Tiny Bubbles: A Primer On Doppler Bubble Detection

By R.Y. Nishi

A considerable amount of interest recently has arisen in Doppler ultrasonic bubble detection and its application to decompression research and diving operations. As a result, some misunderstandings exist about the role of bubbles that the Doppler instruments can detect and the relationship between Doppler-detected bubbles and decompression illness (DCI). Although many mechanisms may be associated with DCI, the most probable initiating factor is still believed to be the formation of bubbles. Early decompression studies suggested the presence of "silent bubbles" that did not result in DCI signs and symptoms, and considerable research was conducted in detecting bubbles with ultrasound. The Doppler ultrasonic bubble detector is the simplest, most convenient and most practical method for observing bubbles in humans. However, it can only detect intravascular bubbles, i.e., bubbles moving through the circulatory system, and it requires skilled personnel to use and interpret the bubble signals.

A History of Doppler

Decompression researchers have used Doppler ultrasonic bubble detection as a tool for almost 25 years. Its origins go back to 1968 when two groups of researchers, Spencer and Campbell (working with sheep) and Gillis, Peterson and Karagianes (working with pigs) reported detecting decompression-generated bubbles with Doppler flowmeters. In 1968 Spencer reported the first detection of bubbles in humans. In 1970, the Spencer Precordial Bubble Detector was developed expressly for detecting decompression-generated bubbles (available from the Institute of Applied Physiology and Medicine (IAPM), Seattle, Wash.). This instrument was designed to monitor blood-flow in the heart's right ventricle or in the pulmonary artery. Spencer and Johanson devised a grading and coding scheme for classifying bubbles, based on a scale from 0 to 4.

Due to its potential for decompression studies, a number of researchers soon adopted the Doppler technique. For example, Pilmanis found that "no-decompression dives" could produce high levels of bubbles and that a short safety stop was effective in reducing bubbles. In Japan, the Doppler ultrasonic bubble detector was used extensively for monitoring compressed air workers as well as divers. Spencer conducted an extensive study on no-decompression (no stop) dives with divers in both hyperbaric chamber and in the open ocean. This work was later used by Huggins to develop the Michigan Sea Grant no-decompression repetitive dive tables and the algorithm for the EDGE dive computer. Although Huggins' No-D table has become commonly known as the "No-Bubble Tables," Huggins actually used Spencer's limits for bubble formation.

In France, Guillerm and Masurel of the French Navy carried out considerable work on Doppler bubble detection. Together with the Institut National des Sciences Appliquees in Lyon, they developed better instrumentation and transducers for bubble detection. (The precordial bubble detector that was developed was later marketed by Sodelec S.A. of Marseilles.) In 1978, Kisman from Canada's Defense and Civil Institute of Environmental Medicine (DCIEM), who was developing a computer program to detect and grade bubbles, went to France to work with Masurel. Together, Kisman and Masurel developed a

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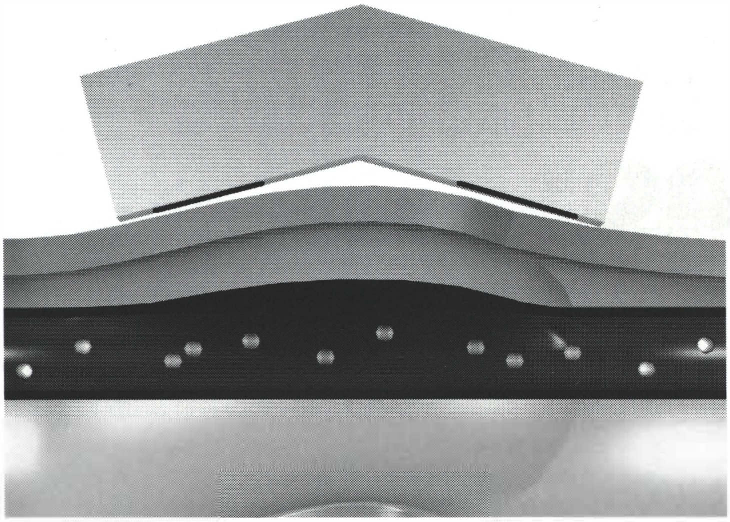


Illustration by: Michael Bielinski

more comprehensive bubble grading scheme that was believed to be much easier to learn than the Spencer Code and that could also be adapted easily for use for computer grading of bubbles.

Research at DCIEM included both theoretical and experimental studies into bubble detection and the scattering and absorption of ultrasonic waves by bubbles. Considerable work was done in developing a computerized method for detecting and grading bubbles. In 1979 DCIEM embarked on an extensive program using the Doppler method to assess decompression models, profiles and diving techniques. This work led to the development and validation of the DCIEM air diving tables and the just-completed helium/oxygen diving tables. Because of a need for a highly reliable and readily available Doppler instrument, DCIEM was also involved in the development of a precordial Doppler ultrasonic bubble detector (manufactured by Techno Scientific Inc., Woodbridge, Ont.).

In recent years, there has been a resurgence in the use of the Doppler bubble detectors for monitoring divers and evaluating dive profiles, particularly in the recreational and scientific diving communities. For example, studies conducted by DAN have shown that typical sport diver profiles can result in detectable bubbles. Doppler was also used in testing the new DSAT/PADI dive tables for multi-dive, multi-day diving. Recent work by Eckenhoff and colleagues on shallow air saturation dives has been directed at obtaining a better understanding of the fundamental mechanisms of bubble formation and decompression in humans. Doppler bubble detection has also been used at altitude for aircrew and in space.

Measurement Techniques

The most common location for monitoring bubbles in humans is the chest (precordium), either the pulmonary artery or the right ventricle of the heart. Ultrasonic waves are transmitted into the blood flowing in these locations, and any bubbles present in the flow can be detected as echoes among the background noise produced by the red blood cells and other particles in the blood. Theoretically, since the entire venous system drains into the right ventricle, any decompression-generated bubbles should be detected at this location. In practice, however, not all bubbles can be detected. For example, sometimes bubbles can be detected in the subclavian veins in the shoulders when none are detected in the chest. There are several reasons for this. The bubbles must be large enough so that the reflected ultrasonic waves from the bubbles can be detected over the background blood flow signal. Echoes from smaller bubbles will be lost in the background signal. The background signal is very complex and noisy and consists not only of the signals from blood cells but also from any moving surface within the sound field. This can include the motion of the heart walls and heart valves. Some of the sounds, notably from the valves, may be quite similar to that from bubbles. The subclavian veins, on the other hand, are superficial veins, and the background is relatively quiet. Thus, it is easier to detect bubbles in these locations. Detecting and classifying bubbles with the Doppler ultrasonic bubble detector requires extremely skilled and well-trained observers.

Because not all bubbles can be detected in the chest, it is necessary to look at other locations in the body. With the Kisman-Mansurel method used by DCIEM, both the right and left subclavian veins (shoulders) are always monitored in addition to the chest. Other locations such as the femoral vein or inferior vena cava can be monitored, but the minimum should be the chest and the two subclavian veins.

Monitoring is done for two conditions: first, with the diver standing at rest and second, after the diver performs some specific movement. For chest monitoring, the diver performs a deep knee-bend, squatting, then rising again. For the subclavian veins, the diver clenches the fist, then relaxes the hand on the side being monitored.

Previously available Doppler bubble detectors (IAPM, Sodelec and the early versions of the TSI units) operated at 5 MHz. At DCIEM, it was found that with the 5 MHz units it was sometimes difficult to obtain good signals, particularly with large individuals, and that a slight shift in the position of the probe could mean the difference in whether bubbles were detected. DCIEM is now using 2.5 MHz instruments manufactured by TSI. The use of the lower frequency results in less attenuation of the signal by the tissue mass between the bubble and the transducer and in a slightly broader beam width, which makes probe placement less critical.

The Kisman-Masurel code

The method Kisman and Masurel developed for identifying and classifying bubbles consists of breaking the bubble signal into its component parts. The diver is monitored for bubbles while standing at rest, then after performing a specific movement. If bubbles are present, the movement condition generally increases the number of bubbles swept into the circulatory system. The signal is first analyzed by determining the bubble frequency, i.e., the number of bubbles per cardiac period. This is graded on a scale of 0 to 4, 0 representing no bubbles, and 4 representing so many bubbles that they cannot be individually distinguished. The signal is then analyzed, once again on a scale of 0 to 4, for the percentage of cardiac cycles containing bubbles for the rest condition, or for the duration, i.e., the number of cardiac cycles with elevated bubble signals, after the movement condition. Finally, the signal is analyzed for the amplitude of the bubble signal relative to the amplitude of the background blood flow signal.

The three parameters—frequency, percentage/duration and amplitude—are then combined into a three-digit code that can be translated into a bubble grade on a scale of 0 to 4 similar to the Spencer scale. Although the KM method may appear to be complicated, it is in fact much simpler to learn, because it treats bubble grading as a systematic procedure. With practice, an individual can classify the three parameters simultaneously and immediately assign the three-digit KM code to the signal.

Doppler Monitoring

The objective of Doppler monitoring is to obtain a history of bubble production for each subject after a dive. For most non-saturation dives, bubbles are not observed until about a half hour after the diver has been on the surface. Delays of an hour or more have also been noted; thus a single monitoring of a dive subject is not sufficient and could result in bubbles being missed. As it is not possible to monitor a single individual continuously, measurements are taken periodically at 20- to 40-minute intervals for at least a two-hour period after the diver surfaces. In stressful dives, bubbles can be observed as soon as the divers surface, and in some cases, the bubbles have been observed to persist at high levels for more than six hours after surfacing.

During the 1970s, the Doppler technique fell into some disfavor, as it became evident that large numbers of bubbles could be detected in many cases with no indication of DCI. In addition, DCI was found to occur in some cases with no detected bubbles. (The latter may have been a result of poor instruments, poor techniques, inadequately trained users, and not looking in the right place or at the right time. In much of the earlier work, bubble monitoring was carried out only once after a dive.) Thus, the original hope of using the Doppler as a diagnostic tool for predicting DCI was not borne out.

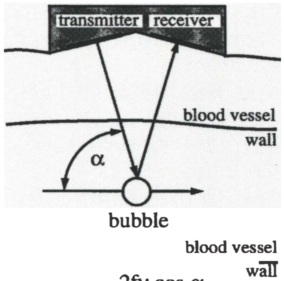
Another early hope for the Doppler bubble detector was as a personal decompression monitor to control decompression by listening to the bubbles at the decompression stops. Although bubbles can be detected at the stops for dives requiring substantial decompression, bubbles generally tend to become observable only after the diver has reached the surface. Thus, a Doppler bubble detector is not practical as a personal decompression monitor. In addition, the skill and training required for identifying bubbles would rule out its use for most individual.

Bubble-DCI Correspondence

Several surveys of Doppler data have shown a relationship between intravascular bubbles and DCI. Many of these studies were based on relatively small data sets; however, they all show that the risk of DCI increases with increasing bubble grades. DCIEM has amassed a considerable amount of Doppler data since 1979. This data has been reviewed and analyzed by D. Sawatzky of DCIEM, who selected a data set consisting of 73 cases of DCI in 3,234 man-dives (1,726 man-dives on air/nitrox and 1,508 man-dives on helium/oxygen breathing mixtures) conducted over an 11-year period. All bubbles were classified according to the Kisman-Masurel code.

Figure 1 shows the relationship between percentage DCI and precordial bubble grades observed in the chest for divers standing at rest. For air/nitrox dives, the inci-

WHAT IS A DOPPLER BUBBLE DETECTOR?



$$\Delta f = \frac{2fv \cos \alpha}{c}$$

Named after 19th-century physicist Christian Doppler, Doppler's principle states that the frequency of an observed sound is different from that emitted by the source whenever the observer and the source are moving relative to one another. The classic example of this is an observer standing at a railway crossing waiting for a train to pass. As the train approaches the crossing, the engineer blows the whistle. To the observer, the whistle changes from a high-pitched sound as the train approaches to a lower-pitched sound as the train passes and recedes into the distance.

In the Doppler ultrasonic bubble detector (DUDB), a transmitting element radiates sound at a constant frequency into a blood vessel (see diagram). Sound waves are reflected back by red blood cells. Because the blood cells are moving, the reflected waves, as picked up by the receiving element, are shifted in frequency (Doppler effect). This frequency shift depends on the frequency of the transmitted wave (f), the velocity (v) of the reflecting objects, the angle (a) between the transmitted wave and the direction of motion, and the velocity of sound (c). In fact, the DUDB is actually a flowmeter, which can be used to measure the flow velocity in, for example, blood vessels or pipes.

A gas bubble passing through a blood vessel is a "hard" reflecting object compared to the blood cells due to the differences in density and velocity of sound between the gas and the blood. Thus a bubble produces a significantly higher echo (depending on the size of the bubble) than the background echoes from the blood cells.

Small bubbles may not be detected, because the echoes, although much larger than those from blood cells, may be overwhelmed by the background signal consisting of the combined echoes scattered back by the millions of red blood cells that may be surrounding the bubble. Also contributing to the background signal is the Doppler shift from any other moving object within the sound field, such as pulsating blood vessel walls and, if monitoring in the heart, the movement of heart valves.

Typically, a DUDB operates at a nominal frequency of 2.5 or 5 MHz. Instruments that have been designed for decompression research such as the Techno Scientific DUDB are continuous wave (CW) instruments. (CW instruments are generally less expensive, less complicated and easier to use than pulsed Doppler systems.) The DUDB output is the difference in frequency between the transmitted and received waves. This frequency difference is in the audio range and can be picked up easily using a set of high-quality headphones.

dence of DCI is very low for Grade 0 (no bubbles) or Grade 1 bubbles. The risk of DCI increases when bubbles at the Grade 2 or higher levels are observed. In the data set, only one of three subjects was on air/nitrox and one of two subjects was on helium with Grade 4 bubbles. Grade 4 bubbles in the chest with the diver at rest are rare, unless the dive profiles are extremely unsafe. All previous studies have also shown that the risk of DCI in these cases is extremely high.

Figure 2 shows the relationship between percentage DCI and precordial bubble grades after movement (deep knee-bend). The movement condition is convenient, because it generally results in a temporary increase in the number of bubbles observed. For example, some individuals with Grade 3 bubbles at rest may have Grade 4 bubbles after movement. For this data set, Grade 4 bubbles were observed in 37 subjects for air/nitrox dives and 132 for helium dives resulting in a 14% and 10% incidence of DCI.

The data presented in Figures 1 and 2 suggest that when bubbles are present, the risk of DCI is higher for

Of the 3,234 dives in the DCIEM data set presented here, 55% had observable bubbles. Of these, only 4% had DCI. Thus, intravascular bubbles are not a good indicator of which individual will develop DCI. However, almost all the cases of DCI (72 out of 73) were accompanied by bubbles. Therefore, if no bubbles are detected, the risk of that individual developing DCI is extremely low.

air/nitrox dives than for dives conducted using helium/oxygen breathing mixtures. A problem in trying to correlate DCI with precordial bubbles is that DCI sometimes occurs without any precordial bubbles being observed. In this data set, there was a 0.6% incidence of DCI for both air/nitrox and helium dives (7/1,164 subjects and 6/945, respectively) when no bubbles were detected. It should be noted that not all bubbles can be detected in the precordial region. If all sites are considered (the chest and both left and right subclavian veins), and if the maximum bubble grades are observed regardless of site and condition used (i.e., rest or movement), the results show that only one case of DCI (out of 1,442 subjects) had no observable bubbles. Thus DCI is almost always accompanied by bubbles. This shows the importance of monitoring other body sites in addition to the chest.

Figure 3 shows the percentage DCI results for the maximum bubble grades observed (regardless of location or condition). When the maximum score is considered, it can be seen that the risk of DCI is low for Grades 0, 1, and 2 bubbles and that Grades 3 and 4 have a much higher risk. Over 90% of the cases of DCI were associated with Grades 3 or 4 bubbles.

It should be emphasized that intravascular bubbles are not believed to be the direct cause of the signs and symptoms in all cases of DCI. They are, however, an indicator of a high inert gas load in the body. As a result, their presence reflects the risk of DCI.

Decompression Stress

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Fig. 1. DCS vs. Maximum Bubble Scores
Precordial Bubbles at Rest

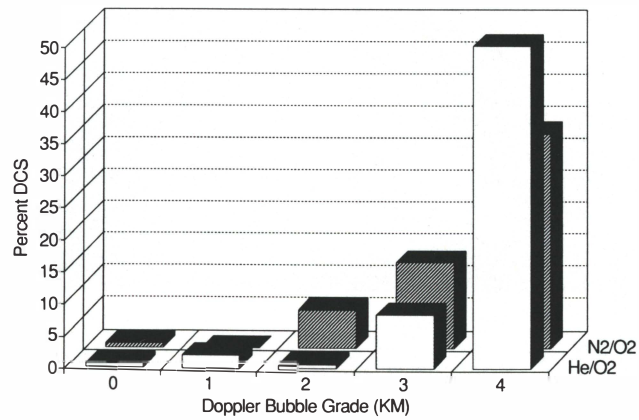


Fig. 2. DCS vs. Maximum Bubble Scores
Precordial Bubbles after Movement

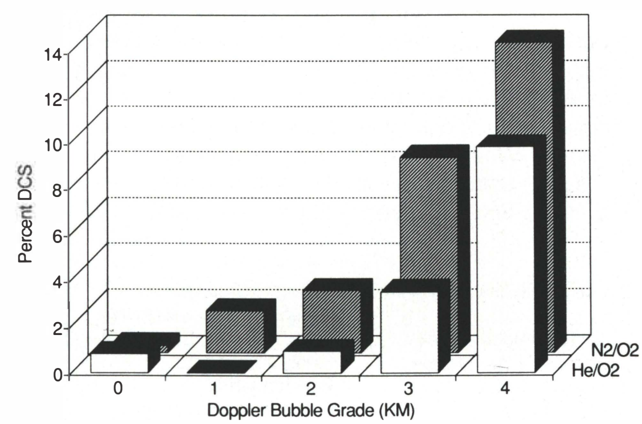
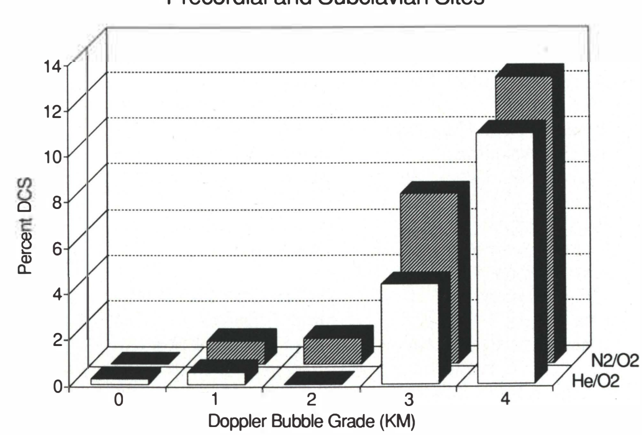


Fig. 3. DCS vs. Maximum Bubble Scores
Precordial and Subclavian Sites



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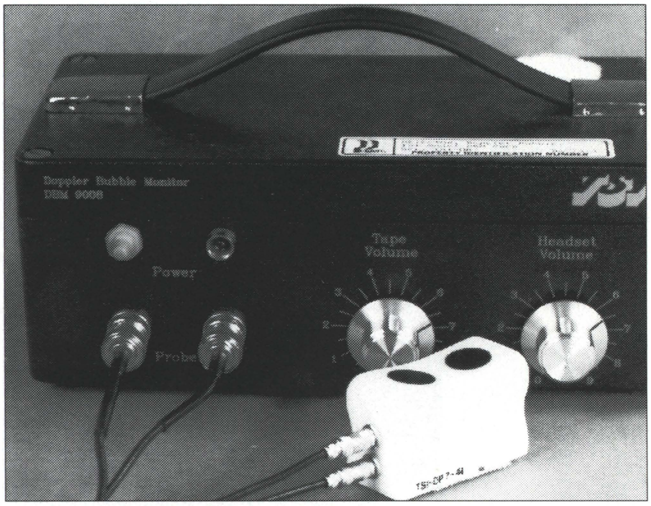
The primary use of the Doppler ultrasonic bubble detector is as a research tool for post-dive assessment of dive profiles. The traditional approach to developing and



evaluating dive tables or profiles has been based on the occurrence or non-occurrence of DCI. From the statistical point of view, proving the safety of dives using DCI as a criterion with any degree of confidence would require more dives than are normally feasible. Moreover, the diagnosis of DCI can be quite subjective. Since intravascular bubbles occur far more frequently than DCI and can be detected even in safe dives, the Doppler ultrasonic bubble detector can provide for more information to assist in the assessment of the severity of the dive profile.

We can speak of "decompression stress" as a criterion for safety. Dives that produce many observable bubbles will have a high risk of DCI and, therefore, high decompression stress. Conversely, dives which produce no

We can speak of "decompression stress" as a criterion for safety. Dives that produce many observable bubbles will have a high risk of DCI and, therefore, high decompression stress. Conversely, dives which produce no observable bubbles or few bubbles will have a very low risk of DCI and low decompression stress.

observable bubbles or few bubbles will have a very low risk of DCI and low decompression stress. In evaluating dive profiles, it is no longer necessary to "bend" divers to know whether the dive profiles are acceptable. (Note the use of the term "observable." The fact that bubbles cannot be detected with the Doppler ultrasonic bubble detector does not necessarily mean that bubbles are not present.)

Simple criteria for estimating the acceptability of dive profiles can be established based on the number of subjects displaying high bubble grades. For example, one criterion to reduce the risk of DCI to less than 5% could be that less than 50% of the subjects have bubble scores of Grades 3 and 4 based on the maximum score observed from all sites and all monitoring conditions (see *Figure 3*). Several complicating factors are the variation in response among different subjects. As with DCI, some subjects are more susceptible to developing intravascular bubbles than others. Also, individual divers can respond differently to similar dive profiles on different days. Thus it is important that a sufficient number of man-dives be carried out on each profile to be tested.

Personal Profiles

Can the Doppler ultrasonic bubble detector be used for personal diving? As described earlier, it cannot be used as a personal decompression monitor to control the rate of decompression. However, there may be a potential for post-dive use. If high bubble levels are detected after a dive, there may be a high risk of DCI, and such dives should be avoided or modified in the future to reduce the risk. With high bubble levels, perhaps some precautionary action could be taken, such as breathing surface oxygen. The movement condition shows that the number of bubbles can increase temporarily; hence, excessive physical exertion should be avoided for several hours after a stressful dive. With high levels of bubbles, the bubbles can persist for many hours after the dive, so flying after diving should be delayed longer than normal. With high bubble levels, the diver should remain in the vicinity of others and remain alert to the possibility of DCI symptoms. It is important that signs or symptoms of DCI not be ignored because no bubbles or only a few bubbles were detected.

The major problem with the use of Doppler for personal diving is the training required to use the instrument correctly and to be able to interpret the Doppler signal to detect and grade bubbles if they exist. It requires a high degree of skill, aptitude and considerable practice working with an expert before any degree of proficiency is acquired. Without this training and skill, there is a great danger of misuse of the instrument and misinterpretation of the signals. Although considerable research has been conducted into automatic systems for bubble detection and analysis, none have been successful because of the complexity of the Doppler signal. Instruments such as the Farallon MacRecorder for the Apple Macintosh, which allow digitization of the Doppler signal and provide an audible and visual representation of the signal, may assist in identifying bubbles but are too simple to be used for automatic bubble detection and classification. Bubble identification and classification are still best done by the human brain.

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Suppliers of doppler ultrasonic bubble detectors

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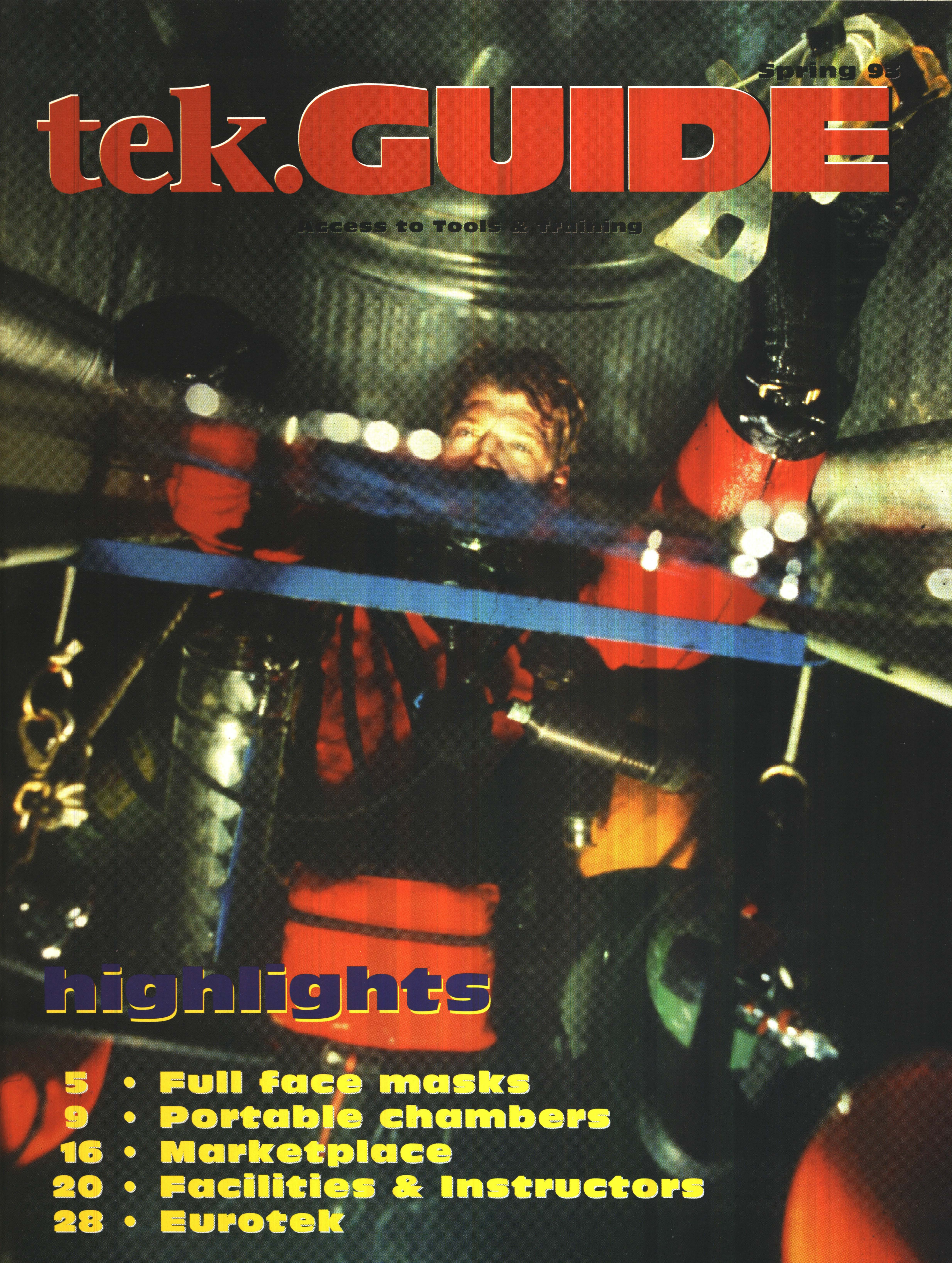
Woodbridge, Ontario Canada L4L 5Y9

Institute of Applied Physiology and Medicine
701-16th Avenue
Seattle, Washington, USA 98122

Sodelec S.A.
31 Traverse Prat
Pointe-Rouge
13008 Marseille, France



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