hour hyperbaric exposures to 2.2 to 2.4 atm abs, equivalent to 40 to 45 feet of seawater pressure (Lehner et al. 1993). The decompression rate was approximately 25 feet per minute. Persistent limb bends were common in the decompressed sheep after the hyperbaric exposure.

Sheep DON: Scintigraphy, MR Imaging, and Gross Pathology

Sheep long bones were examined for DON lesions with bone scintigraphy after single 24-hour hyperbaric exposures (Lin et al. 1993a). Tc-99m methylene diphosphonate (MDP) was used to detect active DON lesions in the decompressed sheep. Tc-99m MDP is a gamma emitter which is sensitive to bone remodelling and marrow calcification. Examples of DON lesions ranged from localized foci to nearly global involvement of the bone and fatty marrow in affected long bones.

Magnetic resonance (MR) imaging is a diagnostic modality especially sensitive to fatty marrow lesions in early osteonecrosis (Brody et al. 1991, Mitchell et al. 1989). Imaging of sheep tibiae was performed with a General Electric 1.5 Tesla Signa machine at the University of Wisconsin's Magnetic Resonance Imaging Center. In one case, a fatty marrow lesion developed in a sheep tibia 2 weeks after hyperbaric exposure. T1-weighted MR imaging of 2 sheep at 2 months indicated regions of low signal intensity mostly at the margins of fatty marrow lesions. Regions of lower signal intensity appeared to be due to bone marrow edema (Hayes et al. 1993) and possible vessel proliferation along the margins of the fatty marrow lesions. Vessel proliferation has been confirmed in sheep femora with microangiography and gross pathology as early as 2 weeks after experimental bone marrow tamponade (Lemos et al. 1990).

At 2 months, gross pathology in sheep long bones confirmed the presence of marrow lesions previously visualized with bone scintigraphy and MR imaging. In gross pathology, typical findings included marrow lesions of necrotic fat that were partially surrounded by reddish, hyperemic tissues, indicating progressive repair in early DON.

Recompression Therapy Prevents Dysbaric Osteonecrosis

We reasoned that the rapid remission of limb bends pain with recompression therapy points to a bubble-initiated causation in limb bends and suggests an important pathogenetic role for bubbles in DON. Recompression that proves effective in treating limb bends symptoms might also prove effective in preventing DON.

We selected the U.S. Navy's Table 1A, an air recompression treatment table, which we modified to include longer "soaks" at shallow decompression stops (Lin et al. 1993b). The compression rate was decreased to accommodate any occurrence of Behnke's "bone squeeze" (Lanphier et al. 1994). Recompression of limb bends patients sometimes causes additional discomfort, and this discomfort is likely due to a "bone squeeze" as first proposed by Behnke (1945). During recompression, the body and its long bones are again placed under increased external pressure. Blood may not immediately fill the bubble "voids" in the marrow cavity, and the resulting negative pressure differential can cause pain. This "bone squeeze" may be likened to the painful aspiration procedure in a bone marrow biopsy.

Sheep that were subjected to a 24-hour hyperbaric exposure and were recompressed after 4 hours at surface pressure usually did not develop DON (Lin et al. 1993a,b). Limb bends signs in the six decompressed sheep were common during the 4-hour surface interval immediately before recompression treatment. Recompression quickly resulted in the remission of limb lifting, a sign of limb bends in decompressed sheep. Bone scans of the long bones in the recompressed sheep were unremarkable, except for their lack of "hot spot" DON lesions. Gross pathology was normal, except for a mild lesion in one long bone.

Summary of Sheep Findings in 24-Hour Hyperbaric Exposures

Results from the 24-hour sheep experiments demonstrated the induction of DON in sheep with a single 24-hour hyperbaric exposure. Two months after hyperbaric exposure, eight of eight sheep had developed DON in the long bones of those limbs affected by limb bends (Lehner et al. 1993). Two months after hyperbaric exposure, five of six decompressed and *recompressed* sheep had long bones

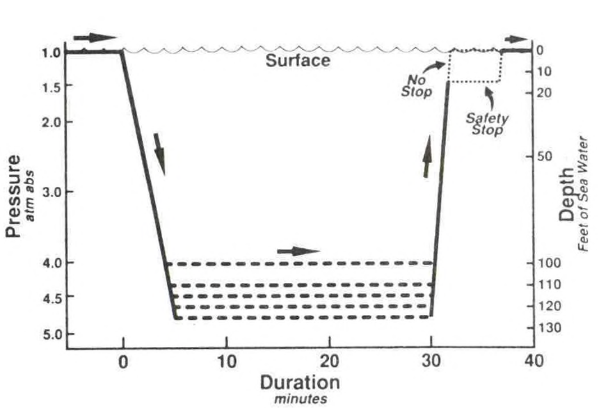

Figure 1. Brief hyperbaric exposures that induced decompression sickness and mild dysbaric osteonecrosis in sheep.

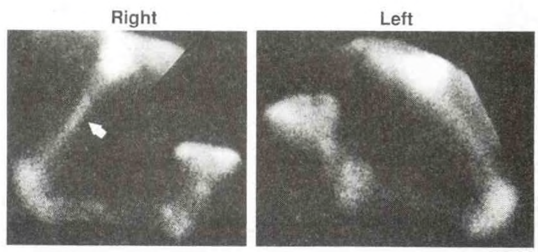

Figure 2. Mild dysbaric osteonecrosis lesion induced in the right radius of a sheep after seven, one-half-hour hyperbaric exposures.

which appeared normal, and only one sheep had developed a mild lesion in one long bone (Lin et al. 1993b).

One-Half-Hour Hyperbaric Exposures of Sheep

Recently, we were surprised by sheep outcomes after one-half-hour hyperbaric exposures to pressures of 100 to 125 feet of sea water. These sheep exposures, with and without a "safety stop," were used to simulate comparatively deep dives in recreational diving (fig. 1). The sheep "dives" were similar to those in recreational diving, but they exceeded the limits permitted by decompression schedules and dive computers.

Decompression from these "dives" was at about 25 feet of sea water per minute. Persistent limb bends sometimes resulted, and mild limb bends signs lasted for as long as 2 days. Some bone scans indicated mild "hot spots" consistent with DON. In one case, a bone scan "hot spot" occurred in the right radius of the decompressed sheep, but her left radius appeared normal (fig. 2). As reported by Taya in these *Proceedings*, similar outcomes also occurred in sheep after 3-hour hyperbaric exposures.

Consequently, these findings in the UW sheep model of DON indicate the potential for DON developing even after brief dives that induce limb bends. Divers should be aware of the risk that DON can develop after persistent limb bends symptoms. These findings also emphasize the need for prompt recompression treatment in limb bends as a means for preventing DON.

Maine Scallop Divers

Scallop divers in Maine who routinely dive to depths of 40-60 feet of sea water 6 or more times per day experience a high incidence of limb bends. Most information about Maine scallop divers has been provided in personal communications to the senior author by Dr. Thomas D. Chayka and Dr. Albert A. Pollard of Maine.

Maine scallop diving often involves numerous repetitive dives in a day, and these daily represent a long cumulative hyperbaric exposure. Diving with scuba is the preferred technique used in gathering scallops. Overfishing in shallow waters has encouraged deeper dives to gather scallops, and this deeper, repetitive diving should increase the risk of limb bends and DON developing in these scallop divers. The high frequency of limb bends in these scallop divers points to a potentially high risk of DON developing in the divers' long bones.

Repetitive Diving

As previously discussed, repetitive diving can increase the risk of DON, especially when repetitive diving cumulatively represents a prolonged hyperbaric exposure. Repetitive diving can raise tissue N_2 levels in "slow tissues" with low perfusion rates to the levels achieved with a prolonged hyperbaric exposure.

Today, recreational divers often conduct several dives per day by using dive computers to guide their decompression schedules (Lang and Hamilton 1989). However, most dive computer algorithms do not compensate for bubble formation and its potential for slowing inert gas elimination. Bubble formation may lead to increased tissue pressures and to reduced tissue blood flows. Such reduced blood flows would enhance *in situ* bubble growth and increase the risk of DCS. In addition, dive computer algorithms model only DCS likelihood in divers and not that of DON. Cumulative hyperbaric exposures in rigorous repetitive diving may represent significant DON risk to the recreational, scientific, and commercial diver.

Research Issues of Dysbaric Osteonecrosis

As a result of recent findings using the UW sheep model of DON, a number of important questions have been raised:

1. What dive profiles carry a significant risk of DON?
2. Would DON risk function modelling be useful for modifying dive computers?
3. What is the DON risk from untreated limb bends?
4. Does the persistence and severity of limb bends predict DON outcome?
5. What is the most effective treatment protocol for limb bends to prevent DON?

6. How long can the diver with persistent limb bends wait before recompression treatment becomes ineffective in preventing DON?

Recommendations

Findings from our sheep studies lead to the following recommendations:

1. A diver should select pressure profiles with a low risk of limb bends;
2. Early recompression treatment in limb bends cases should be used to prevent DON; and
3. Divers must be educated about the implications of "pain-only" limb bends. In light of the link between limb bends and DON, the minimizing term, "pain-only," for limb bends should be discontinued.

Acknowledgments

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Literature Cited

Amako, T., M. Kawashima, T. Torisu, and K. Hayashi, 1974. Bone and joint lesions in decompression sickness. *Seminars in Arthr. Rheum.* 4:151-190.

Behnke, A.R., 1945. Decompression sickness incident to deep sea diving and high altitude ascent. *Medicine* 24:381-402.

Brody, A.S., M. Strong, G. Babikian, D.E. Sweet, F.G. Seidel, and J.P. Kuhn, 1991. Avascular necrosis: early MR imaging and histologic findings in a canine model. *AJR* 157:341-345.

Davidson, J.K., 1976. Dysbaric osteonecrosis. In: J.K. Davidson (ed.), *Aseptic Necrosis of Bone*, pp.147-212. Elsevier, New York.

Davidson, J.K., 1989. Dysbaric disorders: aseptic necrosis in tunnel workers and divers. *Bailliere's Clinical Rheumatology* 3:1-23.

Elliott, D.H., and R.E. Moon, 1993. Manifestations of decompression disorders. In: P.B. Bennett and D.H. Elliott (eds.), *The Physiology and Medicine of Diving*, 4th ed., pp. 481-505. W.B. Saunders Company, Ltd., London.

Hayes, C.W., W.F. Conway, and W.W. Daniel, 1993. MR imaging of bone marrow edema pattern: transient osteoporosis, transient marrow edema syndrome, or osteonecrosis. *Radiographics* 13:1001-1011.

James, C.C.M., 1945. Late bone lesions in caisson disease. Three cases in submarine personnel. *Lancet*, ii:6-8.

Jones, J.P., Jr., 1993. Osteonecrosis. In: D.J. McCarty and W.J. Koopman (eds.), *Arthritis and Allied Conditions*, pp. 1677-1696. Lea & Febiger, Philadelphia.

Jones, J.P., Jr., and A.R. Behnke, Jr., 1978. Prevention of dysbaric osteonecrosis in compressed-air workers. *Clin. Orthop.* 130:118-128.

Kawashima, M., K. Hayashi, T. Torisu, M. Kitano, 1978. Pathological review of osteonecrosis in divers. *Clin. Orthop.* 130:107-117.

Kindwall, E.C., 1994. Optimum schedules for caisson decompression. In: F. Jardine and R.I. McCallum (eds.), *Engineering and Health in Compressed Air Work*, 28-30 September, 1992, Oxford, UK, Construction Industry Research and Information Association (CIRIA), London, pp. 156-171. E & FN Spon, London.

Kindwall, E.C., J.R. Nellen, D.R. Spiegelhoff, 1982. Aseptic bone necrosis in compressed air tunnel workers using current OSHA decompression schedules. *J. Occup. Med.* 24:741-744.

Lang, M.A., and R.W. Hamilton (eds.), 1989. *Proceedings of the American Academy of Underwater Sciences Dive Computer Workshop*, U.S.C. Catalina Marine Science Center, Santa Catalina Island, California, September 26-28, 1988. American Academy of Underwater Sciences, Costa Mesa, CA.

Lang, M.A. and R.D. Vann (eds.), 1992. *Repetitive Diving Workshop*, Proceedings of the American Academy of Underwater Sciences, Duke University, March 18-19, 1991. American Academy of Underwater Sciences, Costa Mesa, CA.

Lanphier, E.H., and C.E. Lehner, 1990. Animal models in decompression. In: Y.C. Lin and K.K. Shida (eds.), *Man in the Sea*, pp. 273-295. Best Publishing Co., San Pedro, CA.

Lanphier, E.H., C.E. Lehner, and S.E. Lemos, 1994. The role of intramedullary pressure in hyperbaric osteonecrosis. In: F. Jardine and R.I. McCallum (eds.), *Engineering and Health in Compressed Air Work*, 28-30 September, 1992, Oxford, UK, Construction Industry Research and Information Association (CIRIA), London, pp. 148-155. E & FN Spon, London.

Lehner, C.E., E.H. Lanphier, M.A. Wilson, M. Kawashima, M. Kitano, Y. Mano, and Y. Taya, 1991. Dive profiles control the risk of dysbaric osteonecrosis: Validation in Japanese diving fishermen and sheep. *Proceedings of the 11th Meeting of the United States-Japan Cooperative Program in Natural Resources (UJNR), Panel on Diving Physiology and Technology, September 26-27, 1991, Hakone, Japan*, pp. 85-101. Yokosuka, Japan Marine Science and Technology Center.

Lehner, C.E., T.F. Lin, E.H. Lanphier, M.A. Wilson, R. Dueland, and R.R. Dubielzig, 1994. Early pathogenesis of hyperbaric osteonecrosis. In: F. Jardine and R.I. McCallum (eds.), *Engineering and Health in Compressed Air Work*, 28-30 September, 1992, Oxford, UK, Construction Industry Research and Information Association (CIRIA), London, pp. 172-187. E & FN Spon, London.

Lehner, C.E., T.F. Lin, E.H. Lanphier, M.A. Wilson, M.D. Markel, and R. Dueland, 1993. Prolonged hyperbaric exposure, persistent limb bends, and early recompression therapy in dysbaric osteonecrosis. *Undersea and Hyperbaric Med.* 20 (Suppl):21.

Lemos, S.E., C.E. Lehner, E.V. Nordheim, D.B. Brunson, and E.H. Lanphier, 1990. Elevated intramedullary pressure causes bone marrow necrosis. *Undersea Biomed. Res.* 17 (Suppl):59.

Lin, Y.C., C.E. Lehner, E.H. Lanphier, M.A. Wilson, A.A. De Smet, M.D. Markel, and R. Dueland, 1993a. Non-invasive diagnostic techniques in the early detection of experimental dysbaric osteonecrosis in sheep. *Undersea and Hyperbaric Med.* 29 (Suppl):71.

Lin, Y.C., C.E. Lehner, E.H. Lanphier, M.A. Wilson, M.D. Markel, and R. Dueland, 1993b. Prompt recompression of sheep with limb bends prevents the development of dysbaric osteonecrosis. *Undersea and Hyperbaric Med.* 20 (Suppl):20-21.

McCallum, R.I., and A.B. Harrison, 1993. Dysbaric osteonecrosis: aseptic necrosis of bone. In: P.B. Bennett and D.H. Elliott (eds.), *The Physiology and Medicine of Diving*, 4th ed., pp. 563-584. W.B. Saunders Company, Ltd., London.

Mitchell, D.G., M.E. Steinberg, M.K. Dalinka, V.M. Rao, M. Fallon, and H.Y. Kessel, 1989. Magnetic resonance imaging of the ischemic hip. *Clin. Orthop.* 244:60-77.

Wade, C.E., K. Hayashi, T.M. Cashman Jr., and E.L. Beckman, 1978. Incidence of dysbaric osteonecrosis in Hawaii's diving fishermen. *Undersea Biomed. Res.*, 5:137-147.

Zizic, T.M., and D.S. Hungerford, 1985. Avascular necrosis of bone. In: W.N. Kelly, E.D. Harris, Jr., S. Ruddy, and C.B. Sledge (eds.), pp. 1689-1710. W.B. Saunders, Philadelphia.

Brief Review of U.S.–Japan Cooperative Diving Research

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Brief History

At the first meeting of the UJNR Diving Physiology and Technology Panel in Tokyo, October 11 and 12, 1972, an agreement was reached in principle to exchange information and promote cooperative research. However, no mechanisms existed for actually implementing the agreement. A cooperative research mechanism developed surprisingly quickly because of two energetic, dynamic, and diligent principals (see below). The Diving Physiology and Technology Panel (the Panel) agreed to put their emphases in areas of saturation diving, marine resources development, caisson work, fishing industry, and basic medical sciences. Whether the areas of interest were shaped by the composition of the panel members and advisors at that time or the other way around did not matter. The Panel became the most active and productive among the 16 UJNR panels. Areas of cooperative effort have expanded since 1991 to include deep-sea research.

This historical meeting deserves further elaboration. Existing records show that Mr. Yajima, Chairman of the Japanese delegation, opened the meeting. His welcoming address was followed by the addresses of Mr. Nakazawa, the Director-General of Agriculture, Forestry and Fisheries Research Council, Dr. Matsushita, Director of Research Department of the Fishery Agency, Mr. Shigihara, UJNR Coordinator and Head of International Affairs Division of the Promotion Bureau, and Dr. Hiatt, Science Attache of the U.S. Embassy.

After these addresses, Mr. Yajima and Dr. James Miller, Chairman of the U.S. delegation, were elected to chair the subsequent sessions, the meeting agenda was adopted, and the secretaries were named. This procedure became a tradition that remained intact for all future biennial meetings — eleven more, so far. The resolution of the first conference reads, in part, "It was concluded, that, we should promote the exchange of information in these areas leading to future cooperative programs relating to the application of diving technology and physiology to marine resource development, caisson work, the fishing industry and basic medical sciences. The increasing interest in the ocean requires more unified effort on an **international basis**." The emphasis was of the authors, as the need for a consorted cooperative international effort in ocean research rather than competition, is now echoed on both sides of the Pacific.

Plans for implementing cooperative diving research took shape quickly after Dr. Motohiko Matsuda, the first Director of the Japan Marine Science and Technology's (JAMSTEC's) R and D, attended the 1972 Inner Space Pacifica Conference in Hawaii in October. Dr. Suk Ki Hong met him there for the first time. They hit it off immediately and instantly established a rapport, since they literally speak the same "language." Informal discussions took place during and after the meeting. One month later, Dr. Matsuda returned to Hawaii for a formal discussion with Dr. Hideaki Nakayama, also of JAMSTEC, attending. Dr. Hong, Dr. Richard Strauss, and Dr. Terry Moore represented the University of Hawaii (UH) in the discussion. The discussion was extensive, covering the underlying philosophy, areas of cooperation, specific joint research programs, budget, educational exchange programs, and service for translating and reproducing documents. The discussion ended with the signing of an agreement for a 5-year (1973-1978) plan to carry out cooperative research between the UH and JAMSTEC. Dr. John Craven, Dean of Marine Programs, signed on behalf of the University, and Dr. Matsuda for the JAMSTEC. The historical page appears as figure 1.

The philosophy of this cooperative research plan remains consistent with all UJNR panels; that is, to exchange information and promote cooperative research. Specifically, they agreed to pool existing resources to improve and facilitate the ongoing diving research programs on both sides. The original 5-year plan has been

UNIVERSITY OF HAWAII

Department of Physiology · School of Medicine

The first consultation meeting between Jamstec and UH personnel was held in Honolulu on December 1 through December 5, 1972. The Jamstec representatives were:

Dr. Matsuda

Dr. Nakayama

the UH representatives were:

Dr. Hong

Dr. Strauss

Dr. Moore

The enclosed proposal was the result of the first conference. It represents the combined feelings and expectations of the joint discussion.

It should be stated that the enclosed is a joint proposal, subject to evaluation and/or revision by the funding agencies involved, and implies no irrevocable commitment by either institution.

It should be emphasized, however, that the proposal signifies an important agreement in principle for future cooperative programs of mutual benefit, and obvious value to the international field of Diving Technology and Physiology.

Dr. M. Matsuda M. Matsuda
Director, Research & Development, JAMSTEC

Dr. J. Craven John P Craven
Dean, Marine Programs, UH

Figure 1. The signature page of the 5-year cooperative diving research agreement (1973-1978) between the Japan Marine Science and Technology Center and the University of Hawaii.

extended to exceed 20 years. The expansion included State University of New York (SUNY) at Buffalo in 1975, when Dr. Hong relocated. Also around this time, the University of Occupational and Environmental Health (UOEH) became an important constituent and contributed heavily thereafter through Dr. Keizo Shiraki of the Department of Applied Physiology. Dr. Shiraki contributed not only fresh ideas but also personnel, instrumentation, biochemical analysis of blood and urine samples, and post-experiment data analysis and publications. A separate 3-year agreement was signed in 1989 between the UH and JAMSTEC to carry out joint experiments in animals for the validation of tables constructed according to the universal decompression table (UDT) concept (Lin 1988). The cover page and the signature page of the agreement are shown in figure 2. The cover page reads from the top, "Cooperative Research, Studies on Decompression Tables for Use in Saturation Diving, Research Plan," and on the lower half, the date, JAMSTEC, and finally the UH. On the signature page, the official seal of Mr. Makimura, the Director of JAMSTEC, and Dr. Lin's signature and the date, July 3, Heisei year one (1989), are shown.

University of Hawaii Diving Program

Dr. Hong led his team conducting diving research at the Manoa laboratories, at Kewalo Basin, and later at the

共同研究

「飽和潜水用減圧表の研究」

実施計画書

平成元年 7 月

海洋科学技術センター

ハワイ大学

この契約の証として本書2通を作成し、甲、乙記名捺印のうえ、各1通これを保持するものとする。

平成元年7月3日

甲. 神奈川県横須賀市夏島町2番地15

海洋科学技術センター

契約担当役理事長 牧 村 信 之

乙. 1960・East.-West Road Honolulu Hawaii

ハワイ大学

生理学教授 Yu Chong Lin

Figure 2. First and the signature pages of the 3-year research program for the verification, revision, and application of decompression tables formulated according the universal decompression table concept.

Makai Testing Range (Makapuu Point, Oahu). The Makai Testing Range was built as a diving facility anticipating use by the U.S. Navy and diving industry. Neither of these materialized. The unfortunate event benefited UH's diving program, though temporarily. The State of Hawaii took over the facility and turned it over to the UH in 1974. Through the support of the Office of Naval Research, NOAA's National Undersea Research Program and the Sea Grant College Program, and the State of Hawaii's Office of Marine Affairs Coordinator, the UH conducted the Hana Kai II dive using the habitat *Aegir* (fig. 3). Dr. Matsuda led a team of Japanese scientists to participate in the Hana Kai II dive in 1975. In addition to investigators from the UH and JAMSTEC, scientists from Webb Associates (Yellow Spring, OH), the Naval Medical Research Institute (Bethesda, MD), and Tokai University also participated. This turned out to be the only dive that the United States hosted under the cooperative diving research program.

The Hana Kai II dive to 580 feet (18.6 ATA) was carried out in the *Aegir* habitat over a 30-day period. Hana Kai II was designed to study human adaptation to a sustained high ambient pressure by keeping its subjects under 18.6 ATA for 17 days. In this heliox dive, comprehensive studies were made on energy balance, body fluid balance, respiratory and cardiovascular functions, maximal oxygen uptake, psychological performance, and physiological responses to cold (Hong et al. 1977). The Undersea Biomedical Research devoted its 1977 September issue to publishing the results of this dive (UBR 1977).

JAMSTEC Diving Program

Japan established JAMSTEC on October 1, 1971, and began their Seatopia saturation dive series in 1972 with the habitat, *Seatopia*, submerged in Suruga Bay, a few miles from the present site. Dr. Hong participated in one of the two dives there. The *Seatopia* habitat is preserved as a monument on the new JAMSTEC campus. JAMSTEC moved to the present site in Natsushima in December of 1972 (fig. 4).

JAMSTEC completed its hyperbaric simulator facility June 30, 1973. Just 2 weeks later, 4 scientists from the UH participated in their very first saturation dive at the new facility, the Seatopia III, a 60 m saturation dive, July 13-

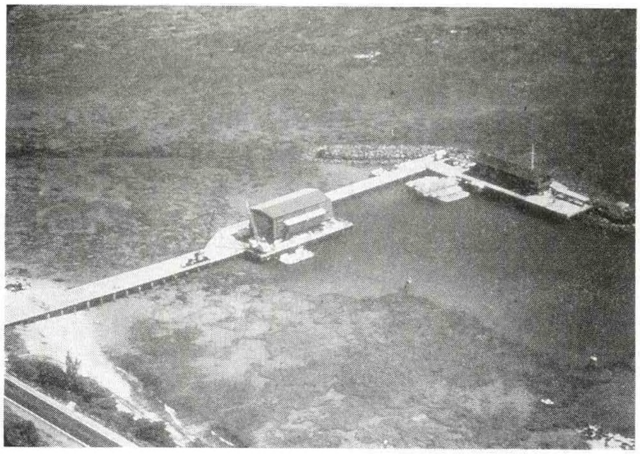

Figure 3. Habitat Aegir *moored at the Makai Testing Range, Makapuu Point, Oahu.*

28, 1973 (Matsuda et al. 1975a, Matsuda et al. 1975b, Nakayama et al. 1978).

JAMSTEC Dive Series

As of February 1995, JAMSTEC has carried out a total of 50 saturation dives in the following series:

Seatopia I–XI: 1972-1975, 20-100 m, safety and applications of existing technology were the main concerns.

Seamecca I–II, 1980-1981, 30 m, short dives to introduce physicians and scientists to the chamber system and hyperbaric environment.

Seadragon I–VI, 1976-1991, 100-300 m, to evaluate physiology, psychology, and safety in prolonged exposure to 300 m through land-based simulation, including water immersion under pressure.

New Seatopia I–XVII, 1982-1991, 60-300 m, to prepare for and perform diver lock-out in the open sea at 300 m depth by utilizing the hyperbaric chamber system on board the mothership *Kaiyo*.

Shinkaiseibutsu, 1991-, 210 m, with the use of deep submersibles for the study of deep sea biology.

Heliox saturation, 1993-, 160-180 m

Nitrox saturation, 1993-, 20 m, in anticipation of building their own habitat. This is the first phase of **Scientists in the Sea** project that began in 1992.

JAMSTEC used 51 divers in 220 man-dives in the above dive series. In most dives, four divers were employed. Occasionally, six divers were involved. Many divers participated in multiple dives. One diver participated in 21 dives. Among these dives, Seadragon IV in 1979 was the most widely known and involved scientists from Japan, the United States, France, and Germany. Results of the Seadragon VI dive were published in the September 1987 issue of *Undersea Biomedical Research*. The cover of this issue features a deep-sea diver returning to the personnel transfer capsule after an open-sea excursion (UBR 1987).

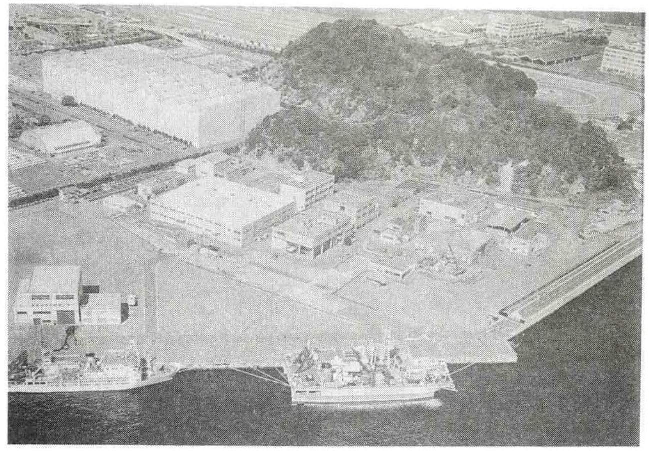

Figure 4. Panoramic view of the JAMSTEC campus. The deep-sea simulators (for humans and animals) are housed in two buildings on the right at the foothill of Natsushima, with the gas storage shack between them. The building at the far right houses the animal hyperbaric simulator. The large building at the top left is not a part of the JAMSTEC campus. The habitat Seatopia stands prominently in front of the cafeteria building. Two of the JAMSTEC ships are shown.

U.S. Participation

The U.S. scientists from the UH and SUNY Buffalo conducted research in the following dives:

Dive	P, ATA	Bottom, d	Total,d*
Seatopia, 1973	7	7	16
Seatopia, 1975	11	8	14
Seadragon IV, 1979	31	14	35
Seadragon VI, 1984	31	7	29
New Seatopia, 1985	31	7	24
N_2-O_2, 1993	3	7	15
He-O_2, 1993	16	7	22
N_2-O_2, 1994	3	7	17
He-O_2, 1994	19	7	24
N_2-O_2, 1995	3	7	18

* Total dive time in days includes predive, postdive, steady- state pressure (bottom), and pressure transients.

In all of the dives, the emphasis has been on physiological changes and adaptation to the sustained high pressure. Therefore, the safest compression and decompression procedures were used. This seemingly missed opportunity for studying the process of pressure changes turned out to be the success story of the JAMSTEC saturation diving program. An unrecoverable setback could have resulted if even the slightest mishap had occurred by using experimental compression and decompression procedures.

Funding and Coordination

JAMSTEC obtained their budget from the Science and Technology Agency, which included funds necessary for carrying out annual facility maintenance, saturation dives, and cooperative research. The Office of Naval Research, NOAA, and the State of Hawaii Marine Affairs Coordinator's Office jointly funded the U.S. dive (Hana Kai II). Travel funds to participate in JAMSTEC dives were provided by the NOAA-NURP through the efforts of Chairmen of the U.S. Panel, Mr. James Miller, Dr. William Busch, Dr. David Duane, and, since 1992, Mr. Eugene Smith.

Dr. Suk Ki Hong served as the U.S. Coordinator between 1972 and 1989, and Dr. Yu-Chong Lin succeeded him in 1989. The Japanese coordinators were Dr. Motohiko Matsuda from 1972 through 1984, and Dr. Hideaki Nakayama for 1984 through 1985. Currently Dr. Motohiko Mohri serves as the coordinator.

Achievements

After each cooperative study, the coordinator submitted a brief report to NOAA, and the results subsequently were published. Hong's review listed 25 publications as of 1987 (Hong 1990). A list of publications since then appears in Appendix I.

In addition to disseminating results through publications, the cooperative dive research program fully realizes the purpose and philosophy of the UJNR program. It takes advantages of strength on both sides, exchanges scientific information, and contributes regularly to scientific meetings, symposiums, and workshops. More importantly, it provides opportunities for and encourages potential researchers to join the hyperbaric research community. Furthermore, this program fosters the development of friendships within and outside the research program. For example, Dr. Shiraki's laboratory hosted many United States researchers in his research program (see the appendix for publications) and created a mechanism to enable scientists from other countries (Dr. Yang Saeng Park of Korea and Dr. Alan Niu of Republic of China) to participate in the cooperative diving research. The UH and University of Wisconsin have hosted JAMSTEC scientists for short study tours. Mr. Mansuke Nakamura of the Nakamura Iron Works of Tokyo and his three sons take an active part in fostering international friendships, within and outside the UJNR framework, and have contributed financially to symposiums and workshops both in Japan and the United States. These were direct and indirect results of personal contact through the cooperative research program. This kind of development cannot be measured in monetary terms and undoubtedly will have a positive effect on further development of cooperative programs.

New Initiatives

In 1989, verification of the UDT concept was added and carried out at JAMSTEC's animal chamber system. So far, Dr. Lin has participated in 3 UDT experiments. This program is continuing.

Since 1989, Suk Ki Hong conducted three studies in Japanese ama in cooperation with the UOEH, JAMSTEC, and Harvard University (Dr. Warren Zapol's group). The latest study was conducted in August-September 1993.

In 1991, Dr. Kawashima initiated cooperative studies on dysbaric osteonecrosis in cooperation with Dr. Charles Lehner and Dr. Edward Lanphier of the University of Wisconsin, Dr. Yoshihiro Mano of the Tokyo Medical and Dental University, and Mr. Yasushi Taya and Mr. Fumiro Shidara of JAMSTEC. The study is continuing.

Dr. Mano and Dr. Peter Bennett of the Duke University are working to expand the Diving Alert Network program to Japan and internationally.

Undoubtedly, other cooperative activities are ongoing that were not coordinated through the Panel and, therefore, we were unaware of their existence. We apologize for any omissions.

Conclusions

International cooperative diving research is the most logical means of gathering physiological data concerning response and adaptation to hyperbaric environments, because of the enormous capital requirement and operating expenses. This approach benefits cooperative parties in many ways, among them the efficiency of facility utilization, personnel development, and cost effectiveness. From the U.S. point of view, the U.S. scientists are able to obtain meaningful data for a small fraction of the cost of conducting a saturation dive. Its continuation is strongly recommended. Nevertheless, we noted some shortcomings with this arrangement. It is not unusual that the dates and the basic objectives of a JAMSTEC saturation dive are finalized shortly before the start of the dive. This leaves little time for requesting funds for the participation of U.S. scientists. Furthermore, since we have to design experiments to fit into the basic JAMSTEC objectives, compromise is often made in devising experiments. Even with these restrictions, it is without a doubt the most cost-effective approach as demonstrated by past accomplishments.

Literature Cited

Hong, S.K., 1990. U.S.-Japan cooperative diving research (1973-1985). In: Y.C. Lin and K.K. Shida (eds.), *Man in the Sea*, pp. 135-160. San Pedro, CA, Best Publishing Co.

Hong, S.K., R.M. Smith, P. Webb, and M. Matsuda, 1977. Hana Kai II: a 17-day dry saturation dive at 18.6 ATA. I. Objective, design, and scope.

Undersea Biomed. Res. 4:211-220.

Lin, Y.C., 1988. Formulation of saturation dive decompression tables based on critical pressures and exponential gas elimination. In: Y.C. Lin and A.K.C. Niu (eds.), *Hyperbaric Physiology and Medicine*, pp. 99-119. San Pedro, CA, Best Publishing Co.

Matsuda, M., H. Nakayama, A. Itoh, N. Kirigaya, F.K. Kurada, R.H. Strauss, and S.K. Hong, 1975a. Physiology of man during a 10-day dry heliox saturation dive (Seatopia) to 7 ATA. I. Cardiovascular and thermo-regulatory functions. *Undersea Biomed. Res.* 2:101-118.

Matsuda, M., H. Nakayama, F.K. Kurada, J.R. Claybaugh, and S.K. Hong, 1975b. Physiology of man during a 10-day dry heliox saturation dive (Seatopia) to 7 ATA. II. Urinary water, electrolytes, ADH, and aldosterone. *Undersea Biomed. Res.* 2:119-131.

Nakayama, H., M. Matsuda, A. Itoh, N. Kirigaya, F.K. Kurata, R.H. Strauss, J.R. Claybaugh, and S.K. Hong, 1978. Physiological functions during a 10-day heliox saturation dive to 7 ATA. In: C.W. Shilling and M.W. Beckett (eds.), *Underwater Physiology VI*, pp. 99-106. Bethesda, MD, FASEB.

UBR, 1977. *Undersea Biomedical Research*, Vol. 4, No. 3, September. Bethesda, MD, Undersea Medical Society.

UBR, 1987. *Undersea Biomedical Research*, Vol. 14, No. 5, September. Bethesda, MD, Undersea and Hyperbaric Medical Society.

Appendix I. Publications

The list below includes publications since 1987 or that were not listed in Hong's review (Hong, 1990).

Claybaugh, J.R., S. Sagawa, K. Shiraki, Y.S. Park, M. Mohri, and S.K. Hong, 1987. Plasma atrial natriuretic factor concentration does not increase during a 31 ATA saturation dive: Implications of central volume receptors in the hyperbaric diuresis. *Proceedings of the Ninth Meeting of the UJNR Panel on Diving Physiology and Technology, November 4-6, 1987, Yukosuka, Kanagama, Japan*, pp. 217-228. Yokosuka, Japan, JAMSTEC.

Claybaugh, J.R., S.K. Hong, A.K.C. Niu, J.M. Goldinger, O. Kwon, M. Li, and C.E.G. Lundgren, 1991. Theories on the depth-dependent control of body-fluid-regulating hormones to saturation dive. In: G.D. Dennis (ed.), *Proceedings of the 10th Meeting of the UJNR Panel on Diving Physiology and Technology, June 4-7, 1989, Kauai, Hawaii*, pp. 1-10. Silver Spring, MD, NOAA's National Undersea Research Program.

Henderson, J., R. Morin, A. Olszowka, B. Laraway, and S.K. Hong, 1991. Underwater physiological data logger. In: M.A. Lang and R.D. Vann (eds.), *Proceedings of the Workshop on Repetitive Diving Workshop* (AAUSDSP-RDN-02-92), pp. 169-174. American Academy of Underwater Sciences.

Hong, S.K., J. Henderson, A. Olszowka, W.E. Hurford, K.J. Falke, J. Qvist, P. Radermacher, K. Shiraki, M. Mohri, H. Takeuchi, W.J. Zapol, D.W. Ahn, J.K. Choi, and Y.S. Park, 1991. Daily diving pattern of Korean and Japanese breath-hold divers (ama). *Undersea Biomed. Res.* 18:433-443.

Hong, S.K., J. Henderson, K. Shiraki, M. Mohri, H. Takeuchi, and Y.S. Park, 1991. Natural diving patterns of Korean and Japanese breath-hold divers (ama). *Proceedings of the 11th Meeting of the UJNR Panel on Diving Physiology and Technology, September 26-27, 1991, Hakone, Shizuoka, Japan*, pp. 204-211. Yukosuka, Japan, JAMSTEC.

Hong, S.K. and J.R. Claybaugh, 1989. Hormonal and renal responses to hyperbaria. In: J.R. Claybaugh and C.E. Wade (eds.), *Hormonal Regulation of Fluid and Electrolytes - Environmental Effects*, pp. 117-146. New York, NY, Plenum Press.

Hurford, W.E., S.K. Hong, Y.S. Park, D.W. Ahn, K. Shiraki, M. Mohri, and W.M. Zapol, 1990. Splenic contraction during breath-hold diving in the Korean ama. *J. Appl. Physiol.* 69:932-936.

Kitano, M., M. Kawashima, Y. Taya, C.E. Lehner, and E.H. Lanphier, 1991. Histopathological analysis of dysbaric osteonecrosis experimentally induced in sheep. *Proceedings of the 11th Meeting of the UJNR Panel on Diving Physiology and Technology, September 26-27, 1991, Hakone, Shizuoka, Japan*, pp. 36-47. Yukosuka, Japan, JAMSTEC.

Lehner, C.E., E.H. Lanphier, M.A. Wilson, M. Kawashima, M. Kitano, Y. Mano, and Y. Taya, 1991. Dive profiles control the risk of dysbaric osteonecrosis: Validation in Japanese diving fishermen and sheep. *Proceedings of the 11th Meeting of the UJNR Panel on Diving Physiology and Technology, September 26-27, 1991, Hakone, Shizuoka, Japan*, pp. 85-101. Yukosuka, Japan, JAMSTEC.

Lin, Y.C., F. Shidara, Y. Taya, Y. Mizushima, and M. Mohri, 1994. Interspecies conversion of tables for decompression from 300 msw (UDT300). In: P.B. Bennett and R.E. Marquis (eds.), *High Pressure Biology, III*, pp. 341-352. Rochester, NY, The University of Rochester Press.

Lin, Y.C., K. Shiraki, and M. Mohri, 1987. New Seatopia, 1985: circulatory responses. *Proceedings of the Ninth Meeting of the UJNR Panel on Diving Physiology and Technology, November 4-6, 1987, Yukosuka, Kanagama, Japan*, pp. 245-261.

Yokosuka, Japan, JAMSTEC.

Lin, Y.C., K. Shiraki, H. Takeuchi, and M. Mohri, 1995. Cardiovascular deconditioning occurs during a 7-day saturation dive at 31 ATA. *Aviat. Space Environ. Med.* 66:656-660.

Mano, Y., M. Shibayama, M. Kawashima, Y. Taya, M. Mohri, and C.E. Lehner, 1991. Recent diving profile of shellfish divers at Ariake Sea. *Proceedings of the 11th Meeting of the UJNR Panel on Diving Physiology and Technology, September 26-27, 1991, Hakone, Shizuoka, Japan*, pp. 124-132. Yukosuka, Japan, JAMSTEC.

Matsuoka, S., K. Inouye, S. Okuda, T. Ishikawa, H.D. Lee, and M. Mohri, 1986. EEG polygraphic sleep study in divers under a 31 ATA He-O_2 environment with special reference to the automated analysis of sleep stages. *J. UOEH* 8 (suppl.):293-305.

Matsuoka, S., S. Okuda, T. Ishikawa, S. Yamamoto, and M. Mohri, 1987. Topographic characteristics of EEG during a saturation dive to 31 ATA helium-oxygen environment. In: A.A. Bove, A.J. Bachrach, and L.J. Greenbaum, Jr. (eds.), *Underwater and Hyperbaric Physiology IX*, pp. 405-414. Bethesda, MD, Undersea and Hyperbaric Med. Soc.

Mohri, M., and M. Okamoto, 1989. Visual and EKG monitoring for safe deep saturation diving at JAMSTEC. *Marine Technol. Soc. J.* 23:47-49.

Mohri, M., F. Shidara, and Y. Taya, 1990. Dizziness of mixed gas dives in stabilometry and high pressure nervous syndrome (in Japanese). *Jpn. J. Hyperbaric Med.* 25: 153-158.

Mohri, M., 1990. Fatigue and performance of divers during a simulated non-saturated oxygen-helium dive to 180 meters (in Japanese). *Jpn. J. Hyg.* 45:619-626.

Mohri, M., N. Naraki, F. Shidara, H. Takeuchi, and Y. Taya, 1991. ECG monitoring instrumentations for the New Seatopia project. *JAMSTEC Techn. Rep.* 25:67-73.

Mohri, M., T. Taya, F. Shidara, and Y.C. Lin, 1991. Changes in blood enzyme activity and hematology of rabbits with decompression sickness in He-O2 saturation dive. *Jpn. J. Hyperbaric Med.* 26: 219-224.

Mohri, J., R. Torii, K. Nagaya, K. Shiraki, R. Elsner, H. Takeuchi, Y.S. Park, and S.K. Hong, 1995. Diving patterns of ama divers of Hegura Island, Japan. *Undersea Hyperb. Med.* 22:137-143.

Naraki, N., F. Shidara, T. Kataoka, G. Tomizawa, and M. Mohri, 1991. Evaluation of static work load by circulatory responses and EMG power spectrum changes under a 28 ATA helium-oxygen environment. *Proceedings of the 11th Meeting of the UJNR Panel on Diving Physiology and Technology, September 26-27, 1991, Hakone, Shizuoka, Japan*, pp. 212-222. Yukosuka, Japan, JAMSTEC.

Okuda, S., S. Matsuoka, and M. Mohri, 1988. Topographic electroencephalographic studies in a hyperbaric environment — specific reference to high pressure nervous syndrome. *J. UOEH* 3:247-261.

Sagawa, S., J.R. Claybaugh, K. Shiraki, Y.S. Park, M. Mohri, and S.K. Hong, 1990. Characteristics of increased urine flow during a dry saturation dive at 31 ATA. *Undersea Biomed. Res.* 17:13-22.

Shidara, F., N. Naraki, H. Yamaguchi, K. Tomiyasu, and M. Mohri, 1987. Measurements of heart rate, oxygen uptake and ventilatory minute volume in cycling exercise at a simulated seawater depth of 300 meters (in Japanese). *Jpn. J. Hyperbaric Med.* 22:147-152.

Shidara, F., H. Yamaguchi, N. Naraki, and M. Mohri, 1988. Submaximal work on an underwater cycle ergometer. *JAMSTEC Techn. Rep.* 20:73-78.

Shidara, F., Y. Taya, Y. Mizushima, M. Mohri, and Y.C. Lin, 1991. Determination of interspecies T1/2 for the formulation of decompression tables (UDT300). *Proceedings of the 11th Meeting of the UJNR Panel on Diving Physiology and Technology, September 26-27, 1991, Hakone, Shizuoka, Japan*, pp. 48-60. Yukosuka, Japan, JAMSTEC.

Shidara, F., Y. Taya, M. Mohri, and Y.C. Lin, 1995. Study of universal decompression table for saturation dives--Validation experiments on rats, rabbits and dogs (in Japanese). *JAMSTEC Techn. Rep.* 31:61-72.

Shiraki, K., N. Konda, S. Sagawa, Y.C. Lin, and S.K. Hong, 1986. Cardiac output by impedance cardiography during head-out water immersion. *Undersea Biomed. Res.* 13:247-256.

Shiraki, K., S. Sagawa, and S.K. Hong, 1989. Thermal problems associated with diving in cold water. *Marine Technol. Soc. J.* 23:72-81.

Shiraki, K., M. Mohri, and H. Takeuchi, 1991. Heart rate responses to breath-hold divers. *Proceedings of the 11th Meeting of the UJNR Panel on Diving Physiology and Technology, September 26-27, 1991, Hakone, Shizuoka, Japan*, pp. 188-204. Yukosuka, Japan, JAMSTEC.

Shiraki, K., and J.R. Claybaugh, 1995. Effects of diving and hyperbaria on responses to exercise. In: J.O. Holloszy (ed.), *Exercise and Sports Science Review* 23:459-485. Baltimore, MD, Williams and Wilkins.

Tajima, F., S. Sagawa, J. Iwamoto, K. Miki, J.R. Claybaugh, and K. Shiraki, 1988. Renal and endocrine responses in the elderly during head-out water immersion. *Am. J. Physiol.* 254:R977-983.

Tajima, F., S. Sagawa, J. Iwamoto, K. Miki, B.J.

Freund, J.R. Claybaugh, and K. Shiraki, 1990. Cardiovascular, renal, and endocrine responses in male quadriplegics during head-out water immersion. *Am. J. Physiol.* 258:R1424-1430.

Takeuchi, H. and M. Mohri, 1990. Changes of serum transaminase activity in saturation dives (in Japanese). *Jpn. J. Hyperbaric Med.* 25:143-151.

Takeuchi, H., M. Mohri, K. Shiraki, Y.C. Lin, J.R. Claybaugh, and S.H. Hong, 1995. Diurnal renal responses in man to water loading at sea level and 31 atm abs. *Undersea Hyperb. Med.* 22:61-71.

Tanaka, H., S. Sagawa, K. Miki, F. Tajima, J.R. Claybaugh, and K. Shiraki, 1991. Sympathetic nerve activity and urinary responses during continuous negative pressure breathing in humans. *Am. J. Physiol.* 261:R276-282.

Tanaka, H., S. Sagawa, K. Miki, B.J. Freund, J.R. Claybaugh, and K. Shiraki, 1994. Changes in muscle sympathetic activity and renal function during positive- pressure breathing in humans. *Am. J. Physiol.* 266:R1220-1228.

Wada, S., S. Matsuoka, C. Kadoya, A. Yokota, and M. Mohri, 1988. Effects of hyperbaric environment on human brain stem function with specific reference to auditory brain stem responses. *J. UOEH* 3:317-324.

Wada, S., A. Yokoyama, S. Matsuoka, C. Kodoya, and M. Mohri, 1989. Effect of hyperbaric environment on human auditory middle latency response (MLR) and short latency somatosensory evoked potential (SSEP). *J. UOEH* 4:441-447.

Yamaguchi, H., H. Kikuchi, M. Enohara, F. Shidara, N. Naraki, and M. Mohri, 1988. Diver's propulsion power by fin-kicking (second report, in Japanese). *JAMSTEC Techn. Rep.* 19:157-165.

Circulatory Index of Deconditioning Was Unchanged During a 7–Day Nitrox Saturation Dive at 3 ATA

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Abstract

Circulatory deconditioning occurs during heliox saturation dives at 300 m or deeper and is shown by a reduced extracellular fluid volume, orthostatic intolerance, a lowered aerobic capacity, an elevated resting heart rate, a reduced stroke volume, and an increased circulatory index of deconditioning (CID). The CID, according to Bungo and Johnson (1983), is the sum of changes in systolic and diastolic blood pressures and the heart rate during orthostatic stress. We used head-up vertical tilt to produce orthostatic stress on the circulatory system. In previous studies at 300 m and 450 m depths, CID was shown to rise within 24 h after reaching the saturation depth, to fall back subsequently, and to increase again after the dive. Associated with the CID increases were cases of fainting during head-up tilt. We attributed the acute diuresis during the night as the cause of the initial rise in CID and the reduced physical activity during the prolonged confinement as the cause of the late rise in CID. In the 7-day, 20-m nitrox saturation dive conducted at JAMSTEC between February 1 and 16, 1993, the CID was unchanged until postdive. The dive consisted of a 3-day predive period, 7 days at 20 m, 30 h decompression, and a 3-day postdive period. The CID in 4 male subjects was 26.8 ± 2.5 predive, 23.8 ± 4.6 and 27.2 ± 12.8 at 20 m depth, 32.8 ± 1.9 postdive (2nd day), and 26.9 ± 3.1 postdive (3rd day). We observed no fainting occurrences. However, clear daytime diuresis, as well as reduced plasma vasopressin concentration, occurred, which is consistent with previous observations. Input-output analysis showed that the increased urinary output was not related to an increased fluid intake. This means that the total body fluid volume must have decreased, but unlike previous observations in 300 to 450 m heliox environments, hemoconcentration did not occur (Hct unchanged), suggesting that the plasma volume was unchanged despite the reduction of the total body fluid volume. This may explain why our subjects showed no increase in CID or fainting during orthostatic stress. Also, the levels of atrial natriuretic factor and aldosterone were unchanged during dive and postdive compared to the predive levels. We concluded that the increased CID postdive was a result of reduced physical activity.

Introduction

In 1979, we observed a postdive tachycardia and a reduced stroke volume (SV) at rest, and a decreased aerobic capacity in four young, fit male subjects (Ohta et al. 1981). In this 7-day saturation heliox dive at 31 ATA (Seadragon IV), their resting heart rate (HR) averaged 93 ± 4 (SE) postdive compared to 63 ± 2 bt/min predive 34 days earlier. The SV at rest was reduced significantly from 46.4 ± 4.4 predive to 40.2 ± 5.0 ml/bt postdive. The maximal oxygen uptake fell from 3.11 ± 0.18 L/min predive to 2.89 ± 0.16 L/min postdive. This led us to suspect that cardiovascular deconditioning may have occurred during the 34-day period. Since then we have established the existence of an orthostatic intolerance during and following an acute exposure to hyperbaric environments in two dives at 31 ATA (Arita et al. 1987, Lin et al. 1987) and one dive at 45 ATA (Lin et al. 1991). Whether deconditioning occurs at 3 ATA saturation dives has not been established.

We recorded fainting episodes during dives where all subjects uneventfully completed the same test predive (Arita et al. 1987; Lin et al. 1987, 1991). Furthermore, we also quantified cardiovascular changes that indicate deconditioning. The cardiovascular index of deconditioning (CID) of Bungo and Johnson (1983) does not require syncope as the endpoint. CID is the sum of changes, upon tilting, in HR, and systolic and diastolic arterial blood pressures (sABP and dABP). An elevation of CID indicates deconditioning. It was consistently observed that

Table 1. Physical characteristics of subjects.

Subject	Age (yr)	Weight (kg)	Height (cm)	Fat (%)
M.O.	42	61.0	163.0	17.1
H.N.	28	64.0	164.8	18.5
F.I.	33	58.0	169.0	8.9
Y.K.	27	76.5	175.8	17.2
Mean ± S.E	32.5±3.4	64.9±4.1	168.1±2.9	15.4±2.2

CID rose within 24 h of exposure to target saturation pressure (31 ATA or 46 ATA), returned to the predive level in the next few days while remaining at the saturation pressure, then rose again toward the end of decompression and postdive. We concluded that the contraction of plasma volume was responsible for the early rise in CID and that the late rise of CID was a result of prolonged lower level of physical activities. In this study, we aimed to ascertain whether or not the same condition existed during a 7-day, 3-ATA nitrox dive over a 15-day period.

Methods

Diving Profile

The N_2-O_2 saturation dive at 3 ATA was held at JAMSTEC in February 1993. Compression to 20 m was accomplished by initial compression at 10 m/min for 9 min, stopping at 9 m depth for 6 min, then completing compression at 20 m/h. The total compression took 48 min. After 7 days at 3 ATA, decompression was carried out with a NOAA procedure lasting 30 h, including a total of 7.5 h breathing O_2 intermittently (NOAA 1975) and an overnight stop at 4.5 m. The decompression ended with a period of 30 min where the subjects were recompressed to 9 m while breathing 100 percent O_2 before surfacing. The ambient conditions were temperature 26°C, relative humidity 60 percent, P_{O2} 0.4 ATA, and gas density 2.97 times the air at 1 ATA. The entire dive lasted 15 days, including 3 days each for predive and postdive periods.

Subjects

Four divers were selected and trained for saturation diving and experimental procedures. Their ages ranged from 27 to 42, body weights from 58 to 76.5 kg, height from 163 to 175.8 cm, and body fat from 8.9 to 17.2 percent (table 1). They were all physically fit.

Measurements

Cardiovascular Changes During Head-up Tilt and CID

An Omron sphygmomanometer (Model HEM-50, Tateishi-Denki, Kyoto, Japan) with digital display was used for determining arterial blood pressures (ABP) and heart rate (HR). Mean arterial blood pressure (mABP) was calculated as one-third of the pulse pressure plus dABP. Circulatory index of deconditioning (CID) was calculated as follows:

$$CID = \Delta HR - \Delta sABP + \Delta dABP \quad (1)$$

where ΔHR, ΔsABP, and ΔdABP are respectively the differences in HR, sABP, and dABP between tilt and pre-tilt values.

Orthostatic responses were tested in each subject at predive, 24 hours after arriving at 3 ATA, 5 days after arriving at 3 ATA, and twice at postdive.

Urine Output

Urine was collected 4 times daily at 0700, 1200, 1700, and 2200, to determine urine volume and flow, osmolal clearance, creatinine clearance, and free water clearance. Associated with urine collection, we measured the intake of liquid and water in the food that the divers consumed.

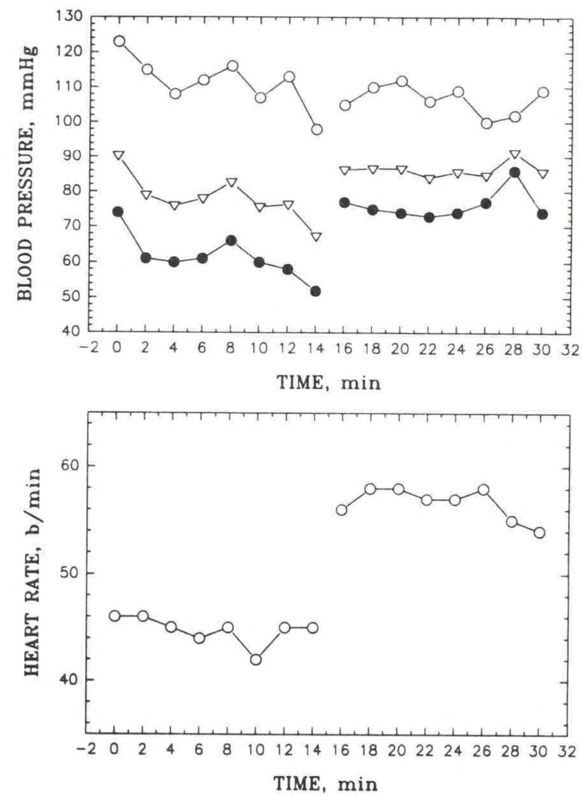

Figure 1. Circulatory responses to head-up tilt. Upper panel: traces from the top are systolic, mean, and diastolic arterial blood pressure; and the lower panel, the heart rate in beats/min. Head-up tilt occurred 15 min into the test.

Table 2. Circulatory responses to head–up tilt.

	Heart Rate		Systolic ABP		Diastolic ABP		Mean ABP	
Period	Supine	Tilt	Supine	Tilt	Supine	Tilt	Supine	Tilt
Predive	55.7±6.0	71.4±8.5*	17.2±6.2	119.1±5.1	74.7±8.5	87.7±6.2*	88.9±7.7	98.1±5.9*
3 ATA-1	51.1±4.3	63.7±5.3*	113.8±3.8	115.1±3.3	69.9±5.5	82.5±4.5*	84.5±4.7	93.3±4.0*
3 ATA-2	51.4±4.1	68.2±7.2*	111.1±2.3	111.4±1.2	69.9±3.7	80.5±2.2*	83.6±2.9	90.8±1.2*
Postdive-1	60.5±6.7	78.8±8.6*	114.5±4.8	110.0±1.3	65.7±2.9	75.7±1.8*	81.9±3.4	87.2±1.3
Postdive-2	60.7±5.9	77.7±7.9*	116.1±4.4	116.4±2.2	72.1±6.5	82.3±2.2*	86.6±5.6	93.6±2.1

Mean ± S.E. for 4 subjects
*,p<0.05 based on paired t-tests between supine and tilt values.

Hormonal Responses

Six venous blood samples were obtained during predive (2), 3 ATA (2), and postdive (2) at 0700. Blood samples were treated immediately to determine plasma epinephrine, norepinephrine, arginine vasopressin, atrial natriuretic factor, hematocrit, and hemoglobin and electrolyte concentrations.

Changes in Plasma Volume

We indirectly estimated the relative changes in plasma volume by using Van Beaumont's method, which assumes a constant red blood cell volume (Van Beaumont 1972).

Statistical Analysis of Data

Data were summarized as mean ± S.E. and subjected to one-way ANOVA for repeat measures followed by Newman-Keuls tests for comparison between periods. Comparisons between supine and tilt values were based on paired t-tests. We rejected the null hypothesis at $p < 0.05$.

Results

Circulatory Responses to Head–Up Tilt

Figure 1 illustrates typical responses of arterial blood pressure and heart rate during a head-up tilt. Tilt occurs 15 min into the dive. Typically, HR and dABP rise with little change in sABP. Mean ABP may also occur as a result of diastolic hypertension. In some cases, sABP also decreased. HR and ABP values were averaged to obtain supine and tilt means (table 2), from which we calculated the CID according to Equation (1). Results are presented in table 3. Head-up tilt causes significant tachycardia, diastolic hypertension, and an increase in mABP during predive and 3 ATA exposure (table 2). No changes in CID were observed during 3 ATA exposure. CID increased

Table 3. Changes in heart rate and blood pressure based on a head–up tilt and circulatory index of deconditioning (CID).

Period	HR	sABP	dABP	CID
Predive	15.8±2.7	1.9±1.7	13.0±2.6	26.8±1.3
3 ATA-1	12.5±1.4	1.3±2.7	12.6±1.6	23.8±2.3
3 ATA-2	16.7±4.4	0.4±2.1	10.7±2.2	27.2±6.4
Postdive-1	18.2±2.6	-4.0±4.8	10.6±4.4	32.8±0.9*
Postdive-2	17.0±2.7	0.3±2.5	10.2±4.4	26.9±3.1

Mean±S.E. for 4 subjects
*p<0.05 based on one-way ANOVA for repeat measures, for comparison between periods.

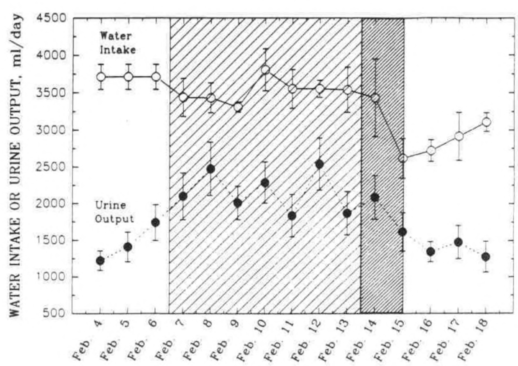

Figure 2. Fluid intake and output over a 15-day period. The period indicated as saturation included 1 and 1/2 days of decompression.

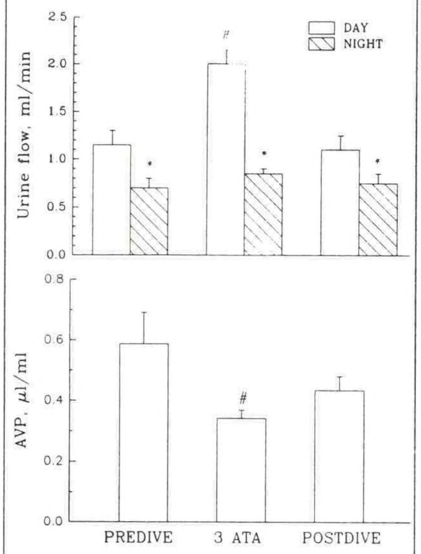

Figure 3. Urine flow and plasma arginine vasopressin (AVP) in 4 male subjects during predive, exposure to 3 ATA, and postdive. Daytime urine flow exceeds the nighttime urine flow (, $p < 0.05$). Daytime urine flow was increased during exposure to 3 ATA environment, while plasma AVP was reduced at 3 ATA (#, $p < 0.05$).*

significantly on the second day of surfacing but returned to the predive level the next day (table 3).

Water Intake and Urine Output

Figure 2 summarizes fluid balance throughout the dive. Hyperbaric diuresis occurred during exposure to 3 ATA, and it was not a result of increased water intake. Total water intake remained unchanged during pressure exposure at the predive level. Urine output increased only during the daytime, i.e., there was no nocturia (fig. 3).

Hormonal Responses

Associated with the diuresis plasma, the AVP level was suppressed (fig. 3). Postdive AVP levels were indistinguishable from the predive value. Table 4 shows that plasma epinephrine was increased during exposure to 3 ATA and during postdive, norepinephrine was unchanged, and plasma aldosterone and atrial natriuretic factor (ANF) levels were also unchanged (table 4).

Table 4. Changes in plasma hormonal level during 3 ATA exposure and post dive.

Hormone	Predive	3 ATA	Postdive
Aldosterone, ng/dl	12.94±2.16	12.87±4.06	12.44±4.51
ANP, pg/ml	42.09±22.03	41.51±11.82	32.88±7.38
Epinephrine, pg/ml	17±2	30±2.5*	23±3*
Norepinephrine, pg/ml	275±15	233±51	273±19

Mean ± S.E. for 4 subjects
*$p<0.05$ compared to predive level.
ANP, atrial natriuretic factor

Hematocrit and Plasma Volume Change

Hematocrit values in percent averaged 44.46 ± 2.39, 45.88 ± 4.02, and 44.71 ± 3.15 for predive, 3-ATA exposure, and postdive, respectively. These values were not statistically different from each other ($F = 0.21$, $p = 0.81$). Therefore, the calculated changes in plasma volume were also indifferent between periods.

Discussion

There are reasons to suspect that cardiovascular deconditioning may occur during exposure to a hyperbaric environment. Prominent diuresis takes place upon exposure to a hyperbaric environment. The "hyperbaric diuresis" resembles other conditions where central venous pressure (CVP) is increased, such as acute exposure to high altitude, in weightlessness, head-out water immersion, bed rest, and hyperbaric environment. These conditions cause an elevation of CVP due to chestward redistribution of blood volume either by hyperventilation, loss of gravitational force, high inspiratory resistance, negative pressure breathing, or supine posture. Although exact mechanisms that cause hyperbaric diuresis have not been worked out, it is known that the central hypervolemia and hypertension suppress AVP release resulting in diuresis and a lowered plasma volume. The combination of a reduced plasma volume and orthostatic stress (head-up tilt) produces greater circulatory perturbations than either one (independently) to the extent that syncope may occur.

In this study, diuresis also occurred but to a lesser degree when compared to previous dives at much higher pressures (Hong and Claybaugh 1989, Shiraki et al. 1987). Since the diuresis was unrelated to increased intake, a negative fluid balance must have existed. However, hemoconcentration did not occur. Therefore, we concluded that the plasma volume also was not reduced. At present, we have no evidence to ascertain whether this was a result of fluid redistribution between compartments. The absence of nocturia preserves plasma volume and strengthens circulatory responses to orthostatic stress. Significant nocturia occurs during the initial phase at ambient pressure greater than 18.6 ATA resulting in acute hypovolemia. Plasma volume returns to the predive level in a few days while still exposed to the saturation pressure (Shiraki et al. 1987). Orthostatic intolerance, indicated by an increased CID or fainting during head-up tilt, appeared initially with plasma volume depletion and disappeared with the normalization of plasma volume (Arita et al. 1987; Lin, Shiraki, and Mohri 1987; Lin et al. 1991).

Another reason for suspecting the existence of deconditioning is that subjects live in a state of reduced physical activity over long periods. Typically, for an experiment at 31 ATA for 1 week, the total confinement lasts 4-5 weeks. Furthermore, physical activities are at a minimum during the protracted decompression period. This notion was supported by the increase of CID during the late decompression period and postdive. However, this may not be a factor in the present study since the total confinement period for this study was 15 days. Nevertheless, CID was elevated during postdive, although short lived (table 3).

Taken together, the data from the present study combined with other studies provides evidence for 1) a decreased VO2 max, 2) an elevated resting HR, 3) reduced plasma volume and stroke volume initially, 4) lowered sympathetic activity (lowered plasma concentration of norepinephrine), 5) orthostatic intolerance (fainting occurred during the test in several dives), and 6) an increased CID during or following exposure to a hyperbaric environment. Any of these factors, singly or combined, can reduce circulatory responses to orthostatic stress. Causes of a reduced maximal oxygen uptake is complex and may be caused by either circulatory or respiratory factors, or both, and non-specific factors such as prolonged inactivity.

In summary, the results of the present study showed that, in contrast to previous findings at 31 and 46 ATA, CID was not elevated during exposure to a 3-ATA nitrox environment. However, CID rose the second day after return to sea level condition and fell to predive level on the third day. Hypervolemia and prolonged reduced physical activity, the two mechanisms involved in the elevation of CID in previous dives, are minimal in the present study. Therefore, minimal changes in circulatory condition occurred. The present finding strengthens our previous suggestion that a prudent fluid management and a physical conditioning program should be enforced in a prolonged hyperbaric and chamber confinement.

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Literature Cited

Arita, H., Y.C. Lin, M. Sudoh, I. Kuwahira, Y. Ohta, H. Saiki, S. Tamaya, and H. Nakayama, 1987. Seadragon VI: a 7-day saturation dive at 31 ATA. V. Cardiovascular responses to a 90° body tilt. *Undersea Biomed. Res.* 14:425-436.

Bungo, M.W., and P.C. Johnson Jr., 1983. Cardiovascular examinations and observations of deconditioning during the space shuttle orbital flight test program. *Aviat. Space Environ. Med.* 54:1001-1004.

Hong, S.K., and J.R. Claybaugh, 1989. Hormonal and renal responses to hyperbaria. In: J.R. Claybaugh and C.E. Wade (eds.), *Hormonal Regulation of Fluid and Electrolytes — Environmental Effects*, pp. 117-146. New York, NY, Plenum Press.

Lin, Y.C., 1987. Cardiovascular deconditioning in hyperbaric environments. In: K. Shiraki and M.K. Yousef (eds.), *Man in Stressful Environments, Diving, Hyper- and Hypobaric Physiology*, pp. 71-92. Springfield, IL, C.C. Thomas, Publisher.

Lin, Y.C., K. Shiraki, and M. Mohri, 1987. New Seatopia 1985: Circulatory responses. *Proceedings of the Ninth Meeting of the UJNR Panel on Diving Physiology and Technology, November 4-6, 1987*, Yokosuka, Kanagama, Japan, pp. 245-261. Yokosuka, Japan, JAMSTEC.

Lin, Y.C., J.R. Claybaugh, J. Holthaus, H.G. Schafstall, and P.B. Bennett, 1991. Orthostatic intolerance during GUSI-18 dive, a simulated trimix saturation dive at 46 ATA. *Undersea Biomed. Res.* 18(Suppl):97-98.

Matsui, N., J.R. Claybaugh, Y. Tamura, H. Seo, Y. Murata, K. Shiraki, H. Nakayama, Y.C. Lin, and S.K. Hong, 1987. Seadragon VI: a 7-day saturation dive at 31 ATA. VI. Hyperbaria enhances renin but eliminates ADH responses to head-up tilt. *Undersea Biomed. Res.* 14:437-447.

NOAA, 1975. *NOAA Diving Manual*, Section 12, Saturation Diving, pp. 12-8 - 12-13. Washington D.C., Government Printing Office.

Ohta, Y., H. Arita, H. Nakayama, S. Tamaya, C.E.G. Lundgren, Y.C. Lin, R.M. Smith, R. Morin, L.E. Farhi, and M. Matsuda, 1981. Cardiopulmonary functions and maximal aerobic power during a 14-day saturation dive at 31 ATA (Seadragon IV). In: A.J. Bachrach and M.M. Matzen (eds.).

Underwater Physiology VII, pp. 209-221. Bethesda, MD, Undersea Medical Society.

Shiraki, K., S.K. Hong, Y.S. Park, S. Sagawa, N. Konda, J.R. Claybaugh, H. Takeuchi, N. Matsui, and H. Nakayama, 1987. Seadragon VI: A 7-day dry saturation dive at 31 ATA. II. Characteristics of diuresis and nocturia. *Undersea Biomed. Res.* 14:387-400.

Van Beaumont, W., 1972. Evaluation of hemoconcentration from hematocrit measurements. *J. Appl. Physiol.* 32:712-713.

A Profile of Japanese Sport Divers

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Abstract

To draw a profile of Japanese sport divers, we conducted personal interviews at three diving spots situated on the Izu Peninsula during the summer vacation periods of 1991 and 1992. The results of 235 interviews are presented. The male:female ratio was 2.8:1; the average of age was 28.4 years. The average diving experience was 230.1 tanks (27.3 tanks per year, 2 tanks per day). In 40 (17%) cases, nitrogen narcosis (NN) was the most frequent dysbaric disorder, followed by barotrauma at paranasal sinus (SB) and ear (EB), dental barotrauma (DB), and decompression sickness (DCS). NN has manifested at the average depth of 35.0 meter, and almost half of the divers with more than 5 years of experience have already gone through this kind of narcosis. Occurrence of EB (12%) was attributed to nontraditional ear-clearing methods, the so-called 'natural' (spontaneous) equalization. Positive answers to questions concerning SB (12%) have pointed to some predisposing factors, such as cold, sleeplessness, and hangover. DCS, reported by 3 percent, exclusively affected divers with 5 or more years of experience.

Introduction

Recently, sport diving has been in fashion, boosting an increasing number of young people to the diving schools throughout Japan. On the other hand, the more unaware divers are of the real risks involved by working in the underwater environment, the larger the incidence of dysbaric accidents. According to the questionnaire conducted by Kakibana et al. (1984) of 135 divers from Okinawa Prefecture, 64.4 percent of them had never heard of decompression tables and, on the onset of symptoms, about half (47.7%) had been recompressed underwater and 22.9 percent did not seek medical assistance. In Kyushu, a questionnaire survey conducted by Hayashi et al. (1981) revealed that 33.5 percent of 391 local divers had past incidences of decompression sickness (DCS). To gather subsidiary information on this issue and draw a profile of the Japanese sport divers not previously reported, we developed a questionnaire focusing mainly on dysbaric disorders.

Material and Methods

We have conducted personal interviews at three of the most popular diving spots situated on the Izu Peninsula (Ohsezaki, Izu-Kayo-Koen, and Shobuzawa), southwest of Tokyo (fig. 1), during the August summer vacation periods of 1991 and 1992. The interviewees were all sport divers. Before answering, the divers were assured that all the information provided would be strictly confidential.

Figure 1. Localization of the three diving spots within Izu Peninsula.

QUESTIONNAIRE

Name ________________________ Age Sex: M / F

Diving spot

1. DIVING EXPERIENCE
   Total years of experience:
   Total tanks used until now:
   Number of tanks used per year:
   Maximum diving depth: _____ meters
2. TODAY'S SCHEDULE
   Number of tanks to be used (or already used):
   Time of each dive: ____minutes Diving depth (s): ____meters
   Rest time: _________ minutes
3. DIVER'S QUALIFICATION
   Do you possess the C-card? Yes / No
   If yes, which diving school did you get it from?
   PADI/NAUI/JP/JUDF/OTHER:
4. [In cases of past instance (s) of DYSBARIC DISORDER]

4.1. How do you clear the ears?
- ( ) swallowing saliva
- ( ) blowing against the clamped nose
- ( ) clamping the nose and swallowing
- ( ) other:

4.2. EAR BAROTRAUMA (EB)

What part of the ear was affected?
- ( ) Eardrum
- ( ) Middle ear
- ( ) Internal ear

Did you seek any medical assistance? Yes / No

If yes, what was the physician's diagnosis?
- ( ) Internal ear disorder
- ( ) Otitis media
- ( ) Eardrum perforation
- ( ) Other:

When the EB occurred, the ear-clearing during descent had been: efficient / inefficient. If inefficient, the pressure equilibration had been difficult
- ( ) on the right ear
- ( ) on the left ear
- ( ) both

4.3. SINUS BAROTRAUMA (SB)

What sinus was affected?
- ( ) Frontal sinus
- ( ) Maxillary sinus
- ( ) Other

The local pain was: intense / mild

How was your physical condition before diving?
- ( ) You had a cold
- ( ) You hadn't slept well the previous day
- ( ) You had a hangover
- ( ) Other:

4.4. DENTAL BAROTRAUMA (DB)

Did you have tooth filling (s) on that occasion?
Yes / No

4.5. DECOMPRESSION SICKNESS (DCS)

The symptoms of DCS:
- ( ) broke out in a rash
- ( ) consisted on myalgia and/or arthralgia (were related to the respiratory/circulatory systems
- ( ) accused spinal cord injury

4.6. NITROGEN NARCOSIS (NN)

Depth when it occurred: ____ meters

4.7. OTHER DISORDERS:

Table 1. Diving experience based on individual diving records and data concerning usage of tanks.

Diving spot	A	B	C	Over. ave.
Total no. of tanks	140.0	207.2	397.4	230.1
No. of tanks/year	19.6	27.6	41.0	27.3
No. of tanks 'today'	2.2	2.0	2.0	2.0
Max. depth 'today'	11.8	17.1	17.3	15.7
Dive time/dive (min)	23.9	24.8	22.8	23.1
Max. depth (m)	21.8	27.1	27.3	25.7
Rest time 'today'	113.5	102.1	119.4	110.8

A = Ohsezaki; B = Izu-Kayo-Koen; C = Shobuzawa; Over. ave. = Overall average

The sequence of questions (below) was not previously made known to the interviewee.

Results

We have interviewed 360 divers, but the interviews taken from beginners (on their first diving experience, without the Certificate-card), the interviews taken from divers with bizarre records, and the interviews not adequately filled in were excluded from the statistical analysis, leaving a total of 235 interviews: 85 were divers from Ohsezaki, 100 were from Izu-Kayo-Koen, and 50 were from Shobuzawa. The male:female ratio was 173:62 (2.8:1), and the respective average ages were 30.2 and 26.6 years (overall average: 28.4 years. The oldest diver was a 57-year-old (male), and the oldest female diver was 44; the youngest male diver was 15, and the youngest female diver was 18. The most experienced diver was a male with 27 years of diving, and the most experienced female diver had a record of 11 years of diving. The youngest to become a diver was a female who began diving when she was 10, and the youngest male began when he was 11. The oldest to begin diving were a 55-year-old male and a 43-year-old female.

Table 1 shows diving records along with data concerning the usage of tanks. The average experience was 230.1 tanks (27.3 tanks per year, 2 tanks per day); 6 divers had records ranging from 1.0 to 1.8 tanks, 4 recorded using 2.0 tanks, 2 used 3.0, 1 used 4.0, and the highest record was for 4.8 tanks. As to the maximum depth experienced, answers ranged from 5 to 75 m, which shows an average of 25.7 m. Of the total, 80 divers (34%) described past instances of barotrauma and/or DCS; the more experienced the divers, the more frequent were such instances. In 40 (17%) cases, nitrogen narcosis (NN) was the most frequent dysbaric disorder, followed by sinus barotrauma (SB) with 12.3 percent, ear barotrauma (EB) with 12.0 percent, dental barotrauma (DB), and DCS (table 2). NN manifested at depths ranging from 18 to 75 m, the average being 35.0 m. According to table 3, almost half (47.5%) of the divers with more than 5 years of experience have already had some kind of narcosis.

Table 2. Frequency of dysbaric disorders.

Dysbaric Disorder	No.	Percent
Nitrogen narcosis	40	17.0
Sinus barotrauma	29	12.3
Ear barotrauma	28	12.0
Dental barotrauma	17	7.2
DCS	7	3.0

Table 3. Percentage of divers (%) with past history of dysbaric disorder.

DE (years)	NN	SB	EB	DS	DSC
< 1	0	5.8	7.7	3.8	0
1≤x<3	8.5	8.5	9.8	7.3	0
3≤x<5	11.9	16.7	11.9	11.7	2.4
≥ 5	47.5	20.3	15.3	6.8	10.2

DE = diving experience

Table 4. Percentage of divers (%) with past history of dysbaric disorder, within age groups.

Age (years)	NN	SB	EB	DS	DSC
< 20	9.1	0	9.1	9.1	0
20≤x<25	10.1	11.3	13.8	5.0	1.3
25≤x<30	9.1	10.4	7.8	10.5	2.6
30≤x<35	36.1	19.4	8.3	2.8	2.8
35≤x<40	38.9	11.1	16.7	0	11.1
≥ 40	30.8	23.1	15.4	23.1	7.7

Table 5. Ear-clearing method and occurrence of EB (plural answers were considered.

Method	No.	EB cases	EB/No. (%)
Valsalva m.	159 (60.2%)	18	11.3
Swallowing	67 (25.4%)	8	11.9
Toynbee m.	23 (8.7%)	3	13.0
Other	15 (5.7%)	3	20.0

Table 6. Sites of SB.

Sinus	No.	Percent
Frontal s.	15	50.0
Maxillary s.	6	20.0
Other	7	23.3
Unknown	2	6.7
Total	30	100.0

Plural answers were considered.

This percentage decreases proportionally with a diver's experience. Accordingly, divers more than 35 years old accounted for 24 (60%) of the case, which means that about 35 percent of this group reported NN, a percentage much higher than that of the group below 35, which counted 16 cases of NN (about 9% of this group) (table 4). Table 5 shows the connection between the ear-clearing method used and the record of EB (26 subjects). Valsalva (60.2%) and swallowing (25.4%) maneuvers, although utilized by the majority, are not associated with high occurrences of EB; but the group of 'other' methods like no specific maneuver during descent (12 divers), head rotation (1), jaw contraction (1), and air aspiration via nasal followed by apnea (1), presented EB in 20.0 percent. The eardrum was the most commonly affected (48.3%), followed by the middle ear (27.6%), inner ear (6.9%), and other sites (17.2%).

All subjects reported consulting a physician on the onset of symptoms; eardrum perforation was diagnosed in 8 cases (30.8%), otitis media in 7 (26.9%), other affections in 6 (23.1%), and 5 (19.2%) were unaware of the diagnosis. EB was registered in 11.1 percent of the divers, and it seems not to have differed with age and diving experience. As shown in table 6, 30 (12.8%) divers referred to past instances of SB. Frontal sinus was affected in half of the cases (15 divers), maxillary sinus in 20.0 percent (6 divers), other sinus in 23.3 percent (7 divers), and 2 could not answer (table 6). Predisposing factors to the occurrence of SB (35 cases), such as cold, sleeplessness, hangover, and others, were documented by 31 divers or 88.6 percent of the cases (**table 7**).

According to age distribution, divers over 35 incurred proportionally more instances of SB; accordingly, divers with more than 3 years of experience accounted for 65.5 percent of the cases. Of the total, 16 (6.8%) described past instances of DB, 12 of whom had tooth fillings (**table 8**). The group over 40 was the most affected (23.1% of the group), and there was no significant difference in diving experience. DCS was reported by 7 interviewees, all with 5 or more years of diving experience, and proportionally more were in the over-40-years-of-age group (tables 3,4).

Discussion

Bove (1989) states that ear squeeze is the most common medical problem in diving; he adds that aural barotrauma occurs for all divers and can only be avoided by careful ear clearing during descent and maintaining open-air passages in the ears and throat. Shibayama et al. (1991) have studied the functioning of the auditory tube during scuba diving and concluded that diving posture affected the opening and closing of the auditory tube.

A questionnaire survey conducted by Lundgren (1965) was answered by 550 Swedish divers. In a few cases, the

Table 7. Physical condition and outbreak of SB

	No.	Percent
Cold	11	31.4
Sleeplessness	8	22.9
Hangover	3	8.6
Other	9	25.7
No answer	4	11.4
Total	35	100.0

Plural answers were considered.

Table 8. Tooth filling treatment (TFT) and outbreak of DB

TFT	No.	DB	DB/No. (%)
(+)	37	12	32.4
(-)	198	4	2.0
Total	235	16	6.8

maneuver of blowing out air with the nose clamped and thus forcing air into the ears produced vertigo combined with horizontal nystagmus, nausea, and loss of balance immediately upon application of pressure.

In another survey, Lundgren and Malm (1966) observed that using the Valsalva maneuver to clear the ears was used more frequently in the vertigo group than in the non-vertigo group. This observation indicates greater difficulties in pressure equalization using the Valsalva maneuver than in swallowing and yawning. On the other hand, frequent dry swallowing, particularly in the head-down position, seems to introduce considerable amounts of gas in the gastrointestinal tract of some individuals; thus, it appears prudent to recommend ear clearing methods other than swallowing (Brattstrom et al. 1975).

Regarding outbreaks of EB, our survey observed no association with traditional equalization techniques, but with the so-called 'natural' (spontaneous) equalization (no maneuver at all), used by 12 divers, one of the reported unilateral hearing loss. Although generally accepted that conditions like the above, or a perforated eardrum, should make a subject unfit to dive, it seems that Japanese divers overlook them or are unaware of the risks involved. Also, at least 15 percent of the divers were normally diving in less than ideal physical condition. A few divers described pain routinely, in the frontal area, and two described regular epistaxis. NN is apparent by changes in the mood and behavior of a diver, particularly at depths over 30 m.

In our survey, 40 divers (17.0%) have experienced that sensation. The frequency is unexpectedly high, partially due to misjudgment and even because a few veterans dive at greater depths just to feel the sensation that NN causes. Marked individual variation had been observed: the less experienced the diver, the lower the depth at which NN manifested. Before the boom in the number of leisure divers in the early 1980's in Japan, the C-card holders numbered only 10,000 (1981). In 1987, this number rose to 300,000; and it is estimated to rise to 1.3 million by 1993. Accordingly, the average age has continuously decreased, which is also shown in our survey: 29.8 years in 1991 and 27.1 years in 1992. At the same time, older people have begun diving recently; for example, we found that the first experience of 4 males and 2 females occurred in their forties and of one male at the age of 55. Another interesting observation of our survey refers to a gap between the records of the veterans and the so-called new generation of divers.

Along with the increased number of leisure divers, there were also increased recorded diving accidents. In 1985, 16 sport diver deaths were reported. While the increase in the number of divers was 1.3 times in 2 years, the record of fatal accidents had doubled during the same period. In 1987, 27 maritime accidents were related to diving and, of these, 16 were fatal or missing cases. In 1989, there were a total of 55 diving accidents, 30 of which were missing or fatal cases; 64 were victimized in 1990, a year when 27 were reported dead or missing (JCSA 1990). In cases of fatal accidents, the real cause and the circumstances involved have usually been difficult to determine, especially in solo dives.

Solo dives are not recommended, but in a survey conducted by us (Mano and Shibayama 1987) from 1975 to 1987, of a total of 113 non-missing cases, 26 (23.0%) were found to have been diving solo and 36 (31.9%), because of dispersion during the dive, had finished the dive solo. Curiously, according to the same survey, the main cause of fatal accidents was drowning; one-third of the victims were on their first dive, and the accident occurred in water deeper than 5 m in almost half of the cases. Thus, in 1989, with the goal of giving immediate aid to this kind of victim, the Civil Alert Network (CAN) was established in Japan. In 1992, the Divers Alert Network - Japan (DAN-JAPAN) was inaugurated, replacing CAN and integrating this country into the international DAN organization for rescue, transport, and medical care of diving accidents victims.

Literature Cited

Bove, A.A., 1989. Health and fitness of sport divers. *MTS J.* 23(4):4-7.

Brattstrom, B., B. Lindvall, C.E.C. Lundgren, and H. Ornhagen, 1975. Influence of body posture and ear clearing on body buoyancy during diving. *Undersea Biomedical Res.* 2(3):161-166.

Hayashi, H., M. Kawashima, K. Hayashi, Y. Ichiba, and H. Onishi, 1981. Medical survey on divers from

Kyushu District: a questionnaire. *Japanese J. of Hyperbaric Med.* 16(1):1-3 (in Japanese).

JCSA (Japanese Coast Safety Agency), 1990. Leisure diving. *Annual Report.* Underwater Research Center Press, Tokyo (in Japanese).

Kakibana, O., R. Matsumura, K. Nakasone, K. Hanashito, S. Yusa, T. Okuda, Y. Watanabe, S. Nakama, and S. Norimatsu, 1984. Questionnaire survey on fishing divers from Okinawa Prefecture. *Japanese J. of Hyperbaric Med.* 19(1):42-44 (in Japanese).

Lundgren, C.E.C., 1965. Alternobaric vertigo - a diving hazard. *British Medical J.* 2:511-513.

Lundgren, C.E.C., and L.M. Malm, 1966. Alternobaric vertigo among pilots. *Aerospace Med.* 32(2):179-180.

Mano, Y., M. Shibayama, (eds.), 1987. Prevention of diving accidents. *Diver's handbook.* Tokyo, JUDF Press, pp. 13-16 (in Japanese).

Shibayama, M., T. Nakayama, N. Yamami, H. Okubo, H. Furuhashi, and Y. Mano, 1991. The auditory tube function and scuba-diving. *Japanese J. of Hyperbaric Med.* 32(2): 57-63 (in Japanese).

Changes in Electromyogram Power Spectrum for Static Exercise During a Saturation Dive at 31 ATA (New Seatopia–91)

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Abstract

The purpose of the present study is to evaluate the effects of compression and decompression on muscle fatigue during static work under 31 ATA helium-oxygen and after decompression to 1 ATA air. Heart rate (HR) and electromyogram (EMG) power spectrum changes were studied during 7 minutes of static work (half-rising posture: knee joint 120° and erect trunk) in four healthy male subjects. During the static work, the EMG of the rectus femoris was recorded by two surface electrodes, and changes in the EMG power spectrum were presented by the ratio of EMG power in a high-frequency band to that in a low-frequency band (H/L ratio) after Fourier transform analysis.

The HR decreased at 31 ATA and increased remarkably after the decompression to 1 ATA. At 1 ATA air environments, HR at post-decompression was lower than that of pre-compression. The lowering phenomena of EMG presented by H/L ratio were observed similarly at all environments. But the changes of the high and low frequency components were different at post-decompression when compared to those of pre-compression and 31 ATA.

As a parameter of static workload, HR might underestimate the workload at the hyperbaric environment by hyperbaric bradycardia and overestimate it after decompression by "decompression tachycardia." The EMG lowering phenomenon might not be caused by the same mechanism after decompression compared to pre-dive and hyperbaric environments. Extreme care must be taken to evaluate the static workload not only at hyperbaric helium-oxygen environments but after decompression from a deep saturation dive.

Introduction

The purpose of the present study is to evaluate the effects of compression and decompression on muscle fatigue during static work under hyperbaric helium-oxygen environments and after long hyperoxic decompression. The most useful physiological workload parameter for the dynamic work is heart rate, but the heart rate decreases under a helium hyperbaric atmosphere. This phenomenon is known as "hyperbaric bradycardia" (Moore et al. 1976, Conn et al. 1981, Hong et al. 1973). The significant changes in oxygen consumption and ventilatory volume are not found between atmospheric air and hyperbaric helium environments (Overfield et al. 1963, Lambertsen et al. 1977, Salzano et al. 1981). For the static work, we chose not to use the same parameters as the respiratory and circulatory parameters often used to assess dynamic work (Bezucha et al. 1982). We evaluated the static workload under a hyperbaric helium-oxygen environment with two parameters: heart rate (HR) and electromyogram (EMG). Studies of static work in a hyperbaric helium-oxygen environment have not been reported to our knowledge.

Methods

Profile of dive

A simulated saturation dive to an equivalent depth of 300 m with excursion dives to 270 m, code-named New Seatopia-91, were conducted in a diving chamber of the Japan Marine Science and Technology Center (JAMSTEC). The dive profile consisted of 5 consecutive periods: 3 days of pre-compression control observations at 1 ATA air, a half-day of compression with helium from 1 ATA to 31 ATA at rate of 2.5 ATA per hour (one-hour compression stop at 16 ATA and at 26 ATA), 6 days of pressure hold at 31 ATA with excursions to 28 ATA, 11 days of decompression to 1 ATA, and 3 days of post-decompression at 1 ATA in air (fig. 1). Every 2 days during pressure hold 31 ATA, the wet chamber was decompressed with the divers to 28 ATA for 8 or 9 hours

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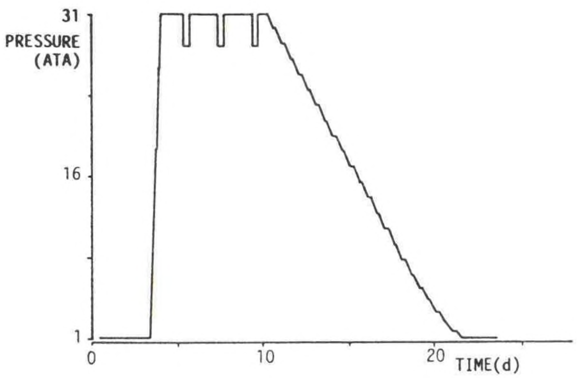

Figure 1. Dive profile of 31 ATA simulated saturation dive with excursion dive to 28 ATA, code-named New Seatopia-91 (November 1991).

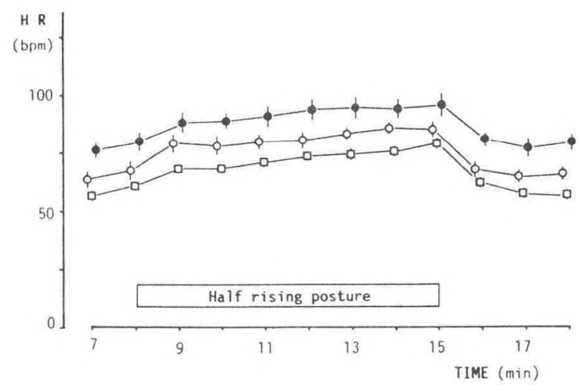

Figure 2. Heart rate changes during static exercise. Vertical lines indicate standard error of the mean values; open circle, 1 ATA air pre-compression (8 data); open square, 31 ATA helium (12 data); closed circle, 1 ATA air post-decompression (8 data).

as a simulated excursion dive. The partial pressure of O_2 at 31 ATA was maintained at 0.40 bar and 0.5 bar during the decompression.

Experimental procedures

The protocol of static work was brief and consisted of 7 minutes of sitting rest, 1 minute of standing, 7 minutes of static work (half-rising posture, with the knee joint at an angle of 120° and an erect trunk), and 3 minutes sitting at rest in recovery, totaling 18 minutes. Heart rate was obtained every minute throughout the observations.

The EMG of the rectus femoris was recorded directly on the digital recorder (SONY: DR-F1, with a 1 MB floppy disk) for 15 seconds of a 1-minute interval during the half-rising posture work. Two surface electrodes were placed lengthwise parallel to the muscle fibers. Each 15 seconds of EMG recording was divided into 60 sample records of 256 msec that were digitized at a sampling rate of 2 kHz. These data underwent power spectral analysis using a fast Fourier transform (Lindstrom et al. 1977, Boxtel et al. 1983). Power spectra were computed in the frequency range 0-1000 Hz, with a resolution bandwidth of 3.906 Hz so that each spectrum contained 256 estimates. The 60 spectra were averaged. As an indicator of spectral shape, we calculated the ratio between the energy in the high (130-238 Hz) and low (20-40 Hz) frequency range to generate H/L ratio (Gross et al. 1979, Bigland-Ritchie et al. 1981, Harry et al. 1982, Lenoir et al. 1990, Naraki et al. 1991). The H/L ratios were also computed for the first 15 seconds of the half-rising posture and maintained for 5 to 20 seconds. Also, the H/L ratio index was obtained to present the relative changes from the start of static exercise: the H/L ratio index at the start of exercise was always 1.00.

Subjects

The four subjects were 26- or 27-year olds, well-trained male divers in excellent physical condition. One week before the study, the subjects began training several times a day for the 7 minutes of half-rising posture. The static work tests were carried out twice at pre-compression, three times at 31 ATA, and twice at post-decompression for each subject.

Results and Discussion

Heart rate changes:HR changes

The HR decreased at 31 ATA after compression and increased 1 ATA after decompression (fig. 2). At the same 1 ATA air, HR at post-decompression exceeded that of pre-compression. The atmosphere in the pressure chamber was slightly hyperoxic, with 0.40 bar O_2. We speculate that the decrease in HR at 31 ATA was caused not only by the hyperbaric environment with high pressure and high density of respiratory gas (Salzano et al. 1970) but also by the hyperoxic breathing gases (Fagraeus and Linnarsson 1973, Shida and Lin 1981). Changes in resting HR for compression and decompression phases showed a similar tendency that has been reported (Ohta et al. 1981, Lin et al. 1987).

Hyperbaric bradycardia levels returned to the pre-compression level when divers were maintained at a given maximal hyperbaric pressure (Gosovic and Radovic 1981). The hyperbaric influence on circulatory function is changed by the HR level (Doubt and Evans 1982). Circulatory indexes used to assess the static workload must be considered on the basis of the hold time period a diver is exposed to hyperbaric conditions, as well as the diver's workload and work time.

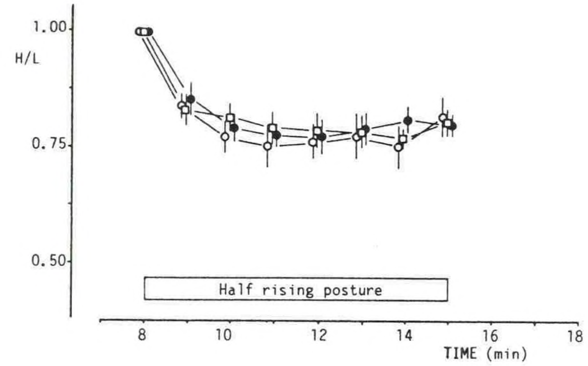

Figure 3. Mean values of the H/L ratio index of the EMG power spectrum during static exercise at 1 ATA pre-compression and post decompression and 31 ATA helium. L represents low frequency component (20 - 40 Hz), and H represents high frequency component (130 - 238 Hz).

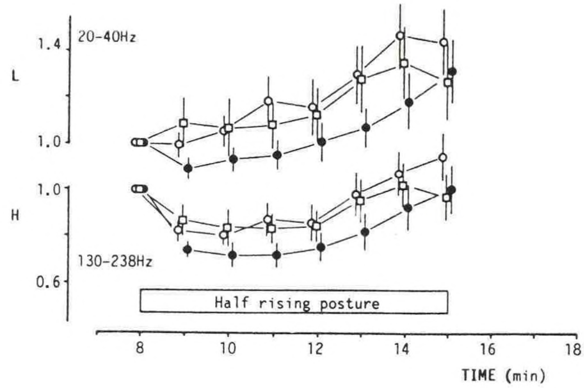

Figure 4. Mean values of each of the high and low frequency components of the EMG power spectra during static exercise.

Electromyogram:EMG changes

The peaks in the EMG spectrum increased and shifted to a lower frequency with work time. We could not find any significant difference between environments on H/L ratio. Then the H/L ratio indexes were calculated to present the relative change of H/L ratio. The H/L ratio index changes in the fatiguing runs showed an exponential decline, and the decrease of the H/L ratio index at 31 ATA was very similar to that of 1 ATA pre-compression and post-decompression (fig. 3). But the changes of high and low frequency components of EMG at post-decompression were different from those of pre-compression and 31 ATA. The reduction of the H/L ratio index by muscle fatigue at pre-compression and 31 ATA was caused by a decrease in the high frequency component and a slight increase in the constant low frequency component. At post-decompression, the H/L ratio index reduction was attributed to the very steep decrease of high frequency component, instead of the slight decrease of low frequency component. The lowering phenomenon of the EMG power spectrum presented by the H/L ratio could not show each of the frequency component changes, but now we must consider the reasons for the low frequency component decrease at post-decompression during muscle fatigue (fig. 4).

EMG analysis, which generally permits an assessment of muscle fatigue during voluntary contraction, shows a shift toward the lower frequencies in the power spectrum. This change is mainly caused by an increase in the amplitude of the low frequency in the EMG power spectrum (Boxtel et al. 1983). The "fatigue indexes" use various spectral estimates, such as the centroid frequency, median frequency, and the high/low frequency ratio. We used the H/L ratio to minimize the noise influence. Our results showed a similar shift of the H/L ratio as a function of time in the half-rising posture (Lindstrom et al. 1977, Gross et al. 1979, Bigland-Ritchie et al. 1981, Harry et al. 1982, Lenoir et al. 1990).

The changes in EMG are discussed in Lenoir et al. (1990). The mechanical failure of an exercising skeletal muscle during fatiguing contractions is preceded by an increase in the low frequency component of the EMG of that muscle (Kadefors et al. 1968, Lindstrom et al. 1977). This shift in the EMG power spectrum during fatiguing contraction is because of neuromuscular conduction velocity reduction. This reduction could be attributed to an inadequate blood flow to the contracting muscle in relation to its power output, which results in lactic acid accumulation.

Synchronizing action potentials also increases the power of the low-frequency component of the EMG during sustained maximum isometric voluntary contraction of limb muscles. Finally, a fall in the discharge frequency of motoneurons is also observed during prolonged maximal voluntary contraction, reducing the power of the high-frequency band. Low frequency component reduction of the EMG power spectrum during muscle fatigue was not reported. The extrinsic factors of lowering phenomenon of the EMG during muscle fatigue may be induced by muscle cooling, a decrease in muscle thickness, the position of the recording electrodes of the skin, and the operating length of the passive stretched muscle during isometric contraction.

We have no proven explanation for the different reduction of high and low frequency components of the EMG power spectrum during muscle fatigue at post-decompression when compared with pre-compression one atmospheric air and hyperbaric helium environments. We propose a hypothesis that these results were caused by adaptation to the long decompression period, with hyperoxic and low density respiratory gas, especially at the end of decompression, and then the decreased oxygen transfer capacity to the tissues. After returning to the normoxic 1 ATA air condition, it must take time for readaptation.

When studying hyperbaric physiology, we have a tendency to look for the differences between the results at pre-compression and those of the hyperbaric environment. Even when studying the decompression phase, much of the research addresses the safety of the decompression tables. As we have shown in present study, without decompression sickness, the effects of slow decompression on physiological phenomena were more severe than the effects of compression. We must use extreme care when we evaluate the static workload between 1 ATA air pre-compression and post-decompression and at the hyperbaric helium-oxygen environments.

Literature Cited

Bezucha, G.R., M.C. Lenser, P.G. Hanson and F.J. Nagle, 1982. Comparison of hemodynamic responses to static and dynamic exercise. *J. Appl. Physiol.* 53:1589-1593.

Bigland-Ritchie, B., E.F. Donovan, and C.S. Roussos, 1981. Conduction velocity and EMG power spectrum changes in fatigue of sustained maximal efforts. *J. Appl. Physiol.* 51:1300-1305.

Boxtel, A., P. Goudswaard, G.M. Molen, and W.E.J. Bosch, 1983. Changes in electromyogram power spectra of facial and jaw-elevator muscles during fatigue. *J. Appl. Physiol.* 54:51-58.

Conn, M.L., P.A. Hayes, and J.B. Morrison, 1981. Contribution of metabolic and respiratory heat to core temperature gain after cold water immersion. *Underwater Physiol.* 7:509-516.

Doubt, T.J., and D.E. Evans, 1982. Hyperbaric exposures alter cardiac excitation-contraction coupling. *Undersea Biomed.Res.* 9:131-145.

Fagraeus, L., and D. Linnarsson, 1973. Heart rate in hyperbaric environment after autonomic blockade. *Forsvarsmedicin* (Stockholm) 9:260-264.

Gosovic, S.M., and A.I. Radovic, 1981. Frequency and regulation of heart rate during open-sea saturation diving. *Underwater Physiol.* 7:257-266.

Gross, D.A., W.R. Grassino, W.R.D. Ross, and P.T. Macklem, 1979. Electromyogram pattern of diaphragmatic fatigue. *J. Appl. Physiol.* 46:1-7.

Harry, D., M.J. Belman, J. Propst, and S. Lewis, 1982. A statistical analysis of the spectral moments used in EMG tests of endurance. *J. Appl. Physiol.* 53:779-783.

Hong, S.K., T.O. Moore, D.A. Lally, and F. Morlock, 1973. Heart rate response to apneic face immersion in hyperbaric helium environment. *J. Appl. Physiol.* 34:770-774.

Kadefors R., E. Kaiser, and I. Petersen, 1968. Dynamic spectrum analysis of myo-potentials with special reference to muscle fatigue. *Electromyography* 8:39-74.

Lindstrom, L., R. Magnusson, and I. Petersen, 1970. Muscular fatigue and action potential conduction velocity changes studies with frequency analysis. *Electromyography* 4:341-356.

Lambertsen, C.J., R. Gelfand, R. Peterson, R. Strauss, W.B. Wright, J.G. Dickson, Jr., C. Puglia, and R.W. Hamilton, Jr., 1977. Human tolerance to He, Ne and N2 at respiratory gas densities equivalent to He-O2 breathing at depths to 1200, 2000, 3000, 4000 and 5000 feet of sea water (predictive studies III). *Aviat. Space & Environ. Med.* 48:843-855.

Lenoir, P., Y. Jammes, P. Giry, J.C. Rostain, H. Burnet, C. Tomei, and C. Roussos, 1990. Electromyographic study of respiratory muscles during human diving at 46 ATA. *Undersea Biomed Res.* 17:121-137.

Lin, Y.C., K. Shiraki, and M. Mohri, 1987. New Seatopia 1985: Circulatory responses. *Proceedings of the Ninth Meeting of the UJNR Panel on Diving Physiology and Technology, November 4-6, 1987,* Yokosuka, Kanagama, Japan, pp. 245-261. Yokosuka, Japan, JAMSTEC.

Lindstrom, L., R. Kadefors, and I. Petersen, 1977. An electromyographic index for localized muscle fatigue. *J. Appl. Physiol.* 43:750-754.

Martin, C.E., J.A. Shaver, D.F. Leon, M.E. Thompson, P.S. Reddy, and J.J. Leonard, 1974. Autonomic mechanisms in hemodynamic responses to isometric exercise. *J. Clin. Invest.* 54:104-115.

Moore, T.O., J.F. Morlock, D.A. Lally, and S.K. Hong, 1976. Thermal cost of saturation diving; respiratory and whole body heat loss at 16.1 ATA. *Underwater Physiol.* 5:741-754.

Naraki, N., F. Shidara, T. Kataoka, G. Tomizawa, and M. Mohri, 1991. Evaluation of static work load by circulatory responses and EMG power spectrum changes under a 28 ATA helium-oxygen environment. *UJNR/MRECC Diving Physiology and Technology* 11:212-222.

Ohta Y., H. Arita, H. Nakayama, S. Tamaua, C.E.G. Lundgren, Y.C. Lin, R.M. Smith, R. Morin, L.E. Farhi, and M. Matsuda, 1981. Cardiopulmonary functions and maximal aerobic power during a 14-day saturation dive at 31 ATA (SEADRAGON-IV). *Underwater Physiol.* 7:209-221.

Overfield, E.M., H.A. Saltman, J.A. Kylstra, and J.V. Salzano, 1963. Respiratory gas exchange in normal man breathing 0.9% oxygen in helium at 31.1 ATA. *J. Appl. Physiol.* 27:471-475.

Salzano, J.V., B.W. Stolp, R.E. Moon, and E.M. Camporesi, 1981. Exercise at 47 and 66 ATA. *Underwater Physiol.* 7:181-196.

Salzano, J., D.C. Rausch, and H.A. Saltzman, 1970. Cardiorespiratory responses to exercise at a simulated seawater depth of 1000 feet. *J. Appl. Physiol.* 28:34-41.

Shida, K.K., and Y.C. Lin, 1981. Contribution of environmental factors in development of hyperbaric bradycardia. *J. Appl. Physiol.* 50:731-735.

Undersea Research Activities in the MSDF Undersea Medical Center

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Abstract

The Maritime Self-Defense Force (MSDF) Undersea Medical Center has been engaged in research that promotes advancement of all MSDF manned diving operations. Research programs are designed to allow useful work performed with safe and effective dives at operational depths and are divided into two major categories: physiological and human engineering studies related to disabled submarine rescue missions and mine-hunting operations. Studies involved at present are: (1) defining and qualifying operational effectiveness of one-man atmospheric diving systems, namely, Newtsuit, which has been perceived to have a useful role for rescue, inspection, and recovery missions; (2) collecting physiological and psychophysiological information that allows useful work to be done at deeper depths (more than 300 m of sea water); (3) determining optimal decompression schedules utilized in bounce diving; and (4) improving the semi-closed-circuit underwater breathing apparatus used for mine-hunting operations at deeper than currently operational depths for longer diving duration and lower water temperature. Recent activities of these programs will be discussed.

Introduction

The MSDF Undersea Medical Center (UMC) was organized in 1978 as tile MSDF Research and Development Command, under the direction of the Chief of Staff, MSDF. The Mission of UMC is to enhance the safety of MSDF submarine and diving personnel through research of medicine and human engineering. The UMC is also responsible for education, providing the MSDF with specialized training of saturation divers and undersea medical officers. Research and development is carried out in three areas: health care, human engineering, and underwater physiology. Training of medical personnel and saturation divers is performed by the Education and Training Division.

Research programs are designed for safety and effectiveness of the divers working at operational depths. These programs are aimed specifically at improving the physiological and human engineering related to disabled submarine rescue missions and mine hunting operations.

Current Research Programs

The UMC research program in FY93 is divided into four broad categories:

(1) Operational test of one-man atmospheric diving systems.

This is to further define and quantify the operational effectiveness of the Newtsuit, which has been perceived to have a useful role for rescue underwater search and objective recovery missions.

(2) Effects of saturation diving on MSDF divers.

This program is collecting physiological and psychophysiological information in order to perform work at deeper depths (greater than 300 m of sea water).

(3) Develop improved methods for bounce diving utilizing PTC-DDC diving systems.

This program is mainly aimed at determining optimal decompression schedules utilized in bounce diving operations onboard the ASR Chiyoda.

(4) Develop an improved semi-closed-circuit breathing apparatus.

Our MSDF Semi-Closed Diving Apparatus has not met all the requirements for current mine-sweeper operations. A Japanese EOD Unit in the Persian Gulf disposed of 28 of 34 mines while using the Semi-Closed Diving Apparatus. The underwater breathing apparaties (UBA) needs improvement in maximum operation depth, maximum endurance time, and temperature sensitivity with the backing of operational requirements.

Research Works

Let me briefly discuss how the UMC works:

Newtsuit (fig. 1) was purchased from a Canadian company by the Commander of the Sub-marine Fleet to

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Figure 1. Newtsuit at the UMC.

test the Newtsuit's effectiveness of sub-rescue missions for the perceived role of rescue-chamber operations. Under the requirement of this plan, a test water tank is now under construction at the UMC and will be completed in March 1994. The tank (fig. 2) is a water tower with a variable water current and temperature control, observation blisters, and mobile capsule, with visual recording systems.

This program is conducted in two phases from April 1993 to March 1994 at the UMC. Phase 1 is conducted to standardize operational procedures in underwater tasks. Phase 2 evaluates the characteristics of the life-support, handling, and maintenance of the systems from technical information.

A saturation dive based on the MSDF Defense Planning of FY92 was safely conducted for 30 days from October 1-30, 1992, at the UMC, using the UMC Deep Diving Simulator (fig. 3). This deep saturation dive to 440 m involved 6 saturation divers. Bottom stays lasted for 6 days with excursion dives to 450 m performed for 16 man-hour over 2 days. Linear decompression from 440 m lasted for 18 days, 18 hours, and 40 minutes.

The 440 m saturation dive simulation pursued two major focuses: one to assess the physicopsychological effects at a depth of 450 m, and the other to evaluate diver health both during the dive and during the recovery period to re-entry. The following studies were undertaken during the dive:

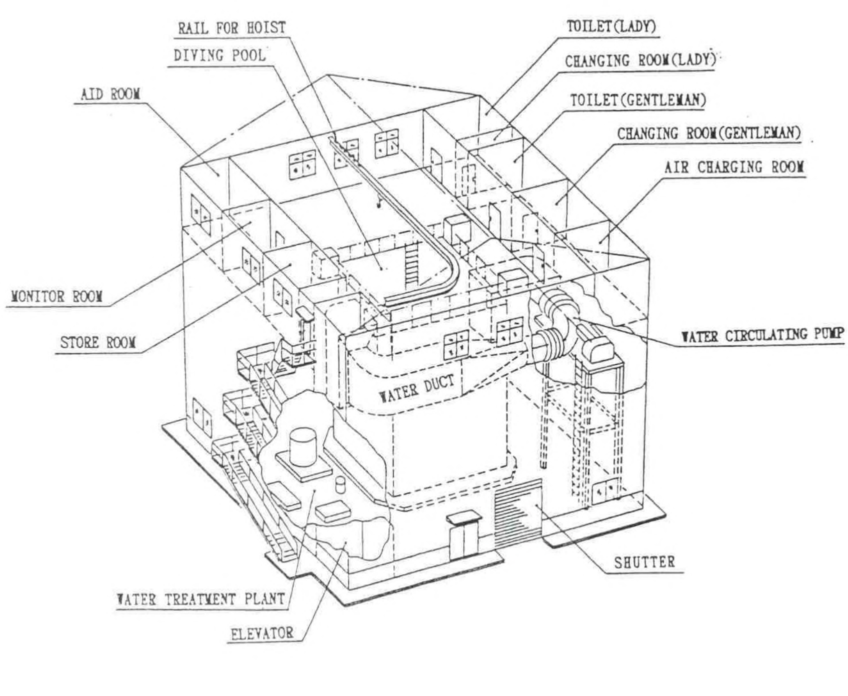

Figure 2. UMC test water tank.

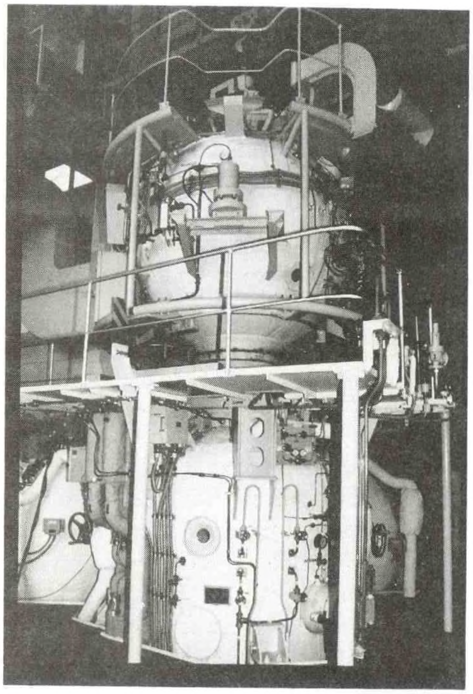

Figure 3. UMC deep diving simulator.

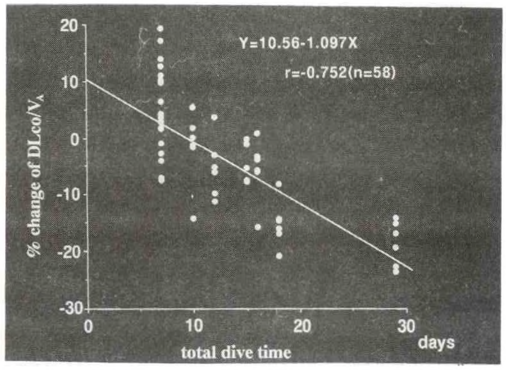

Figure 4. Effect on pulmonary defusing capacity after total dive time of saturation dives.

(1) neuropsychological assessment during and after deep saturation diving;

(2) effects of exposure to prolonged oxygen partial pressure near 0.5 ATA during the period of saturation diving;

(3) cardiorespiratory limitations designed to allow optimal workload in deep saturation diving; and

(4) safety controlled ascent rates from 450 m using the Duke-GKSS linear decompression manner.

Generally speaking, the 450 m saturation dive simulation as a target for saturation depths ranging below 300 m was conducted successfully.

Because of the staged compression profile and maintenance of PN_2 at 1.6 ATA, only minor symptoms of HPNS and other neuropsychological defects were noted during the compression period and on the bottom. EEG monitoring by topography showed considerable emphasis of theta waves during this time, but it did not reveal any symptomatic abnormalities in the divers.

The linear decompression procedure modified the Duke-GKSS method, and its safety and effectiveness were demonstrated by the lack of bubble detection among all divers utilizing pericardial ultra-sound of M-Mode scanning. The modified decompression profile slightly increased the rate of decompression to a depth of 14 meters (adjusting it automatically to control the systems). This reduced the decompression time by 10 hours without bubble detection or other observed side effects.

Optimal physical work was performed at 450 m at one atmosphere. While performing 100 watt work load at 440 m, the divers at steady state with a maintained heart rate of approximately 140 without any sign of distress or exhaustion. During a recent saturation dive to 100 m, divers performing 150 watt work load had an intensity that resembled physical stroke at 440 m, with a heart rate of 150 and subjective signs. Decreased cardioventilatory function at depth showed great inter-individual differences. Further accumulation of individual data is needed to assess the optimal workload at depth.

To investigate the effect of the oxygen-derived free radicals on lung function after saturation dives where a partial oxygen pressure(P_{02}) was maintained between 0.42 to 0.495 ATA, we measured lung volumes, diffusing capacity ($DLco/V_A$), and the amount of ethane in the alveolar expiate.

In the 440 m saturation dive, vital capacity surfacing did not significantly decrease in all divers in comparison with predive values. $DLco/V_A$ however, decreased significantly (about a 20% reduction after the total dive time of 30 days in a 440 m saturation dive, fig. 4), and the ethane production rate significantly increased right after surfacing compared to predive values (fig. 5). Although ethane expiration returns to normal soon, recovery of the diffusing capacity requires a much longer period.

These observations indicate that the decrease of $DLco/V_A$ is assumed to be caused by oxygen-derived free radicals. We must consider the risk of pulmonary oxygen toxicity even when the P_{02} is below 0.5 ATA. A DLco test

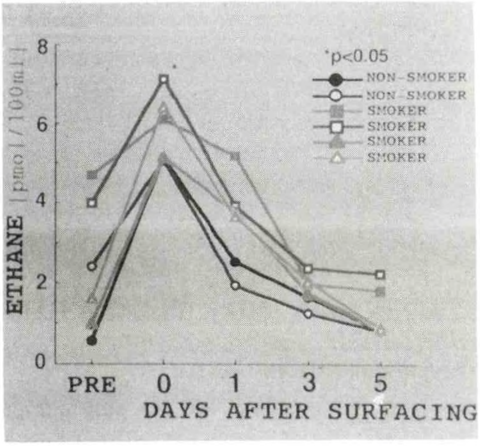

Figure 5. Ethane expiration affected by a 440 m saturation diving.

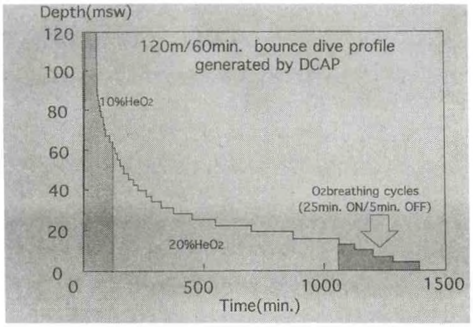

Figure 6. Decompression table calculated by "D-CAP".

or a regular routine health examination of saturation divers should be included in post-dive tracking.

Optimal decompression schedules for bounce diving were tested with decompression tables calculated by the Decompression Computation and Analysis Program (DCAP) from Hamilton Research, Ltd. Various types of decompression tables computed by DCAP referred to the databank at Hamilton Research, Ltd., that is used by NEG VAN/QUIK COMM (fig. 6). Over 30 dives were conducted at the UMC, ranging in depths from 60 to 120 m (max. 150 m) and lasting from 30 to 60 min. This program provides maximum benefit for the MSDF diving operations onboard the ships.

The current MSDF Semi-Closed Diving Apparatus (SDA) is shown in figure 7. Developing an improved semi-closed circuit breathing apparatus has just started and will incorporate some features of the Canadian Underwater Mine Apparatus (CUMA). The mixture of gases, no decompression and repeated decompression schedules, maximum endurance time, and CO_2 scrubber capacity in the cold water environment need to be addressed as operational requirements. The themes of the improvement are focused on the mixture gases replaced with oxy-nitrogen gases below the depth of 42 m and the scrubber characteristics for breathing resistance and the cold-water environment.

Functional evaluation and operational tests, using several types of new semi-closed UBA, have been budgeted for 3 years beginning in 1994.

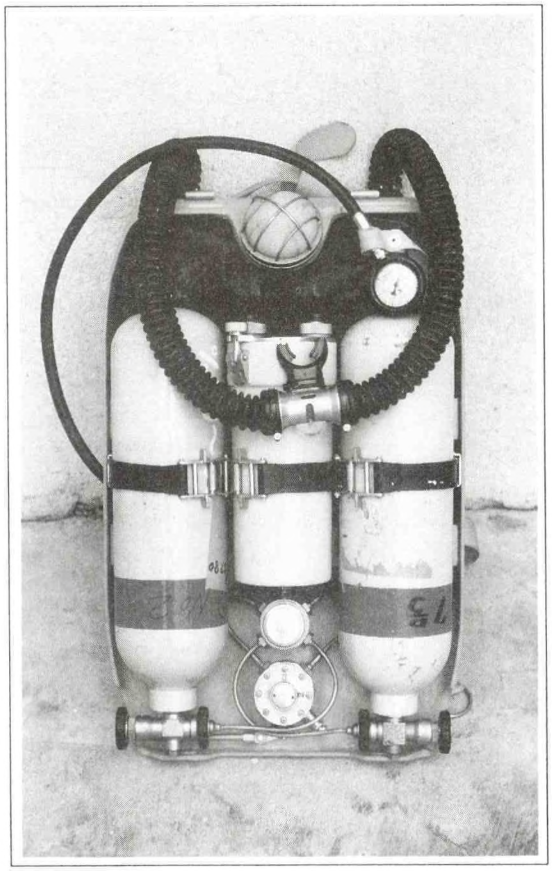

Figure 7. MSDF semi-closed diving dpparatus (SDA).

Background

The research in the MSDF Undersea Medical Center has been conducted to promote health and secure safety of personnel who are engaged in submarine and diving operations to solve various problems related to medicine, physiology, psychology, and human-factors engineering.

Since the new Japanese era (Heisei) in early 1989, dramatic changes in international circumstances have led

Japan to help secure peace and safety in the world. In response to this goal, the MSDF began to operate the International Peace Cooperation and the Japan Disaster Relief Team. As a consequence, MSDF medical and diving specialists play an obscure important role. Medical specialists should demonstrate their ability to maintain the safety and health of the personnel engaged in difficult diving conditions. They also should know the research activities being conducted in other countries.

Acknowledgment

The author wishes to sincerely thank his colleagues in the UMC. They are: Undersea Medical Officer, LCdr Shinya Suzuki, and Senior Researchers, Kuniaki Okonogi and Akio Hashimoto.

References

Oiwa H., I. Nisbi, N. Ogawa, H. Ishii, and K. Okonogi, 1992a. Exercise (Aerobic) capacity at a simulated depth of 330 M. 1992 Undersea and hyperbaric medical society annual scientific meeting, Bethesda, Maryland.

Oiwa H., I. Nisbi, N. Ogawa, H. Isbii, and K. Okonogi, 1992b. Hypercapnia during steady state exercise at aerobic threshold(AT) under a simulated depth of 330 meters. 40th International Congress of aviation and space medicine, Tokyo

Okonogi, K., 1993. Physical work performance at a 440 msw saturation diving, personal communication.

Suzuki S., Y. Sakamoto, K. Okonogi, K. Nakabayasbi, A. Hashimoto, N. Shinomiya, T. Ikeda, 1993. Decrease in the single Breath diffusing capacity of the lung and increase in the amount of ethane in the alveolar expiate after 440 msw saturation dive, 1993 Undersea and Hyperbaric Medical Society annual scientific meeting, Halifax, Nova Scotia, Canada.

Manned Diving as a Method for Coastal Sea Research

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Abstract

To know the present situation, future prospects, and the role of manned diving (scuba) for progressing in coastal sea research, we mailed some questionnaires to 169 Japanese scientists studying the coastal sea area in January 1993. As a result of this inquiry, 70 percent (119) of the scientists answered the questionnaire through the end of February 1993. Of the 119 personnel, the areas of specialty represented were 60 basic study (13 Physics, 7 Chemistry, 31 Biology, 3 Geology, and 6 Others) and 59 applied study (33 Marine productivity, 14 Coastal engineering, 6 Coastal management, and 6 Others). Regarding diving as a method of research, 51 of the 119 scientists have diving experience using scuba. Of the 88 answers received, only 44 divers indicated that their diving organization has some instruction or control for qualification and safety of divers. The consensus of those who responded was that Japanese scientists often dive under conditions that could be considered dangerous. Each scientist diver who replied wants to see more strict standards and safer operational procedures.

On the other hand, researchers from JAMSTEC visited 54 of the 169 scientists to survey developing an N_2-O_2 saturation diving technology and undersea laboratory similar to AQUARIUS as a tool for progressing in coastal sea research. Of these, 29 scientists had diving experience. As a result, various concepts of an undersea laboratory were collected, and 52 scientists of the 54 wished to use it when the safety was confirmed. The diving needs summarized that underwater phenomena have to be studied and measured directly by scientists.

From April 1992 to March 1993, JAMSTEC started a new nitrox saturation dive project called Scientist in the Sea. The purpose of the project is to develop and evaluate N_2-O_2 saturation diving procedures by using a diving simulator. The first 20 m of diving simulation was completed in February 1993, and Okamoto joined the simulation team as one of the four divers. Although a practical dive program at sea is not planned yet, we expect that the N_2-O_2 saturation diving technology will be fundamental and useful for progressing in coastal sea research.

Introduction

JAMSTEC has been engaged in developing heliox deep diving technology for 20 years and completed several 300 m offshore diving experiments under project New Seatopia. During the past 2 years, deep offshore diving technology has been preserved and renewed by simulation diving experiments held once a year. During FY 1992 (April 1992 - March 1993), JAMSTEC started a new nitrox saturation dive project known as Scientist in the Sea. The purpose of the project is to develop and evaluate N_2-O_2 saturation diving procedures using a diving simulator. The first 20 m diving simulation was completed in February 1993. Although a practical dive program at sea is not planned yet, we expect that the N_2-O_2 saturation diving technology will be fundamental and useful for progressing in coastal sea research.

In order to know the present situation, future prospects, and the role of manned diving (scuba) for progressing in the coastal sea research, a questionnaire and visiting survey were carried out on Japanese scientists studying the coastal sea area. As a result of the survey, the concept of Scientist in the Sea proved its importance.

This paper describes JAMSTEC's new direction of diving research activity and the future prospect of it.

Diving Project of JAMSTEC

JAMSTEC has been engaged in developing heliox deep diving technology for 20 years, as shown in table 1. JAMSTEC was established in October 1971, and the first project was a heliox manned habitation dive called SEATOPIA. The maximum habitation depth was 53 m. Project SEADRAGON was an on-land dive to study diving physiology, and SEAMECCA was a shallow on-land dive for scientists. Project NEW SEATOPIA was an experimental offshore dive up to 300 m, and we have completed several 300 m dives during the project. During

Table 1. Saturation diving program at JAMSTEC sin ce October 1972. Numerals denote the maximum diving depth during each project.

PROJECT NAME	1972	1982	1992
SEATOPIA			
HABITAT/PTC/DDC	↔60m		
PTC/DDC	↔100m		
SEADRAGON	←——→300m		
SIMULATOR			
SEAMECCA		↔30m	
SIMULATOR			
NEW SEATOPIA		←——→300m	
SDC/DDC			
HELIOX SAFE DIVE			←100-200m
SIMULATOR			
NITROX SIS			
SIMULATOR			←20-30m
HABITAT			?

these 2 years, deep offshore diving technology has been preserved and renewed by simulation diving held once a year.

Since 1992, JAMSTEC started a new nitrox saturation dive project known as Scientist in the Sea. The purpose of the project is to develop and evaluate N_2-O_2 saturation diving procedures by using a diving simulator. The first 20 m diving simulation was completed in February 1993, and Okamoto joined the simulation team as one of the four divers (fig. 1).

Although a practical dive program at sea is not planned yet, we expect that N_2-O_2 saturation diving technology will be fundamental and useful for coastal sea research in areas such as biology, oceanography, and so on.

Figure 1. Nitrox saturation dive to 20 m. (From left to right: Dr. Motohiko Mohri, Mr. Yasushi Taya, and Dr. Mineo Okamoto)

New Direction of the Coastal Research Effort in JAMSTEC

Project NEW SEATOPIA has been completed. Its purpose was to develop deep diving technology up to 300 m that covers a broad continental shelf area around Japan. The four research groups in the Diving Department were reduced to two and combined to form a new Marine Development Research Department. The Department promotes new coastal sea research program as follows:

(a) Research on the coastal environment and ecosystems embracing such varied sciences as ocean physics, chemistry, biology;

(b) Ocean engineering such as mechanical engineering, naval architecture, electronics, marine instrumentation, computer science, etc.; and

(c) Research and development of new technologies to attain an adequate level of quantitative understanding of the coastal environment and ecosystems.

Long-term goals of coastal research include:

(a) Observing and investigating changes in the coastal ecosystem surrounding Japan;

(b) Analyzing cause-and-effect relationships between such changes and the coastal physical and chemical changes of the environment; and

(c) Developing methods to understand coastal processes quantitatively and to predict future changes.

Items for research and development include:

(a) Observe and analyze the coastal environment and ecosystems;

(b) Study on experimental ecosystem; and

(c) Develop models of the marine ecosystems and study for predicting changes in marine ecosystems.

Research and development of technologies, instruments, and facilities for observation, measurement, and analysis of the marine ecosystems are summarized as follows:

(a) Develop instruments, equipment, and techniques

- to monitor the coastal environment
- to automatically measure zooplanktons
- to monitor organisms used as an index to the marine environmental changes
- Facility for experimental coastal ecosystems
  - for single process experiments
  - for complex process experiments

(b) Develop instruments, equipments, and techniques for

- an undersea coastal research laboratory system
- a research submersible for shallow coastal seas
- a seaside laboratory for studying coastal ecosystems

(c) Develop technology to better utilize coastal areas and improve the coastal environment.

Assessment Survey of Research Diving Activity in Japan

To know the present situation, future prospects, and role of manned diving (scuba) for progressing in coastal sea research, some questionnaires were mailed to 169 Japanese scientists in January 1993. They were all famous and active scientists in the coastal research area, and the approximate age was between 30 and 70. The questionnaire criteria were as follows:

(a) Their specialty;

(b) Research area;

(c) Specific research interests, present and future;

(d) Special instruments and technology needed for a coastal sea research vessel;

(e) Experience using undersea technology for research; and

(f) Organization's follow-up system for scuba diving as a method for research.

As the result of this inquiry, 70 percent (119) of the scientists answered the questionnaire through the end of February 1993. Specialties of the 119 personnel were 60 basic study (13 Physics, 7 Chemistry, 31 Biology, 3 Geology, and 6 Others) and 59 applied study (33 Marine productivity, 14 Coastal engineering, 6 Coastal management, and 6 Others). Regarding diving as a method of research, 51 of the 119 scientists (42.9%) have diving experience using scuba. Regarding their organization's follow-up system for scuba diving, for example, safety training, insurance, facilities, supporting staff, and so on, 88 of 119 answered this question, and only 42 of the 88 (47.7%) wrote that there was any follow up by their organization. This means that more than half of the Japanese well-known scientists who are studying the coastal sea area have no support for their diving activity. Those scientists have to dive at their own private responsibility. So, many scientists earnestly desire standardization in scientific diving by an authorized organization. It means that JAMSTEC desires to carry out for Japanese divers what the National Undersea Research Program in NOAA does for the U.S. divers.

Table 2. Proposed research items using the undersea laboratory

Marine biology	
Ecological study of marine life	25
Relation between environmental changes and marine life	6
Schooling behavior of marine life	3
Life cycle of marine life	2
Landing mechanism of drifting larvae	2
Study on speed constant for modeling ecosystems	2
Study on gelatinous organisms	2
Study on marine snow	1
Marine physics	
Movement of sand	2
Current just above the bottom	1
Current and turbulence under rough sea	1
Micro-current structure	1
Marine chemistry	
Useful material of marine life	1
Continuous sampling and analysis	1
Marine geology	
Micro-scale mapping	1
Movement of organisms	
Movement and change of organisms	6
Study on muddy layer above sea bottom	1

Estimated Scientific Needs Using a Habitat

During the same period, researchers of JAMSTEC visited 54 of the 169 scientists to survey developing N_2-O_2 saturation diving technology and an undersea laboratory like AQUARIUS as a tool for progressing in coastal sea research. Of the scientists visited, 29 of them had diving experience. As a result, various concepts of an undersea laboratory were collected and 51 of the scientists wished to use it when the safety of the systems was confirmed. Proposed research using the undersea laboratory in basic study areas are shown in table 2. The results concluded that undersea phenomena have to be studied and measured directly by scientists while they are watching the object and thinking about the phenomena.

Table 3. Direction of manned diving activity

Commercial diving	Shallow <---------- Deep Replaced by Machine
Scientific diving	Shallow ----------> Deep Bounce + Saturation
Sports diving	Bounce + Stay (House)

New Direction of Diving Research Activity in JAMSTEC

JAMSTEC is renewing deep heliox dive technology that is aimed at the commercial diving activity. The new research program stresses safe and efficient nitrox diving using a procedure just starting with a UJNR cooperative study. The next phase will be a habitation dive at sea to prove the procedure, and a future target will be a Japanese habitat for all Japanese research divers.

The direction of manned diving activity is estimated as shown in table 3. In a commercial underwater activity, one diver will be replaced by another quickly using an improved machine from a deeper depth to a shallower depth. We have no idea about this changing velocity and balanced depth; but, even after 30 years, diving activity at a 10-m depth will never be replaced by machines because of the economical viewpoint. As for deep diving technology, JAMSTEC will maintain 300 m diving technology and study about basic technology and physical matters, but a new and enhanced offshore deep diving program will pause until practical and scientific needs appear.

Regarding scientific diving, diving up to 20 or 30 m by scuba or nitrox is very important for practical study. As the coastal area is very important for human existence as well as marine life, the scientists need to know what is happening and changing in those areas, present and in the future. Nevertheless, Japanese scientific diving in a coastal sea area is very poor because of the lack of a research diver assist system. Since a diver follow-up system in case of emergency will be provided by a sports diver organization, JAMSTEC's mission will be to promote and support diving technology, safety training, research diver network, and so on, for scientists who belong to a research institute or university. Developing new undersea technology, nitrox saturation diving technology, and shallow water undersea habitats like AQUARIUS will be most important for Japan. In this area, JAMSTEC's activity will progress by a cooperative study through UJNR.

Sound Absorption Coefficients of Acoustical Materials in Hyperbaric Gas Mixtures

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Abstract

Perpendicular incident sound absorption coefficients in hyperbaric helium-air and nitrogen-air gas mixtures were measured. Cotton felt, glass wool felt, and polyurethane sponge were chosen as experimental objects in this study because they are the most popular sound absorbing materials. Measurement was performed in a hyperbaric chamber according to the method specified in the Japan Industrial Standard. As a result, the value of the sound absorption coefficient is low for low frequency incident sound, whereas it becomes higher for the higher frequencies; for example, in a case of cotton felt in 1 ATA air, 5 percent for 250Hz, 20 percent for 1kHz, 60 percent for 3kH, and approximately 100 percent for 3.5kHz, respectively. The important result of this research is that the sound absorption coefficient is remarkably reduced when the gas pressure is high. In the case of cotton felt in a helium-air mixture, for example, the sound absorption coefficient for 1kHz sound is 20 percent at 1 ATA; but it is reduced to 10 percent at 5 ATA, 7 percent at 15 ATA, and 4 percent at 30 ATA, respectively. For the sound frequency of 3kHz, the sound absorption coefficient is 22 percent at 5 ATA, 12 percent at 15 ATA, and 8 percent at 30 ATA, respectively, whereas it is almost 100 percent at 1 ATA. Thus, the curves of frequency versus sound absorption coefficient shift to the higher frequency side when the ambient pressure is increased.

A general trend similar to that found in cotton felt was also found in glass wool felt, but the polyurethane showed a little different frequency character that has a few peaks at specific frequency regions.

Introduction

We have been engaged in the research for a speech communication system for divers in a hyperbaric helium-oxygen atmosphere. We have already investigated the acoustic characteristics of microphones (Suzuki and Oohashi 1986), headphones (Satsukawa et al. 1991), and loudspeakers (Oohasi et al. 1986) and developed a digital helium speech unscrambler (Suzuki and Nakai 1991). In addition, we have developed the database of helium speech (Suzuki and Nakai 1992). In the process of this research, we have often noticed that the noise level in the experiment room (i.e., submergence simulation tank in JAMSTEC, Japan Marine Science and Technology Center, at Yokosuka, Japan) becomes higher and more irritating at high ambient pressure than at normal air atmosphere. We need to reduce the room noise for comfortable and sure speech communication.

This noise was partly caused by heavier operation of ventilation fans for circulating ambient gas. But the noise still remained higher than normal air atmosphere when the fan was stopped. There must be another reason for the increased noise level at the higher ambient pressure of a helium gas mixture. We speculate that deterioration of the sound absorption capacity of cotton or wool fabrics, such as the blankets and clothes, that are working as sound absorbers might be the cause. This paper is a result of our first trial approach to the noise problem. We measured the sound absorption coefficients at several pressures from 1 ATA to 30 ATA in N_2-Air and He-Air gas mixtures. We chose cotton felt, glass wool, and polyurethane sponge as the experimental objects because they are quite popular as sound absorbing materials.

In general, three coefficients are defined to specify characteristics of any sound absorbing material. They are the perpendicular incidence, oblique incidence, and random incidence coefficients. The first one can be measured, according to a method authorized by Japan Industry Standard, JIS-A1405. This is called the tube method because it uses a specially designed metal tube (Japan Industry Standards Committee 1963). We set up a measuring system including the tube in the hyperbaric chamber at the author's laboratory. To obtain the latter two kinds of coefficients, according to a method authorized by Japan Industry Standard, JIS A1409, a reverberation room whose volume is at least 100 m^3 is necessary.

From a point of view of evaluating the sound absorbers, the random incidence coefficient is better than the perpendicular incidence one because it expresses more directly

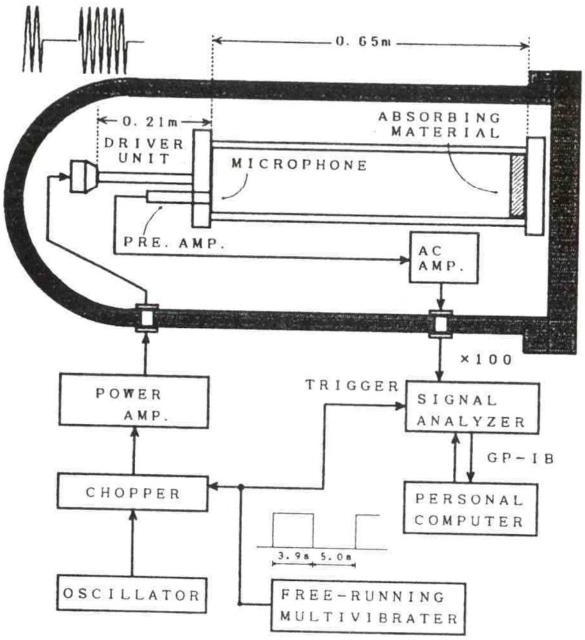

Figure 1. Schematic diagram of the measuring system for perpendicular incidence sound absorption coefficient by the tube method.

the ability of reducing noise and room reverberation. To measure the random incidence coefficient, however, we need a sound reverberation room much larger than 100 m^3 and filled with the high pressure gas mixture. Needless to say, this is impossible. Therefore, we chose the perpendicular incidence sound absorption coefficient.

Measuring Method

Measurement was done in a hyperbaric chamber in the author's laboratory according to JIS-A1405 that specifies a measuring method for perpendicular sound absorption.

The hyperbaric chamber has an inner diameter of about 0.36 m and is about 1 m long. The measurement system was designed for hyperbaric chamber use. Figure 1 shows the measurement system. The main tube has an inner diameter of 5 cm, a length of 65 cm, and a thickness of 5 mm. The tube that connects the speaker driver unit and the main tube has an inner diameter of 8 mm and a length of 21 cm. These tubes are made of brass. There are 41 stainless steel wires of 1 mm diameter in the connecting tube so that it has a high acoustical resistance. Thus the main tube is equivalently isolated from the driver unit as an acoustic circuit.

The sinusoidal wave signal from the oscillator, SHIBASOKU 590R, is chopped to short duration alternative signals of on or off by the chopper circuit, whose input is a signal from the astable multivibrator. Its output is amplified by the power amplifier, TRIO L05M, and drives the driver unit of the horn speaker, TOA TU15L. Sound from the driver unit passes through the connecting tube and is input to the main tube. The sound in the main tube is received by a sound pressure type microphone, B&K 4134. The output signal from the microphone is amplified by the preamplifier, B&K 2619, and then amplified by 100 times by the AC amplifier. This signal is then input to the signal analyzer, IWATSU 2 ch FFT analyzer 2111.

Measured frequencies, f_n, are resonance frequencies of the main tube as given by Equation 1, where n is a positive integer number, L is length of the main tube, 65 cm, and c is sound velocity.

$$f_n = \frac{nc}{2L} \quad (1)$$

When the signal of the oscillator is switched from on to off by the chopper circuit, the sound from the driver unit stops and after that, the amplitude of sound in the main tube is gradually reduced. Simultaneously, the signal analyzer is triggered by the astable multivibrator. The signal analyzer takes in the output of the AC amplifier from 10 periods before the trigger signal and its input is digitized by A/D converter. Data from the signal analyzer are transferred to the personal computer, NEC PC-9801VX, through a GP-IB interface.

The reverberation time is calculated as follows. In the computer, each succeeding peak value of the gradually reducing sinusoidal wave is extracted and expressed in decibel units (dB). A data series consisting of the peak values is stored in the memory. The time length during which the amplitude of sinusoidal signal is decayed from the stable state value to the value of 30 dB less than the stable state is calculated using the least mean-square method. The reverberation time is calculated as twice the time length. We used this method to avoid a disturbance caused by poor signal to noise ratio of the system while recognizing that the reverberation time is generally defined as the time length of decay from stable state to 60 dB, less value. This measurement process is repeated 20 times, and the reverberation time at a frequency is given by averaging the 20 time measurements.

The reverberation time T_1 is calculated from the data when the sound absorber is set at one end of the main tube. Also, the reverberation time T_2 is calculated from the data when there is no sound absorbing material at the same end of the main tube. Then, the sound absorption coefficient, is calculated by substituting T_1 and T_2 in Equation 2.

$$\alpha = 1 - \log_{10}^{-1}\left\{\frac{12L}{c}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right\} \quad (2)$$

where c is sound velocity and can be calculated by resonant frequencies of the main tube. In this case, c is calculated by substituting the fourth resonant frequency, f_4, and the length of the main tube, L, in Equation 3.

$$c = f_4 \frac{L}{2} \quad (3)$$

We use f_4 because if we use the lower resonant frequency, f_1, the tube length, L, must be compensated considering end effect, and it becomes more difficult at the higher resonant frequencies f_7, f_8, ..., by the higher resonant mode in the tube. Measurements were done at various resonant frequencies given in Equation 1 by changing the value n.

Gas pressure was varied in the range from 1 ATA to 30 ATA. Compression and decompression rates are 10 minutes to 15 minutes per 1 ATA. The sound absorption coefficients are measured at 1, 5, 10, 15, 20, 25, and 30 ATA in compression and decompression processes. Every time the gas pressure is changed, the system takes about 1 hour to make equilibrium pressure changes in the chamber and main tube. In order to feed the gas in the main tube, a 0.1-mm-diameter hole is drilled in the wall of the connecting tube. The diameter of this hole is small enough to not give a serious effect such as sound leakage from the main tube.

Measured sound absorbing materials are 10-mm-thick cotton felt, 10-mm-thick glass wool nominated as No. 2-32K, and two polyurethane sponges of 10-mm and 30-mm thickness; respectively.

The ratios of components of He:Air at 5, 10, 15, 20, 25, and 30 ATA in the compression process are 0.97:1, 2.3:1, 3.9:1, 5.3:1, 7.5:1, and 9.1:1, respectively. In the decompression process, the ratio of components of He:Air at 25, 20, 15, 10, and 5 ATA are 11:1, 11.5:1, 11.9:1, 12.3:1, and 14.2:1, respectively. In the case of N_2-Air, since the chamber is compressed by adding N_2, the ratio of components of N_2:Air is almost equal to that of the He-Air mixture. Thus, the component of gas in a compressed N_2-Air mixture becomes approximately pure N_2. (N_2-Air is simply denoted as N_2 hereafter.)

3. Result of Measurement

As shown in Equation 2, the two sets of reverberation time must be measured. One set, T_1, is reverberation time measured with the sound absorbing material at one end of the main tube. The other set, T_2, is the one without the sound absorbing material. Figures 2 and 3 show the reverberation times, T_2, without any sound absorber in the tube, at 5, 15, and 30 ATA in the decompression process in N_2-Air and in He-Air, respectively. The reverberation time is shorter at higher frequency and is longer at higher pressure. The reverberation time in N_2-Air is approximately three times longer than that in He-Air. There are some frequencies when the reverberation time is considerably shorter than that of the curves of figures 2 and 3. At those frequencies, the acoustical impedance seen from the right end of the main tube is greatly reduced by the resonance effect at increased pressures. Therefore, the reverberation times at those frequencies are estimated by interpolation between the lower and the higher frequencies.

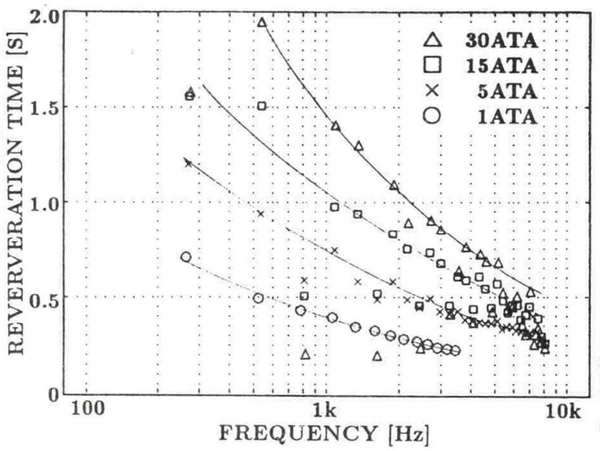

Figure 2. Reverberation time of measuring tube without sound absorber as a function of frequency of incident sound for N_2-Air.

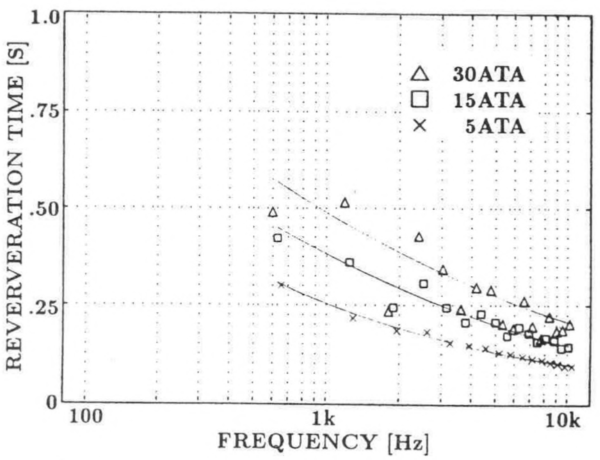

Figure 3. Reverberation time of measuring tube without sound absorber as a function of frequency of incident sound for He-Air.

The reverberation time, T_1, measured with the sound absorbing material is shorter than that without it. However, the relation between the frequency and the reverberation time is the same as that between the frequency and the reverberation time without the sound absorber. When frequency is higher, the reverberation time is shorter.

The sound absorption coefficients are calculated by substituting measured T_1 and T_2 in Equation 2. Figures 4

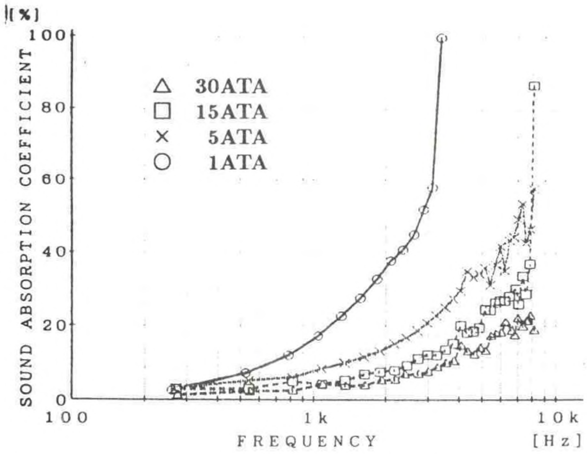

Figure 4. Sound absorption coefficient of cotton felt in N_2-Air.

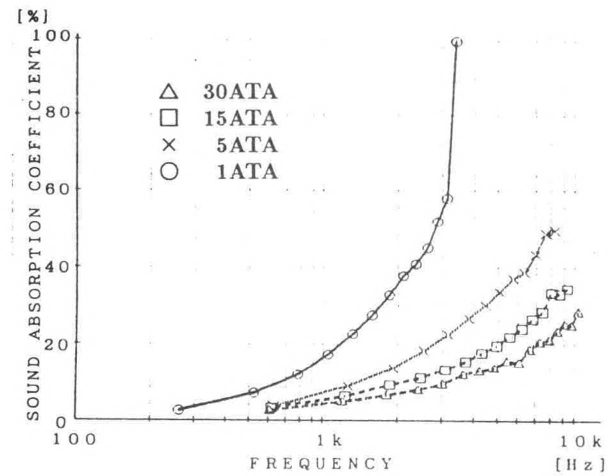

Figure 5. Sound absorption coefficient of cotton felt in He-Air.

and 5 show correlations between frequency and the sound absorption coefficient of the cotton felt in N_2-Air and in He-Air, respectively. Note that when frequency is higher the sound absorption coefficient is larger. When pressure is higher, the curve of the sound absorption coefficient is shifted to a higher frequency and the sound absorption coefficient at the same frequency is lower. The sound absorption coefficient in N_2-Air is almost the same as that in He-Air.

Figure 6 shows the relationship between frequency and the sound absorption coefficient of the glass wool in He-Air. Characteristics of the sound absorption coefficient are the same as those for the cotton felt. When the frequency is higher, the sound absorption coefficient is larger; and when pressure is higher, the curve of the sound absorption coefficient is shifted to a higher frequency and the sound absorption coefficient at the same frequency is lower. We found that characteristics of the sound absorption coefficient at 1 ATA are the same as those of the cotton felt, but

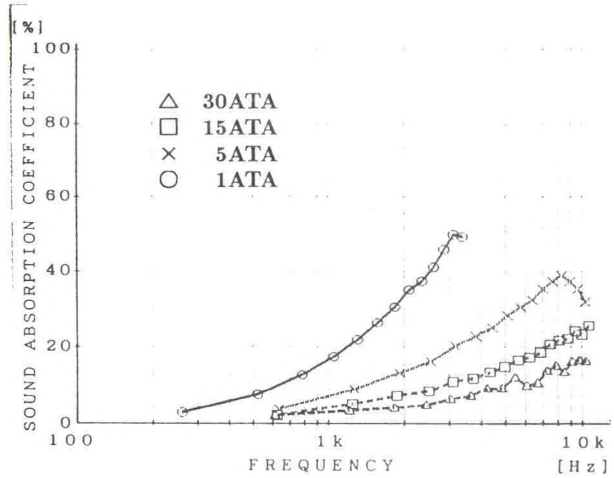

Figure 6. Sound absorption coefficient of glass wool felt in He-Air.

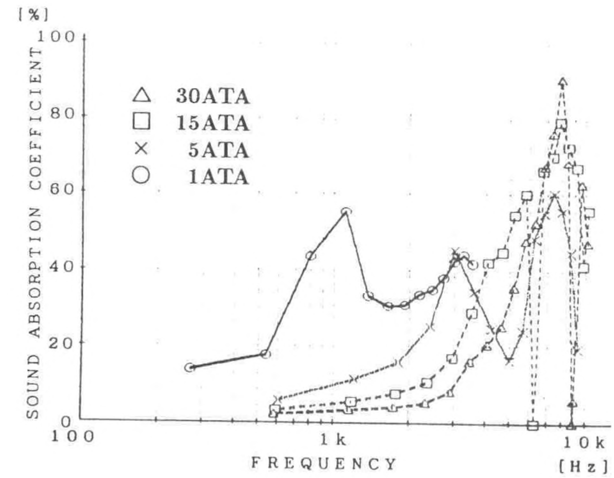

Figure 7. Sound absorption coefficient of a 1 cm-thick polyurethane sponge in He-Air.

when pressure is higher, those of the glass wool are lower than those of the cotton felt.

Figure 7 shows the relationship between frequency and the sound absorption coefficient of a 10-mm-thick polyurethane sponge in He-Air. The characteristics are different from those of the cotton felt and the glass wool and show intricate curves having some peaks and dips. When pressure is higher, the curves of the sound absorption coefficient are shifted to a higher frequency. This phenomenon is the same as those of the cotton felt and the glass wool. When pressure is higher, there are frequencies where the sound absorption coefficient is reduced to zero. The curve of the sound absorption coefficient in hyperbaric He-Air is more complex than that at 1 ATA.

Figure 8 shows the relationship between frequency and the sound absorption coefficient of a 30-mm-thick poly-

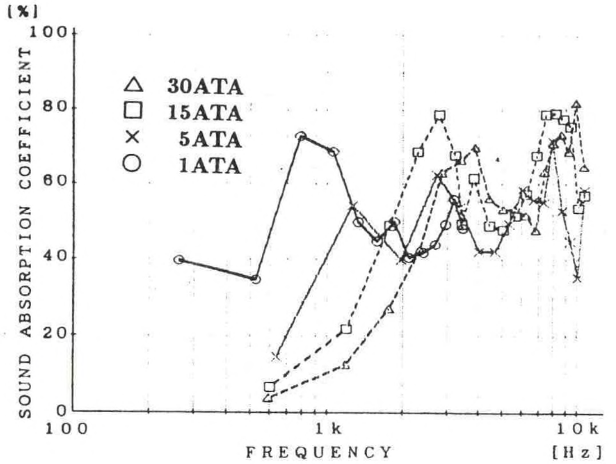

Figure 8. Sound absorption coefficient of a 3 cm-thick polyurethane sponge in He-Air.

urethane sponge. The first peak of the sound absorption coefficient is lower than that of the 10-mm-thick sponge. This phenomenon is a result of the thickness of the absorbing material. There is no frequency where the sound absorption coefficient is reduced to zero and the curve of the sound absorption coefficient is simpler than that of the 10-mm thickness.

Conclusions

Perpendicular incident sound absorption coefficients in hyperbaric helium-air and nitrogen-air gas mixtures were measured. The sound absorption coefficients were calculated by Equation 2 using the measured data of reverberation times, T_1 and T_2, with and without the sound absorber, respectively, in the measuring brass tube.

Reverberation time measurement was done in a hyperbaric chamber in the author's laboratory according to JIS A1405 standards. The reverberation times and, therefore, the sound absorption coefficients were measured/calculated at a signal frequency range between 250Hz and 10kHz.

The ambient gas mixtures were helium-air and nitrogen-air, and the gas pressures were 1, 5, 15, and 30 ATA. When there is no sound absorber in the tube, the reverberation time becomes longer as the pressure becomes higher.

As to the effect of changing gas, the reverberation time in N_2-Air is longer than that in He-Air.

Cotton felt, glass wool felt, and polyurethane sponge were chosen as the experimental objects because they are popularly used as sound absorbers.

The value of the sound absorption coefficient is low for low frequency incident sound, and it becomes higher for the higher frequencies. In the case of cotton felt in 1 ATA air, the values are 5 percent for 250kHz, 20 percent for 1kHz, 60 percent for 3kHz and approximately 100 percent for 3.5kHz, respectively.

An important result is that the sound absorption coefficient is remarkably reduced when the gas pressure is high. In the case of cotton felt in a helium-air mixture, for example, the sound absorption coefficient for 1kHz sound is 20 percent at 1 ATA and is reduced to 10 percent at 5 ATA, 7 percent at 15 ATA, and 4 percent at 30 ATA, respectively. For the sound frequency of 3kHz, the sound absorption coefficient is 22 percent at 5 ATA, 12 percent at 15 ATA, and 8 percent at 30 ATA, respectively, whereas it is almost 100 percent at 1 ATA.

Thus, the curves of frequency versus sound absorption coefficient shift to the higher frequency side when the ambient pressure is increased. The general trend found in cotton felt was also found in glass wool felt, but the polyurethane showed a little different frequency character that has a few peaks at specific frequency regions.

In He-Air, the curves of the sound absorption coefficients of cotton felt and glass wool are roughly the same as those of the cotton felt in N_2-Air. In air, the sound absorption coefficient of the cotton felt is almost the same as that for the glass wool. In high pressure He-Air, the absorption coefficient of the cotton felt is higher than that of the glass wool at the same frequency.

For the polyurethane sponge, the characteristics of the sound absorption coefficient in air have some peaks and dips and, at high pressure in He-Air, they shift to a higher frequency.

Acknowledgment

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Literature Cited

Japan Industrial Standards Committee, 1963. *Methods of test for sound absorption of acoustical materials by the tube method*, JIS-A1405. Japan Standards Association, Tokyo, Japan.

Oohasi, Masanao, Kazuyoshi Matsui, Takayoshi Nakai, and Hisayoshi Suzuki, 1986. Acoustic instruments in high ambient pressure--small size laud speaker. *Technical Report of ICICE*, Institute of Electronics, Information and Communication Engineers, Japan. EA86-8, May. (in Japanese).

Satsukawa, Yoshiyuki, Takayosi Nakai, and Hisayoshi Suzuki, 1991. Characteristics of headphones in high ambient pressure. *Technical Report of IEICE*, Institute of Electronics, Information and Communication Engineers, Japan. EA91-13, May, pp.17-24 (in Japanese).

Suzuki, Hisayoshi, and Takayoshi Nakai, 1989. A new helium speech unscrabler using DSP. In: G.D. Dennis (ed.), *Proceedings of the 10th Meeting of the U.S.-UJNR Panel on Diving Physiology and Technology, June 4-7, 1989, Kauai, Hawaii,* pp. 261-275. Silver Spring, MD, NOAA's National Undersea Research Program.

Suzuki, Hisayoshi, and Takayoshi Nakai, 1992. A database of Japanese helium speech. In: *Proceedings of China-Janpan Joint Meeting of Underwater Medicine and Technology, Shanghai*, pp. 115-122.

Suzuki, H., and M. Oohashi, 1986. Measurement of characteristics of condenser microphone in high pressure ambient gas. In: *Proceeding of the 12th ICA*, L3-4, Toronto, Canada.

Maintenance and Management Technology on Durability of a Mid-Layer Floating Type Marine Cultivation Facility

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Abstract

To make use of bays in a Rias Coast, which are less useful for fisheries, a submersible floating marine cultivation facility with capabilities of submerging and surfacing known as ARTIFICIAL SEA FLOOR was developed. The facility was completed and deployed at a 16 m sea water depth area in bays at a Rias Coast in Iwate Prefecture in December 1990.

The facility has a shelf structure of 20 m x 20 m at 4 m sea water depth layer and a machinery hut above the surface standing from the center of its shelf. The facility was loosely moored with four mooring lines. The criteria for designing the facility were to make the operation as simple as possible, to decrease the operation cost as low as possible, and to give sufficient strength and durability that neither special maintenance nor inspection is necessary.

After a pre-operation test of about 5 months, a demonstration test of the facility including the cultivation of abalones *Haliotis discus hannai* and black rockfish *Sebastes schlegeli* was carried out for about 1 year beginning in May 1991. As a result, the facility proved its capability as a stable platform for mariculture especially for a rough sea area. Since April 1992, the second phase study was started, and the entire artificial sea floor surface was filled with an abalone cultivate basket containing about 50,000 shells between 35 and 100 mm in length.

The facility was inspected periodically according to the inspection manual, and the long-term follow-up data on durability were obtained. The periodical annual surveys were carried out in August 1991 and 1992, mainly through the diving work. All of the undersea work (appearance inspection,cathodic protective potential measurement, anode volume measurement, mooring chain diameter measurement, anchor position survey, etc.) were carried out by a TV system through which the diver instructed and communicated with researching staff on board. There was no anomaly in all of the survey items, and it was confirmed that safety and durability of the facility was good as designed.

Introduction

In the bay of the Rias Coast, the seafloor is steep and deep. Therefore, sunny rocky areas suitable for growth of shells and seaweeds and the proper area for a mariculture of fishes are narrow. Also, the deep sandy or muddy bottom is not as useful for a fishing ground. In Iwate Prefecture, the coastal area is rich with rias bays. The abalone is one of the important resources for the coastal fishery, and its propagation business has been practiced for many years. However, its yield keeps decreasing year by year. The annual catch amount of abalone was approximately 1,500 tons/year 20 years ago and is around 150-200 tons now. Therefore, practical and effective countermeasures to stop the decreasing of abalone resources have been requested. One possible measure was thought to utilize the undersea space in the rias bay by constructing an artificial seafloor.

As a link in the chain of the "Aqua-Marine Plan" of Science and Technology Agency, the Japan Marine Science and Technology Center (JAMSTEC) and Iwate Prefectural Government developed a mid-layer floating type marine cultivation facility known as ARTIFICIAL SEA FLOOR with capability of submerging and surfacing. The facility named Marine-Aya No. 1 was deployed at a depth of 16 m in Ryohri-Minato Bay, Iwate Prefecture, in December 1990. Its demonstration test including the cultivation of abalone and black rockfish was carried out for about 1 year from May 1991 and its evaluation as a cultivation facility was obtained. Since April 1992, the second phase study was started, and the whole artificial seafloor surface was filled with an abalone cultivate basket containing about 50,000 shells between 35 and 100 mm in shell length.

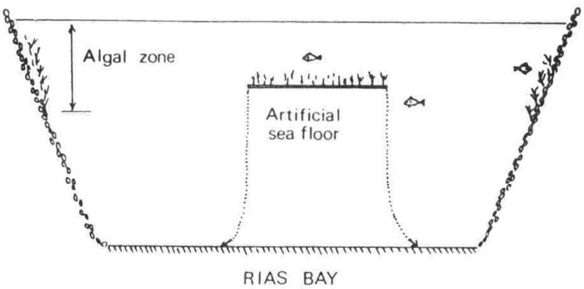

Figure 1. Conventional concept of the Artificial Sea Floor.

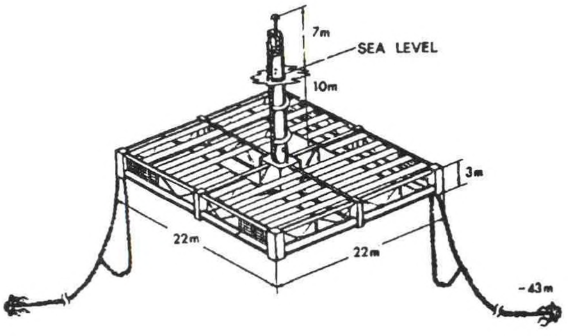

Figure 2. Artificial seaweed farm plant.

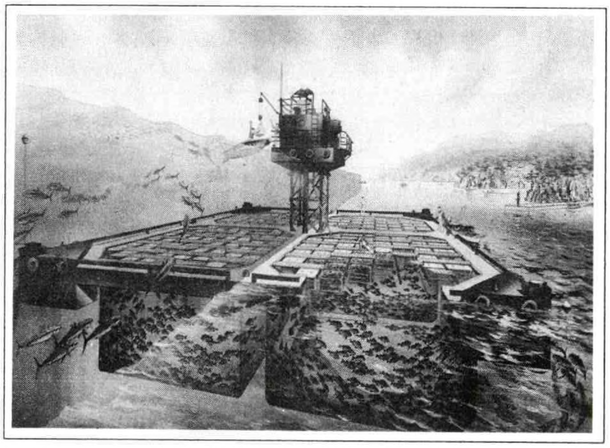

Figure 3. Concept of submersible Artificial Sea Floor, a mid-layer floating type marine cultivation facility.

The facility was designed for simple operation, low operation cost, and strength and durability for 5 years during which neither special maintenance nor inspection is necessary. To demonstrate the durability for 5 years, the facility was inspected periodically according to the inspection manual. The periodic annual surveys were carried out in August 1991 and 1992, mainly through the diving work. All of the undersea work (appearance inspection, protective potential measurement, anode volume measurement, mooring chain diameter measurement, anchor position survey, etc.) was carried out by a TV system through which the diver instructed and communicated with researching staff on board. There was no anomaly in all survey items, and it was confirmed that safety and durability of the facility was good as designed.

This paper reports the concept of the artificial seafloor, outline of the facility, the at-sea test results of it, and the inspection items and results.

Concept of Mid-Layer Floating Type Marine Cultivation Facility

The Artificial Sea Floor concept has been recognized as popular among Japanese fisheries researchers. Figure 1 shows the conventional concept of it. A flat surface at the mid-layer is created to yield seaweed by natural producing power. Animals and fishes will gather around it. A prototype of a mid-layer seaweed farm plant was installed off Tajima, Hyogo Prefecture, to conduct a feasibility study between 1979 and 1982. The farm consisted of a square steel platform 22 m x 22 m, floated at 10 m from the surface and anchored at the bottom (43 m depth) (fig. 2). An observation tower in the middle of the plant provided human passage to and out of the system. A series of monitoring surveys were carried out to ascertain the plant (Okamoto 1983a,b). The farm proved good functioning as a seaweed bed and a floating fishing reef. Nevertheless, estimated catch amounts around the farm were little compared to the high cost of building the farm.

Clearly, it is unprofitable when the artificial seafloor relies on natural producing power only. Therefore, it is necessary that the seafloor can make most of the underwater space three dimensional, can be used not only for propagation but also for culture, does not disturb the ecosystem in the installed area, and the facility is sufficiently rigid and requires a low maintenance and management cost. (Note: "Propagation" is to plan increasing resources such as recapturing of young abalone in the sea, and "culture" is to breed and feed abalone for their artificial growth).

The new concept of the artificial seafloor - mid-layer floating type marine cultivation facility - was planned as shown in figure 3. The plan is to build a structured so that the under water space can be utilized in multi-stage conditions, floated and moored in the middle layer of a sandy bottom area in a Rias Bay, and can be utilized for culture of abalone and fish. Also, it functions as a floating fishing reef, and can be utilized as an oceanographic monitoring station. The most remarkable feature is its capability to ascent the mid-layer artificial seafloor to the surface when necessary. By surfacing the floor, abalone can be fed seaweed easily without diving.

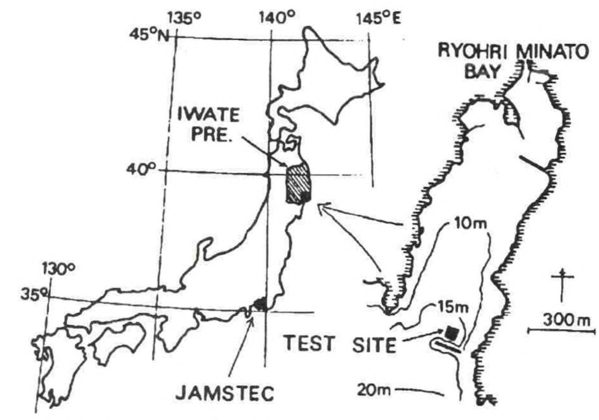

Figure 4. Location of test site.

Construction and Deployment of the Facility

Test Site

The mid-layer floating type marine cultivation facility was designed to deploy at the test site as shown in figure 4, a 16 m deep area inside the break-water at the mouth of Ryohri-Minato Bay of Sanriku Town, Iwate Prefecture. The concept design of the facility considered the sea conditions of the above sea area. To determine the depth layer of the artificial seafloor, the habitat of natural abalone around the experiment site was previously examined by diving survey. As a result, the ideal habitat depth was between 3 and 5 m; the layer of the artificial seafloor was decided to be 4 m. The artificial seafloor dimensions would be 20 m long and 20 m wide and be anchored in the sandy sea bottom with catenary-type anchors and chains.

Design Conditions

The themes in designing the artificial seafloor were to make the operation as simple as possible, to decrease the operation cost as low as possible, and to give a long life on the sea were no special maintenance and inspection are necessary, considering its usefulness and cost-efficiency as a culturing facility. In designing the facility, the following were referred to:

- Nihon Kouwan Kyoukai: Technical criteria for harbor facilities and their comments.
- Coastal Fishery Promote and Development Society: Coastal fishery arrangement/development project structure design guideline.
- Nippon Kaiji Kyoukai: Rules and regulations for the construction and classification of ships, Part C Hull construction and equipment.

The design conditions for the break-water at the mouth of Ryohri-Minato Bay were used to make the sea conditions at the test site. The diffracted waves and surpassed waves caused by the break-water were calculated to determine the design values.

- Waves: $H_{1/3}$ height 5.2 m, Period 16.1 sec (at the break-water)
- Tide speed: 0.5 knot
- Wind speed: 40 m/sec

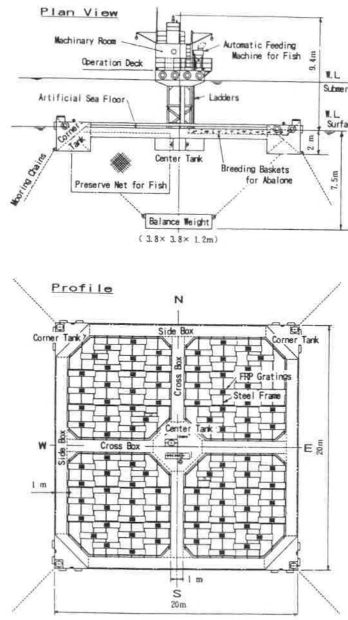

Figure 5. General arrangement of the facility.

The facility was designed to be used for 5 years, with sufficient strength and durability so that no special maintenance and inspection are necessary while placed on the sea.

Outline of Facility

General arrangement and principal particulars of the artificial seafloor facility are shown in figure 5 and table 1. The facility is a welded steel structure composed of the artificial seafloor section and an operation machinery room supported above the sea surface with struts just above the center of the seafloor section and anchored to the seafloor at four points with anchors and chains. The underwater section of the facility is protected by the aluminum alloy anodes designed for a 5-year life.

The upper face of the artificial seafloor section is a steel frame structure divided equally into four square parts that can support various experiment devices of up to about 30 tons. The artificial seafloor section and the space beneath this section can be used for mariculture.

The ballasting system is mechanically simple and easy to operate as shown in figure 6. The center tank governs submerging and surfacing of the facility. By charging or discharging about 20 tons of sea water, the position of the artificial seafloor surface switches from the submerged 4-m depth layer to the surfaced layer slightly above the sea surface. The corner tanks govern draft and attitude adjustment at the surfacing position. When the facility is built

Table 1. Principal particulars of the facility.

Length x Width x Height (overall)	:	20 m x 20 m x 11.4 m
Draft	:	Surfacing approx. 2.0 m Submerging approx. 6.0 m
Height of superstructure	:	Surfacing approx. 9.4 m
Draft adjusting capacity	:	Loading weight of up to approx. 30 tons
Time required for submerging	:	approx. 10 min.
Time required for surfacing	:	approx. 60 min.

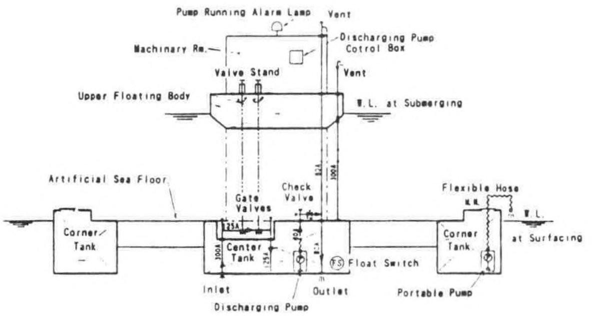

Figure 6. Piping diagram of the ballasting system.

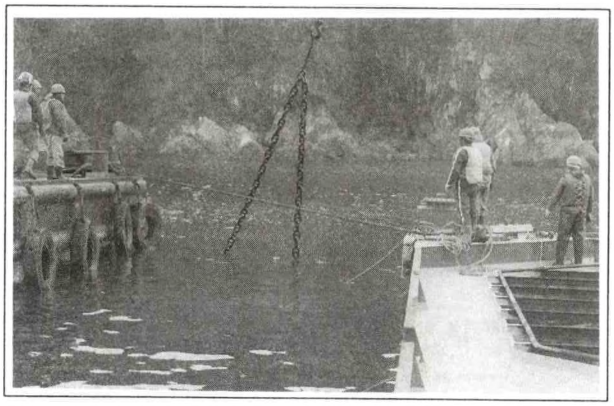

Figure 7. Mooring work.

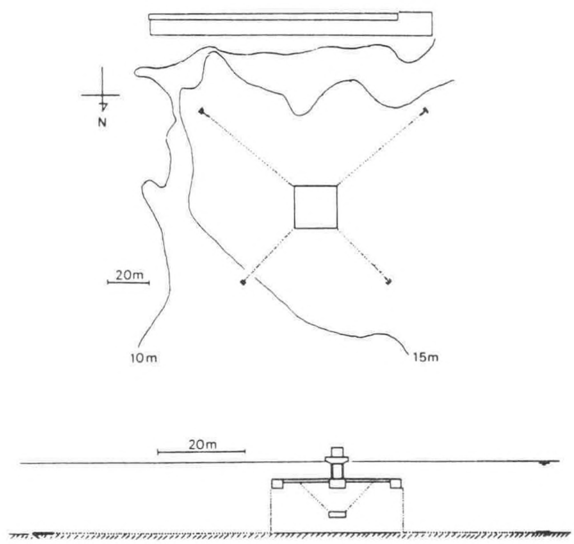

Figure 8. Mooring plan.

and just placed at the site, these four tanks are in nearly full with ballast water. However, when the unbalanced load change occurred after loading culture equipment and experiment devices, growth of bred fish, and shells or adhesive creatures, the draft and attitude of the facility can be altered easily by adjusting the water contents of these tanks.

Submerging/surfacing operation procedures of the facility are very simple. For surfacing, enter the machinery room, start the diesel generator (3.8 kVA in output), and then start the center tank discharging water pump. About 1 hour after starting the surfacing operation, the seafloor section breaks above sea surface and the pump stops automatically. For submerging, open the double flooding valves from the machinery room, and the facility will submerge through natural flooding in about 10 minutes.

Deployment at the Test Site

The artificial seafloor was built in Shiogama City, about 85 nmi from the test sea area, by Kawasaki Heavy Industries, Ltd. After completion, it was towed to Ryohri-Minato Bay and its mooring work (fig. 7) was finished in December 1990. The facility was loosely moored with four mooring lines, extended diagonally as shown in figure 8. Considering the direction of progressive waves, heavy lines are used for two mooring lines on the break-water side(south side) and light lines for two lines on the bay interior side (north side).

- South side : 4.5 t Dunforth type anchor x 1 set + 76(Gr.2) chain x 13.5 m + 40(Gr.2)chain x 41 m
- North side : 1.4 t Dunforth type anchor x 1 set + 64(Gr.2) chain x 13.5 m + 40(Gr.2) chain x 27.5 m

Results of at-Sea Test

The pre-operation test completed in April 1991 included the submerging/surfacing test (figs. 9, 10), aging of the facility, study of manufacturing/fitting method of culture baskets and culture preserve nets, etc. The first phase at-sea demonstration test of the facility was carried out for about 1 year beginning in May 1991. The following items were examined:

1) Abalone *Haliotis discus hannai* culture test;
2) Black rockfish *Sebastes schlegli* culture test;
3) Monitoring of sea conditions and atmospheric phenomena;
4) Study of floating fishing reef functions;
5) Study of maintenance/management technique; and

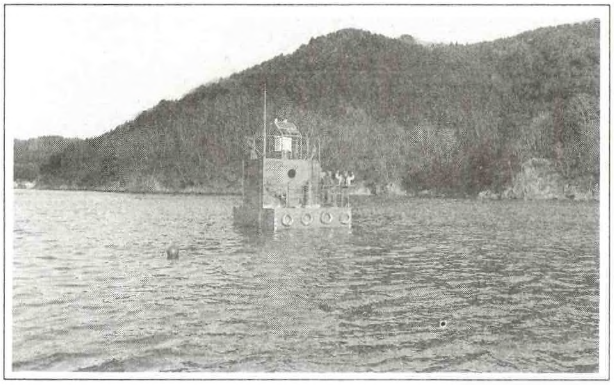

Figure 9. The facility submerging.

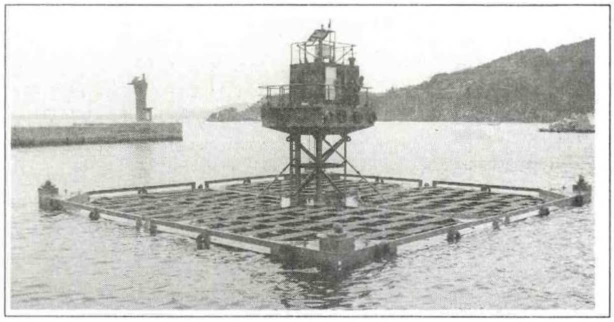

Figure 10. The facility surfacing.

6) System evaluation.

From the results of the first phase at-sea demonstration test, the features of this facility are summarized as follows:

(a) The facility is strong against waves.

In the main body and mooring system, any anomaly caused by strong winds and/or waves from typhoons or low atmospheric pressures was not recognized. The effect of normally submerging its main body in the sea was confirmed.

(b) The operation cost is low.

Since the simplified identification lamp and automatic feeding machine are powered by solar cells, they require no operation cost. The facility submerging/surfacing cost is about 1 liter of light oil used by the diesel generator for surfacing but none for submerging because of natural flooding. About 150 times of submerging/surfacing operations were performed, and the required operation cost was only about 10,000 yen (about $80) for fuel in a year.

(c) The facility is suitable to mariculture in North Japan.

As a mariculture facility, the artificial seafloor could be operated by one man and was rigid and stable in waves; therefore, work on the sea (breeding management) was very easy. Because of the low temperature and strong winds and waves in winter, work on the sea is severe in North Japan. However, by surfacing of the artificial seafloor, work can be carried out safely without the worker's body getting wet with sea water.

(d) The underwater space can be utilized three dimensionally.

Abalone and black rockfish were cultivated in one facility. In addition, various kinds of fish and shells, such as oysters and scallops, can be bred simultaneously. By cultivating many kinds of fish and shells, the artificial seafloor surface and the space beneath it can be utilized multipurposely and three dimensionally.

(e) Water quality control for bred life is unnecessary.

As the sea water flowed horizontally and vertically in the artificial seafloor, water quality around the abalone breeding basket and black rockfish breeding net was kept in a good condition, so it needs no cost compared with a mariculture facility on land. When a typhoon brought heavy rainfall, a lot of fresh water and soil flowed from the rivers into the bay. Surface sea water salinity in the whole bay decreased and was colored brown. However, since the artificial seafloor was submerged to the 4-meter-depth layer, abalone and black rockfish were not affected at all.

(f) The facility has functions of a floating fishing reef.

Young jack mackerel *Tachurus japonica,* sand launces *Ammodytes personatu*, etc., crowded in large quantities around the facility during their respective seasons and many other fishes were seen there also. As an added value, the artificial seafloor manufactured mainly for cultivation also functions as a floating fishing reef.

The most remarkable result was a possibility of functioning as an abalone cultivating facility. Abalone are cultivated with covered breeding baskets fixed to the steel frames of the artificial seafloor surface (figs. 11-13). They are fixed in positions such that their covers are slightly above the water surface when the facility has surfaced. Seaweeds such as kelps are fed every 15 to 25 days, and the artificial seafloor is surfaced to carry out this work on the sea surface. As one example, average increases of the shell length and weight in 8 months are shown in table 2. From this result, the economy of the facility was estimated fairly well even when the use is limited to breeding the abalone. It is estimated that the facility can produce about 4 tons/year (start breeding on May as 1 ton of 60 mm size and sell on next March as 4 ton of 90 mm size; price is about 13,000 yen/kg : $115/kg). The abalone were fed 2 to 5 tons of kelp every 20 days. The cost of kelp is almost negligible, because it can be produced naturally in large quantities around the Iwate area. Also, there is an easy and inexpensive cultivating method. The maintenance/management operations, such as feeding, can be carried out on the facility far more easily, safely, and effectively, compared

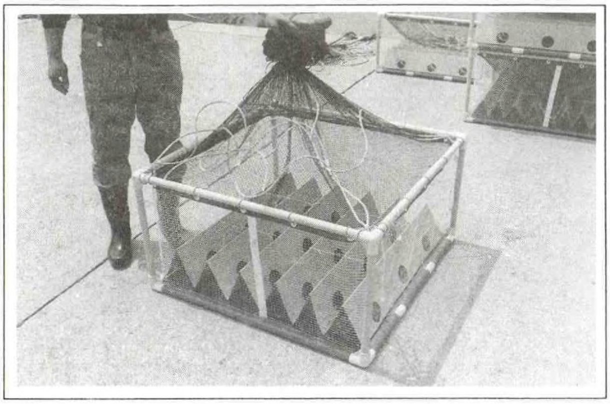

Figure 11. Abalone breeding basket.

Figure 12. Abalone in a breeding basket.

Figure 13. Fixed abalone breeding baskets.

with the operation on a boat. The management cost is lower and profitability is good. Even when 5 to 6 sets are placed for one fishery cooperative association, mass culture will be possible by managing them one set a day, in order, with two workers. The cost of the facility was 90,000,000 yen ($800,000) including deployment work.

Table 2. One example of abalone culture test.

Size class	No. of shells	5 May 1991 length (mm)	5 May 1991 weight (g)	16 Jan. 1992 length (mm)	16 Jan. 1992 weight (g)	Survival rate in 8 months (%)
30 mm	520	33.5	5.5	59.0	32.5	95.1
45	220	47.0	18.0	71.9	57.8	98.6
60	110	63.1	35.3	84.9	95.8	97.4

Table 3. The artificial seafloor routine check standards.

A. Inspection on every working day
  a. General visual inspection
    • Handrail and ladder
    • Structure (Paint, Damage)
    • Draft mark
    • Diesel generator
    • Automatic feeding instrument for fish
    • Obstruction light
B. Monthly inspection (and maintenance)
  a. Measurement
    • Draft at submerged/afloat condition
    • Time for surfacing/submerging
    • Voltage of generator
    • Voltage of battery for automatic feeding instrument
  b. Cleaning
    • Surface of solar panel
    • Cover of objection light
C. Every 3 months inspection
  a. Close visual inspection
    • Watertight integrity of manhole cover
    • Watertight integrity of objection light cover

Maintenance and Management Technology

The artificial seafloor is a large offshore steel structure and has been designed and manufactured so that it can be used for 5 years without requiring special inspection and repair. The Ships Safety Act of the Japanese Government does not apply to this facility. Since there was no precedent for the inspection method during long-term mooring, a standard had to be prepared. Therefore, the artificial seafloor maintenance/management standards were prepared, and the facility was inspected periodically on the basis of the standards. The initial data necessary for long-term follow-up data on durability were obtained.

Maintenance/Management Standards

The Artificial Sea Floor Maintenance/Management Standards were based on rules of Classification Societies (DNV 1980, NK 1991) on underwater inspection and the offshore structure maintenance/inspection techniques from

Table 4 The artificial seafloor annual surveys standards.

A.	Cathodic protection system
	a. Measurement of potential
	b. Measurement of anode volume
B.	Mooring line
	a. Measurement of position of anchors
	b. Visual inspection of chain links and eye plates
	c. Measurement of chain diameter
C.	Balance weight
	a. Visual inspection of the balance weight
	b. Visual inspection of chain links and eye plates
	c. Measurement of chain diameter
D.	Structure
	a. Visual inspection of outside of floor structure
	b. Visual inspection of inside of water ballast tank
E.	Water ballast system
	a. Visual inspection of pump, valves, and piping

Figure 15. Measurement of cathodic protection potential.

Figure 14. Measurement of chain diameter.

current literature. The Artificial Sea Floor Maintenance/ Management Standards are composed of the routine check and the annual surveys as shown in tables 3 and 4.

The routine check consists of general visual inspection on every working day, monthly check, and every 3 months inspection. The annual surveys are performed to get long-term data to confirm the safety and durability of the facility.

Results of Routine Check

More than 2 years and 7 months have passed since placing the submerging/surfacing type artificial seafloor MARINE-AYA NO. 1, and about 230 submerging/surfacing operations have been carried out. There was neither damage nor anomaly of the facility. For a while during the summer, the submerging/surfacing time tended to take longer, but after opening and cleaning the sea water piping in August 1991, the time became nearly equal to the initial values and constant. As for the draft and inclination, the water ballast was adjusted by about 200 kg in one of the corner tanks in May 1991. Abalone baskets and a black rockfish preserve net also were loaded. Since then, there has been no change in drafts and ballast re-adjustment has been unnecessary.

Results of Periodic Survey

In August 1991 and August 1992, periodic surveys were carried out mainly through diving work by JAMSTEC research divers. The underwater work was monitored by an undersea TV onboard the facility, and the inspector instructed the divers with an undersea communication system. There was no anomaly in all of the survey items, and it was confirmed that safety and durability of the facility was as good as the design. No trouble was estimated for upcoming long-term mooring (figs. 14-19).

Conclusions

The at sea-test made it clear that the submerging/surfacing type of artificial seafloor provides easy operation, safety, and low operation cost. Also, it verified that the facility was useful for mariculture, was not affected by waves and rains, and made use of marine space in three dimensions.

It is estimated that the facility could produce 3 to 4 tons/ year of abalone, working only 1 day every 2 weeks for kelp feedings. Since April 1992, the second phase, a 3-year study, was started for putting the facility to practical use. JAMSTEC, the Iwate Prefectural Government, and the Ryohri Fishery Cooperative Association are joining this study. The themes are as follows:

1) Durability demonstration of facility.

2) Study of abalone seed size selection and breeding period to increase economical efficiency.

3) Evaluation of operational and economical efficiency of facility in breeding/managing abalones on a large scale.

This study is proceeding successfully, and the artificial seafloor is filled with abalone cultivated baskets. We expect that, through development of such cooperative

Figure 16. Measurement of anode volume.

Figure 17. Measurement of anchors and artificial seafloor position.

studies, facilities like this will be placed at many. Japan Coast and effectively utilize the continental shelf spaces in the future.

Acknowledgment

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Literature Cited

Okamoto, M., 1983a. Diurnal-Nocturnal Activity of Fishes near the Artificial Seaweed Farm Plant. *Bull. of the Japanese Soc. of Scient. Fish.* 49:177-182.

Okamoto, M., 1983b. Studies on the Behavioral Character of Fishes around Artificial Seaweed Farm Plant. *Bull. of the Japanese Soc. of Scient. Fish.* 49:687-692.

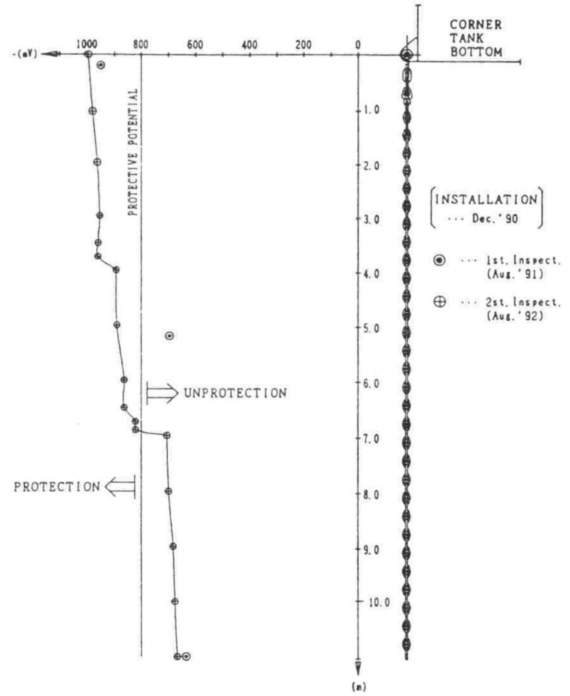

Figure 18. An example of cathodic protection potential of mooring chain.

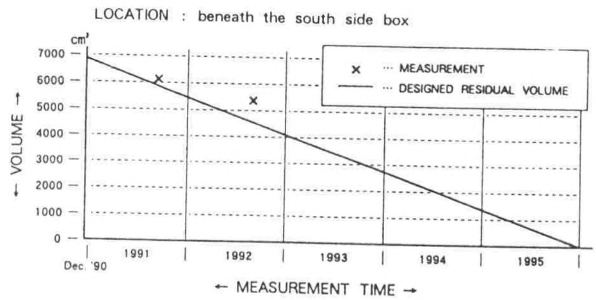

Figure 19. An example of residual volume of aluminum anode.

DNV (Det Norske Veritas), 1980. *Rules for the design, construction and inspection of offshore structures,* 1977 pp. Appendix I. In service inspection--see pp. 17-19 and 110-118. Norway.

NK (Nippon Kaiji Kyokai), 1991. *Rules for the Inspection of Vessels.* 47 pp.

Potential Risk of Dysbaric Osteonecrosis to Japanese Diving Fishermen

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Abstract

Dysbaric osteonecrosis (DON) is an important occupational health problem for helmet fishermen in Japan. DON is a form of nontraumatic bone necrosis prevalent not only in helmet divers, who breathe compressed air to harvest shellfish, but also in caisson and tunnel workers. We investigated the dive profiles of 10 helmet fishermen in the Ariake Sea (March 1993) with a dive recorder. Most divers did not use standard dive tables; they dived according to their own experience. The risk of DON to Japanese helmet fishermen has been demonstrated by surveys of diver patients and by experiments that use sheep as a model of diving fishermen. Five sheep (70-90 kg) were each subjected to a hyperbaric exposure equivalent to 17-18 meters of sea water (2.7-2.8 atm abs) for 3 hours; this is similar to the dive profiles of Ariake helmet fishermen. Mild to severe limb bends were observed in four of the five sheep after no-stop decompression. Preliminary results from these sheep experiments indicate that a significant risk of decompression sickness (DCS) and DON remains despite safer diving practices now employed by Ariake helmet fishermen. Further study is needed to design new dive procedures that will sustain the fishing industry and improve occupational safety for Japanese diving fishermen.

Introduction

Except for the breath-holding Ama divers, it is well-known that Japanese diving fishermen, especially helmet fishermen, sustain a high incidence of decompression sickness (DCS) (Amako et al. 1974). There is a high incidence of DCS manifestations in helmet, scuba, and hookah divers of the Kyushu area: 78 percent limb bends, 9 percent spinal cord DCS, 7 percent cerebral injury, and 5 percent chokes (Kawashima et al. 1991). Recently, Lehner et al. (1993) and Lin et al. (1993) reported that a high incidence of DCS, especially persistent limb bends, is strongly correlated with a high prevalence of dysbaric osteonecrosis (DON). This means that dive profiles that provoke a high incidence of limb bends also presumably carry a high risk of DON. Dysbaric osteonecrosis remains a significant occupational hazard of helmet fishermen and compressed air workers not only in Japan but also in other countries (McCallum and Harrison 1993).

With this background, we conducted research on the potential risk of DON in diving practices of Japanese helmet fishermen using the sheep model of DON. We used the sheep model (Lanphier and Lehner 1990) to investigate DON by cooperative research conducted with members of JAMSTEC, the University of Wisconsin - Madison, Tokyo Medical and Dental University, and Kawashima Orthopedic Hospital through our affiliation with UJNR, the Diving Physiology Program of UW-Madison, and NOAA.

In field investigations, the dive profiles of Ariake shellfish divers have been studied to evaluate potential risk factors in Japanese diving practices and to recommend procedures that can prevent DON and DCS. Diving fishermen in the Ariake Sea area were selected because of their high prevalence of DON and because there are about 400 helmet fishermen accessible in the area. The prevalence of DON exceeded 50 percent in these fishermen during the 1970's (Kawashima et al. 1977).

This study was designed to evaluate the potential risk factors of DON in Japanese diving practices. The overall goal of this study is to modify diving practices so that

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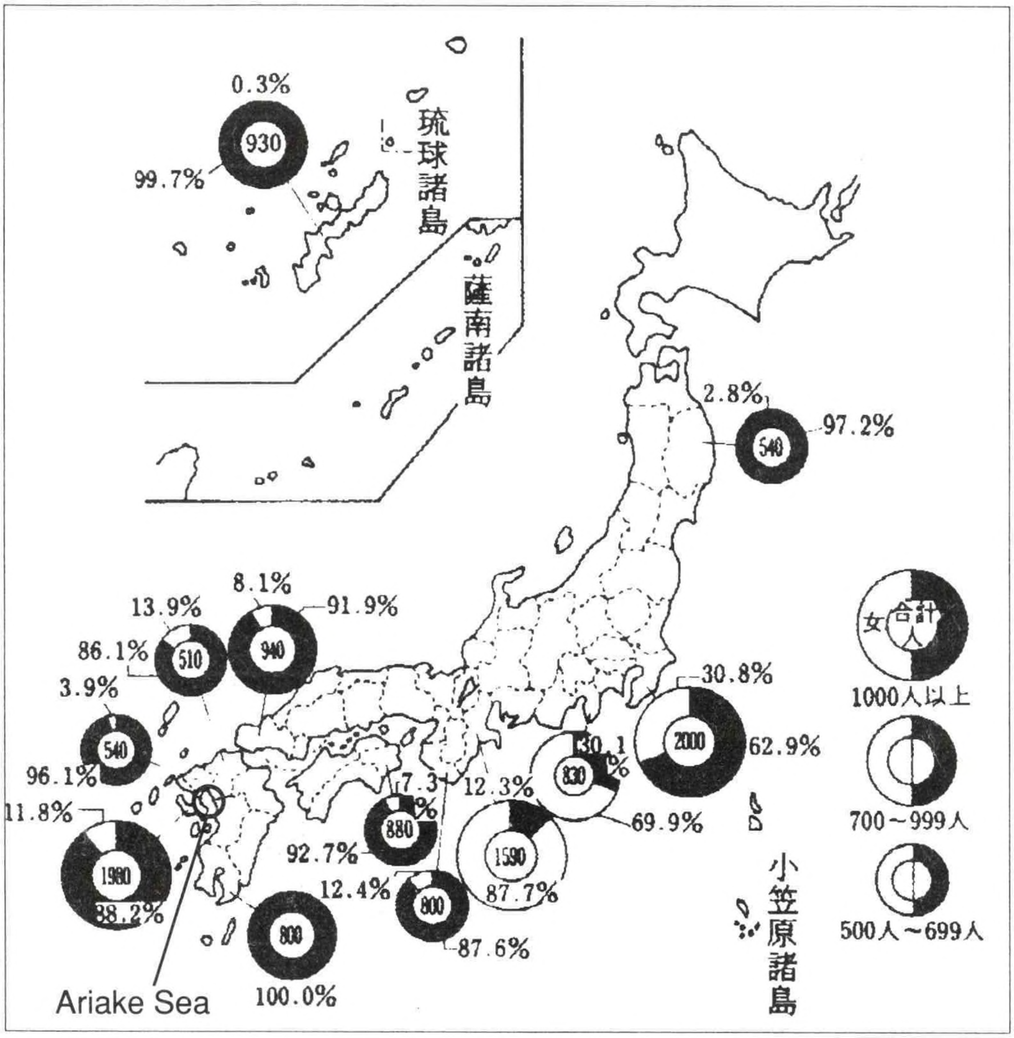

Figure 1. Distribution of professional divers in Japan in 1986. (Modified and reproduced with permission from Takeuchi and Mohri 1987)

diving fishermen and compressed air workers will have lower risk of DON and DCS and can successfully harvest shellfish.

Shellfish and Seaweed Divers in Japan

Figure 1 shows the geographic distribution of professional divers in Japan in 1986. There were approximately 16,600 divers (13,000 male and 3,600 female) who collected shellfish, seaweed, and fishes. About 37 percent of these divers used compressed air: 17 percent with scuba, 10 percent with helmet, and 10 percent with hookah equipment (Takeuchi and Mohri, 1987).

Diving methods vary according to locality. Typically, the helmet diving technique is used to collect the pen shell *(Atrina pectinata)* in the Ariake Sea of the Saga Prefecture and to collect sea urchins in the offshore waters of Hokkaido. Scuba diving is mainly used to collect edible fishes in the Niijima Island group east of Tokyo and from the shores of the Okinawa Prefecture. Hookah is mainly used to collect seaweed along the Izu Peninsula of the Shizuoka Prefecture and from the Okinawa Prefecture.

Clinical Histories and Dive Profiles of Ariake Divers

In 1991, we surveyed 83 Ariake helmet fishermen to gather each individual's clinical history and dive profiles. Table 1 shows the clinical histories of reported DCS from interviews of 83 Ariake shellfish divers. Thirty-two divers reported symptoms of limb bends in their diving. Five divers reported only incidents of chokes or CNS-DCS but no limb bends symptoms. Twenty-one divers reported symptoms of both limb bends and chokes or CNS-DCS. Of the 83 divers surveyed, 58 divers or 70 percent reported DCS symptoms in their diving.

Table 1. Reported DCS among 84 Ariake shellfish divers in 1991.

	N	Percentage
DCS		
Limb bends (Type 1)	32	39
Chokes, CNS (Type 2)	5	6
Type 1 & 2	21	25
No DCS	25	30
Total	83	100

Table 2. Diving experience and reported DCS of Ariake divers.

Experience (years)	N	Divers with DCS				NO DCS
		Limb bends	Chokes	CNS	Type 1&2	
1 - 5	11	2	—	—	—	9
6 - 10	13	7	1	—	2	3
11 - 15	16	8	1	—	3	4
16 - 20	14	7	—	2	3	2
21 - 25	22	5	—	1	9	7
26 - 30	6	3	—	—	3	—
38	1	—	—	—	1	—
Total	83	32	2	3	21	25

Table 3. Dive profiles of Ariake divers: from past to present.

	1970 - 1975 (N=15)*	1985 - 1990 (N=15)*	1992 - 1993 (N=14)**
Maximum Depth (meters)	45.4 ± 14.1 (57 - 15)	22.6 ± 9.6 (48 - 10)	17.3 ± 2.5 (20.4 - 13.7)
Bottom time (minutes)	200.0 ± 75.6 (360 - 90)	189.0 ± 47.1 (360 - 180)	200.4 ± 10.1 (219 - 184)

*Reported data; **Data from dive recorder. Values, mean ± S.D.

Table 2 shows the years of diving and the reported DCS among Ariake divers. In the group of least-experienced divers who have dived for 1 to 5 years, 2 of the 11 divers reported limbs bends, and 9 reported no DCS. In the most experienced group, divers with 16 to 20 years of diving, 12 of the 14 divers had reportedly sustained DCS. An increased number of reported DCS cases correlates with the years of diving experience.

Dive profiles used by Ariake divers are shown in table 3. From 1970 to 1975, the reported typical dive profile used by Ariake divers was deep and prolonged. Reported maximum depths reached 57 meters, and maximum bottom times were as long as 360 minutes. Recently,

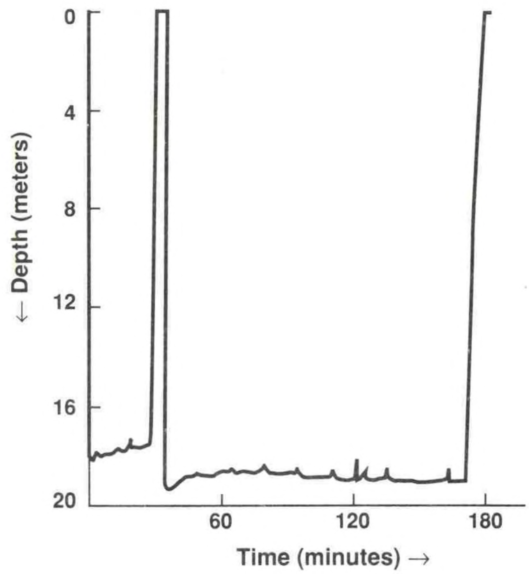

Figure 2. Dive profile of a helmet fisherman in the Ariake Sea, March 1993.

diving profiles of the Ariake divers have become more shallow, and bottom times have decreased.

Figure 2 illustrates a typical dive profile now used by Ariake helmet divers. The diver was a 38-year-old male who had dived for 20 years. In this profile, he dived to a depth between 18 and 19 meters for 170 minutes and used no-stop decompression. According to the U.S. Navy Standard Air Decompression Table (70 feet, 170 min), he should have taken two decompression stops, one at 6 meters for 19 minutes and another at 3 meters for 79 minutes. However, he dived according to his own experience and did not use conventional decompression tables.

The diver reported that the seawater temperature was low, approximately 10°C. He also reported that he had difficulty tolerating the severe cold at the end of his dive. If the diver had used decompression stops, he would have experienced additional hypothermia. Cold seawater temperature is a factor that controls the duration in dive profiles and limits decompression times of these helmet fishermen. Fortunately, this dive was uneventful, without any clinical symptoms of DCS. Such dive profiles are, however, associated with a high incidence of DCS as pointed out by Kawashima et al. (1991) and Mano et al.(1991) in previous reports of these Proceedings. Such dives also carry a high risk of DON (Lehner et al. 1991).

Hyperbaric Experiments with Sheep

The risk of DON to Japanese helmet fishermen has been extensively demonstrated in long-bone x-ray surveys of divers and by recent diving physiology experiments which used sheep as a surrogate of the diving fishermen. Experi-

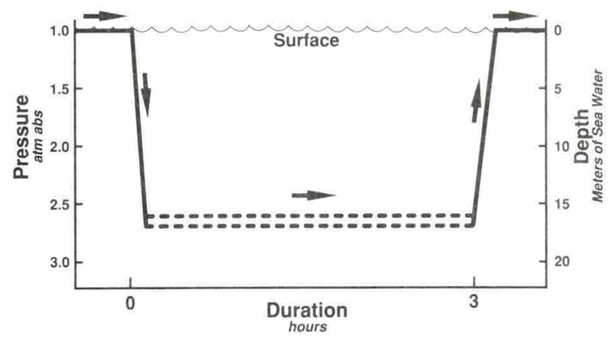

Figure 3. "Dive" profile of sheep experiments.

Table 4. Development of limb bends signs in a sheep after a 3-hour hyperbaric exposure (2.7 atm abs).

Sheep	Limbs	Predive	1 hr	2 hr	3 hr	4 hr	24 hr
#1126	RF	0	1	1	1-2	3-4	2
	LF	0	0	0	1	2-3	1
	RH	0	1	2	3-4	4	3
	LH	0	1	1	3-4	3-4	1

Limbs: RF, Right fore; LF, Left fore; RH, Right hind; LH, Left hind.

Graded clinical signs of limb bends: 0, negative; 1, possible; 2, mild; 3, moderate; 4, sustained lift.

ments that induced both DCS and DON in sheep were conducted with the pressure chamber in the Biotron, University of Wisconsin-Madison.

Five crossbred female, 4-year-old sheep (70 to 90 kg) underwent a single 3-hour exposure to maximum pressures of 2.7 to 2.8 atm abs with compressed air. These pressures are equivalent to 17-18 meters of sea water. The dive profile simulated in the sheep experiments is shown in figure 3. The compression rate was 6 m/min and decompression was rapid but less than 10 m/min. The air temperature in the pressure chamber was approximately 24°C. This profile closely matched the pressure and duration of recorded dive profiles of Ariake helmet fishermen that were investigated in March 1993 (fig. 2).

Diagnostic Methods and Results

Sheep were observed for clinical signs of limb bends for more than 24 hours after decompression. Four of the five sheep developed limb bends signs after a single, 3-hour hyperbaric exposure.

Table 4 shows the development of limb bends signs in one sheep (#1126) that experienced a 3-hour hyperbaric exposure at a pressure of 2.7 atm abs. She showed definite signs of limb bends, in all 4 limbs, after decompression. Intermittent episodes of mild to sustained lifting of her limbs were frequent and persisted for more than 24 hours.

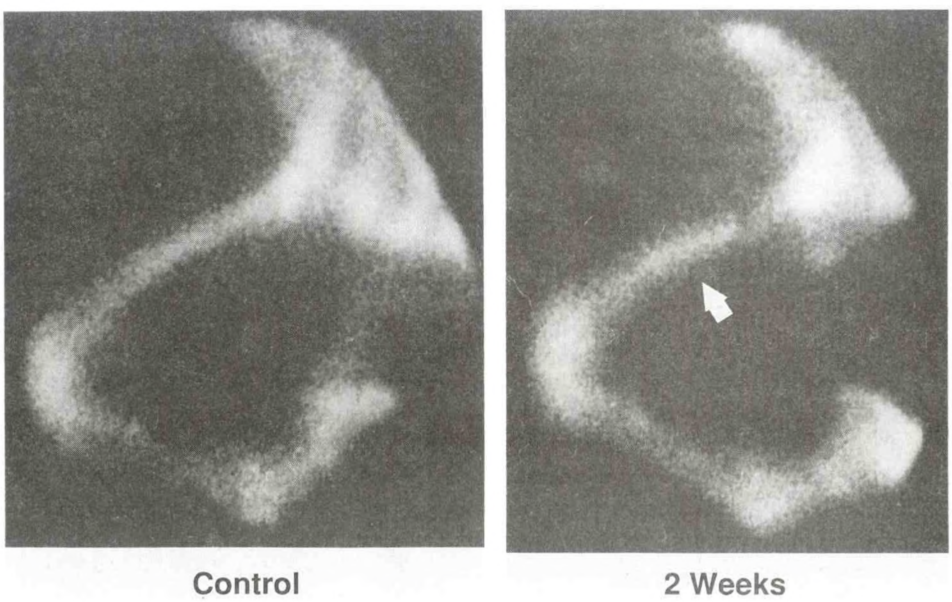

Figure 4. Bone scans of a sheep (#108) right radius with a mild "hot spot." This "hot spot" indicates that a dysbaric osteonecrosis lesion developed within 2 weeks after hyperbaric exposure.

In addition, non-invasive bone scintigraphy with ^{99m}Tc-methylene diphosphonate was used to evaluate the condition of the distal long bones, the radius and tibia. Scintigraphy was performed before hyperbaric exposure, and 1 day, 2 weeks, and 7 weeks after the hyperbaric exposure. Figure 4 shows bone scans of the right radius of a sheep (#108) that underwent a 3-hour hyperbaric exposure at a pressure of 2.8 atm abs. Bone scans conducted 2 weeks and 7 weeks after decompression indicated that the sheep developed a mild "hot spot" that signified an early DON lesion.

Discussion

Bone scans qualitatively indicate the rate of bone mineralization and, indirectly, the rate of bone blood flow. "Hot spots" indicate a high rate of bone blood flow associated with lesions and active bone repair in early DON. Mild DON, which was induced after a simulated dive profile, indicates the potential risk of DON developing in Ariake helmet fishermen who experience similar dive profiles.

While there have been numerous attempts to produce DON in experimental animals by rapid decompression from a high pressure, much of this research has been carried out in small animals. These results have been inconsistent and difficult to extrapolate to the human diver. McCallum and Harrison (1993) pointed out that the more convincing model for the study of DON would be the exposure of large animals to compressed air repeatedly over weeks or months. However, in this study single 3-hour exposures of sheep to 2.7 to 2.8 atm abs produced many cases of mild but persistent limb bends and induced comparatively mild DON lesions in sheep long bones. We view sheep to be a suitable animal model for the study of DCS and DON because of the similarities in body weight and long bone size in adult sheep and humans.

Conclusions

Preliminary results from sheep experiments suggest that a significant risk of DCS and DON remains during the shellfish harvesting by Ariake helmet fishermen despite safer diving practices now being used. The high incidence of persistent limb bends in sheep also points to a potentially significant risk of DON with the dive profiles employed by Ariake shellfish divers. Further study with sheep is needed to improve diving safety and to recommend diving procedures designed to lower DCS and DON risks. Furthermore, there is an important need to improve the diving safety education for young helmet fishermen.

Literature Cited

Amako, T., M. Kawashima, T. Torisu, and K. Hayashi, 1974. Bone and joint lesions in decompression sickness. *Seminars Arthur. Rheum.* 4: 151-190.

Kawashima, M., H. Tamura, K. Takao, T. Tsunosue, Y. Mano, Y. Taya, C.E. Lehner, and M. Kitano, 1991. Decompression sickness and dive profiles. *Proceedings of the 11th Meeting of the United States-Japan Cooperative Program in Natural Resources (UJNR), Panel on Diving Physiology and Technology. September 1991, Hakone, Japan*, pp. 61-84.

Kawashima, M., K. Hayashi, K. Torisu, M. Kitano, 1977. Histopathology of the early stages of osteonecrosis in divers. *Undersea Biomed. Res.*, Vol. 4, pp. 409-417.

Lanphier, E.H., and C.E. Lehner, 1990. Animal models in decompression. In: Y.C. Lin and K.K. Shida (eds.), *Man in the Sea*, Vol. 1, pp. 273-295. San Pedro, CA: Best Publishing Co.

Lehner, C.E., E.H. Lanphier, M.A. Wilson, M. Kawashima, M. Kitano, Y. Mano and Y. Taya, 1991. Dive profiles control the risk of dysbaric osteonecrosis: Validation in Japanese diving fishermen and sheep. *Proceedings of the 11th Meeting of the United States-Japan Cooperative Program in Natural Resources (UJNR), Panel on Diving Physiology and Technology. September 1991, Hakone, Japan*, pp. 85-101.

Lehner, C.E., T.F. Lin, E.H. Lanphier, M.A. Wilson, M.D. Markel, and R. Dueland, 1993. Prolonged hyperbaric exposure, persistent limb bends, and early recompression treatment in dysbaric osteonecrosis. *Undersea and Hyperbaric Medicine*, Supplement, Vol. 20, p. 21.

Lin T.F., C.E. Lehner, E.H. Lanphier, M.A. Wilson, M.D. Markel, and R. Dueland, 1993. Prompt recompression of sheep with limb bends prevents the development of dysbaric osteonecrosis. *Undersea and Hyperbaric Medicine*, Supplement, Vol. 20, p. 20.

Mano, Y., M. Shibayama, M. Kawashima, Y. Taya, M. Mohri and C.E. Lehner, 1991. Recent diving profile of shellfish divers at Ariake Sea. *Proceedings of the 11th Meeting of the United States-Japan Cooperative Program in natural Resources (UJNR), Panel on Diving Physiology and Technology. September 1991, Hakone, Japan*, pp. 124-132.

McCallum, R.I., and A.B. Harrison, 1993. Dysbaric osteonecrosis: Aseptic necrosis of bone. In: P. Bennett, and D. Elliott (eds.), *The Physiology and Medicine of Diving*, 4th Edition, pp. 563-584, London, W.B. Saunders Company.

Takeuchi, H. and M. Mohri, 1987. Current status of diving fishermen in Japan - Distribution, age and diving method. *Japanese J. Hyperbaric Medicine*, Vol. 22, pp. 227-234.

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