Reports

Some Principles of Self-Contained Underwater Breathing Apparatus

With the increasing use of self-contained underwater breathing apparatus in archeological collection work, geological and petroleum prospecting, and biological collecting, diving equipment has taken on real importance as a scientific tool. Numerous techniques have evolved to make diving units easier to breathe from so that divers can make longer work or exploratory dives and so that neophytes will be less likely to suffer lung fatigue. This report (*1*) presents a brief résumé of some of the principles of existing apparatus along with concepts leading to more advanced forms. The principal emphasis is on "open circuit" equipment in which air is inspired from a high-pressure tank and expired into the surrounding water. In such cases the compressed air is also an energy source, which allows incorporation of certain forms of regenerative feedback leading to easier breathing.

Such equipment uses a regulator which feeds the diver air at a pressure just equal to that of the surrounding water. In essence, a regulator is a box with a flexible side which activates an internal valve. If the air pressure within this box is reduced to below that of the surrounding water, then the valve will be opened by the diaphragm, thus allowing air from the high-pressure cylinder to enter the box, until the equality of internal and external pressure is returned. Through a hose, the diver breathes from this box. When he exhales, his breath travels through the other hose attached to the mouthpiece or mask and out through a one-way valve which is positioned close to the diaphragm. If the outlet (for example, a "Bronx cheer") is $\frac{1}{2}$ in. from the diaphragm, then the tension in the valve is set so that slightly more than $\frac{1}{2}$ in. of water vacuum must be produced in the diver's mouth before air will be fed, or else, in some diving positions, air will spontaneously stream from the regulator and out through the exit valve. Other factors being the same, single-stage regulators tend to breathe more easily, while two-stage regulators tend to give more uniform breathing difficulty as the tank pressure drops.

If a small collapsible bag is attached to this air system, then as one breathes out, a few hundred cubic centimeters of the breath are saved and will be the first air to be inspired on the succeeding breath, of which it makes up only a fraction of the total (the rest being supplied by the regulator). Some of the early observations on such a method should be credited to C. Lambertson. The advantage to be obtained by such a partial rebreathing process in practice is not simple to predict and seems to decrease with active work.

If one builds a unit from which it is easy to breathe on land, one will still inevitably find that there is an appreciable amount of work required to draw in a breath when one is below the surface of the water and in the usual face-down position. Because the diaphragm is then situated above one's lungs, the air that one must inspire is at a slightly lower pressure than the average water pressure on the lungs. When a diver is on his back the pressure differential is in the opposite sense, and one's lungs have no greater strength to work against such pressure differentials, so the strain is again appreciable. Most people have little concept of the relative weakness of their breathing apparatus compared with typical small hydrostatic forces (*2*). One can effectively locate the regulator within the lungs and obtain normal equally easy breathing in all positions by loading the diaphragm of the last-stage regulator with a suitable weight (Fig. 1). This weight must supply a force to the diaphragm that a column of water extending between the diaphragm and the center of the chest will exert. A diaphragm-sized weight's thickness is thus approximately half the chest thickness divided by the specific gravity of the weight material. The weight can be supported by the linkage and then, depending on whether the weight pushes or pulls on the diaphragm, the regulator must face toward or away from the person; the direction it faces will be reversed if the regulator is worn on the chest rather than upon the back. If a regulator is oriented so that the weight's line of motion passes through the center of the lungs, then it can be compensated though fixed to some part of the body other than the center of the back. Such a unit allows perfectly free inspiration under all conditions, but in one set of positions the effort in exhaling will be as difficult as it is with an uncompensated unit. Voiding the air into a lower-pressure reservoir such as a branched arrangement of tubes pointing in several directions, each with a one-way valve at its far end, can do away with even this slight inconvenience. The effect of separation of regulator and outlet valve by this procedure can be overcome by making the outlet slave-controlled by diaphragm motion, besides having its normal one-way action. There can then be no leakage of air or water in any position. A closed circuit (rebreather) unit can be similarly compensated with a weight, and in this case there is no outlet valve. Questions of hunting because of the extra mass included in the feedback loop, or of difficulty in obtaining a sudden breath because of diaphragm inertia, prove experimentally unfounded in a reasonable design.

The action of a regulator can be im-

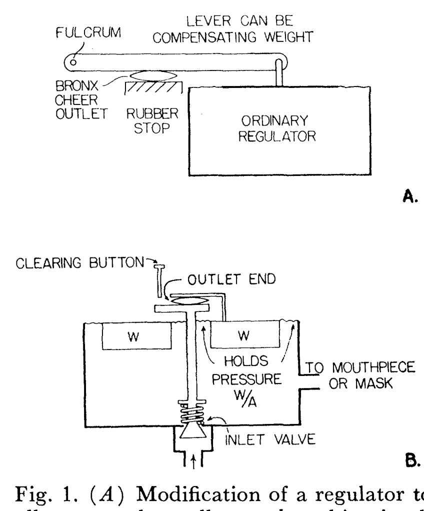

Fig. 1. (*A*) Modification of a regulator to allow normal equally easy breathing in all positions. Bending the end of the "Bronx cheer" is found to seal it more easily than clamping or compressing. (*B*) Configuration that allows the inclusion of a clearing button to expel water accidentally entering the unit, and which insures that one valve will close before the other opens. A lever is not needed if the area of the outlet is considerably less than that of the diaphragm.

Instructions for preparing reports. Begin the report with an abstract of from 45 to 55 words. The abstract should *not* repeat phrases employed in the title. It should work with the title to give the reader a summary of the results presented in the report proper. (Since this requirement has only recently gone into effect, not all reports that are now being published as yet observe it.)

Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to Contributors" [*Science* 125, 16 (1957)].

proved by positive feedback which brings about increased air flow by the act of starting to pass air. If the feedback factor is made high enough so that the loop gain in this system is greater than or equal to unity, then the system will become bistable (3)—that is, a small suck will bring about a self-perpetuating air flow that will persist until back pressure builds up. No effort is involved in breathing in the intermediate condition. Limited positive feedback makes breathing easier, but the use of hysteresis or bistability requires further experiment to determine whether, due to nonlinearity in muscle response, it may not take more work to start and stop a self-perpetuating flow than to produce a steady vacuum in the usual fashion. However, human muscles do seem to be able to give a short intense effort more readily than a weaker prolonged one. Methods of producing the bistability (feeding air or not feeding air) include constructing the diaphragm in the fashion of an oil-can bottom, spring-loading the linkage as in a toggle switch, shaping the valve seat so that opening gives an increasing area to produce an increased opening force, or the use of a Venturi tube in which air flow reduces the pressure applied to the diaphragm, thus sucking it in. By analogy with the generation of a nerve impulse, or the action of monostable multivibrator, one can visualize another type of unit in which a bistable regulator is returned after a short interval to its original off state by some auxiliary process such as a slow leak into the main chamber from the high pressure region.

Breathing can be made easier by eliminating impedance to flow through the inclusion of the hoses in the feedback loop. For any such configuration two essentially isolated chambers are involved. For example, sucking, via one hose, could cause the diaphragm to move in and feed air into and from the second hose until the pressure backs up through both. One exhales into and from the chamber containing the diaphragm through the first hose.

One problem of deep diving might be touched upon. It is necessary that the partial pressure of oxygen at all depths be roughly within a factor of ten above normal at the surface in order to avoid either oxygen deficiency or poisoning. In discussion, M. Bradner suggested storing oxygen in a hemoglobin-like material which would always then maintain the surrounding partial pressure constant at the equilibrium value. The extra pressure, to match that in the surroundings, would be supplied through a regulator by a high-pressure cylinder of helium or nitrogen which would have to supply gas only during descent, and thus could be small. Alternatively, a mixed-gas apparatus could either receive oxygen from a pressure-insensitive, constant-flow-rate device, or else an oxygen-detecting element could be used to control the flow. For a detector, for example, one might employ the output voltage of a fuel cell (4). H. Bradner has suggested that oxygen content might be controlled by the mechanical changes in size of certain chelates or else by the output voltage of any oxygen-depolarized battery. Alternatively, one could control oxygen flow by monitoring the generation of carbon dioxide.

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References and Notes

1. This work was supported in part by a grant from the Schussler Fund. The weight-compensated regulator was previously described in *Seafarer* [1, No. 2, 3 (1954)].
2. R. S. Mackay, *Am. J. Phys.* 16, 186 (1948).
3. ———, *ibid.* 26, 60 (1958); *J. Appl. Phys.* 25, 424 (1954).
4. *Chem. and Eng. News* 35, No. 38, 25 (1957).

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Preservation of Whole Blood in Frozen State for Transfusion

Abstract. Addition of sugars to whole citrated human blood permits freezing and thawing with recovery of a large percentage of erythrocytes. Survival of erythrocytes thus frozen, transfused without further modification after thawing, has been satisfactory after 6 months of storage at $-93°C$.

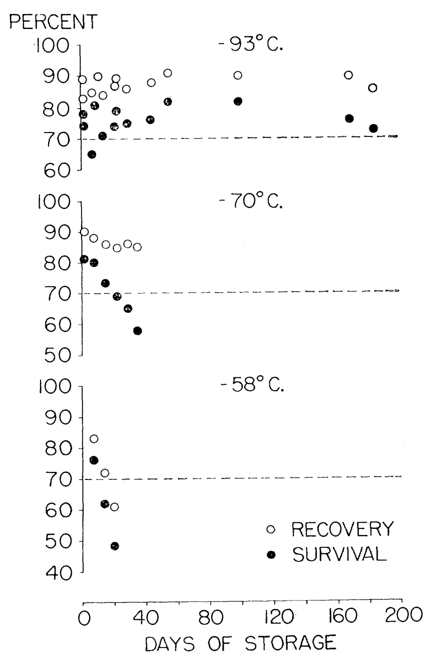

Fig. 1. Effect of temperature of storage on recovery and survival of frozen human erythrocytes. Each solid circle represents a transfusion.

Hemolysis due to freezing of erythrocytes at temperatures below $-3°C$ (*1*), followed by thawing, may be avoided to a considerable extent by ultra rapid freezing (*2*) or by modification of freezing with the addition of glycerol (*3*).

In the study described in this report (*4*) modification of erythrocytes to prevent hemolysis has been obtained with varying concentrations of dextrose and lactose, alone or in combination. Modification consists in mixing equal parts of acid-citrated blood with the sugar solution to obtain a $0.2M$ concentration of lactose, a $0.7M$ concentration of dextrose, or an additive molarity of 0.6 with both sugars. The length of modification is not critical, and periods of 5 to 270 minutes have given similar results.

Modified blood is frozen in flat containers made of thin aluminum or tin-plated copper, measuring inside 3 mm in thickness, by immersion, in CO_2–ethanol mixture at -60 to $-78°C$. Thawing is obtained by immersion in a water bath at 37°C. Optimally the time of cooling and freezing, from $-3°$ to $-40°C$, and the time of thawing must not exceed 10 seconds.

The results of freezing and thawing of erythrocytes will be expressed as "recovery" and "survival." By "recovery" is meant the number of intact red cells remaining after freezing and thawing; "survival" indicates the amount of radioactivity of frozen, stored, thawed, and transfused red cells remaining in circulation in the recipient 24 hours after transfusion, as determined with the Cr^{51} tagging technique. The values reported as survival include all losses occurring in vitro and in vivo. Blood has been transfused within 1 hour of thawing, without any further preparation.

Without use of sugars the recovery of human erythrocytes frozen and thawed with the technique described averages 29.3 percent. With the modification of freezing obtained with sugars the average recovery rate is optimally about 95 percent. The 24-hour survival of erythrocytes in five transfusions of human whole blood frozen and thawed without appreciable period of storage is only 2 percent below the optimal established for fresh, autotransfused erythrocytes; the curve of disappearance of erythrocytes after the first 24 hours parallels that of fresh cells.

The recovery and posttransfusion survival of erythrocytes of whole blood frozen as described and stored in the frozen state depend on the temperature of storage. With storage at $-58°C$, both rate of recovery and rate of survival deteriorate rapidly, as shown in four transfusions (see Fig. 1). At $-70°C$, the rate of recovery is fairly well maintained for about 40 days, but the survival in six transfusions deteriorates progressively