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DEPTH LIMITS OF BREATH HOLD DIVING (AN EXAMPLE OF FENNOLOGY)[1,2]

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Abstract. It is generally accepted that the depth to which a breath hold diver can descend is determined by the ratio of the RV to the TLC. If the diver descends farther, it is predicted that he would develop a "thoracic squeeze" as the intrathoracic pressure became less than the ambient pressure. The fact that divers have gone to depths at which the lung volume must have been less than 20% of the surface volume suggests that some mechanism other than a decrease of the thoracic cage to RV must occur. The subject in the present study started each dive after expiring maximally. He was able to go as deep as 4.75 m without the development of a significant difference between the esophageal pressure and the ambient pressure at depth, both measured and recorded directly. These experiments indicated that the gas volume must have been compressed from the subject's RV of 2.0 litres to 1.4 litre. It is suggested that this change of 600 cc could be due to a shift of blood from the peripheral to the central circulation. This additional mechanism of gas compression would help explain man's demonstrated ability to dive to 65 m.

Breath holding
Central blood volume
Free diving
Thoracic squeeze

It is generally believed that the depth to which a breath hold diver can descend is limited by the ratio of the subject's residual volume to the total lung capacity (RV: TLC) (SCHAEFER, 1965; CORRIOL, 1966). RAHN (1965) has defined the problem more accurately as the ratio of non-compressible: compressible air containing spaces. The non-compressible spaces include the volumes of the diving mask, mastoid air cells, middle ear, sinuses, airway as well as the RV.

As the diver descends the lung volume and, in fact, the volume of all the air containing spaces must be compressed to maintain pressure equalization. If gas compression does not occur, pressure differences between the air containing and the fluid filled parts of the body will be created. The usual result of such pressure differences is engorgement of small vessels, rupture, and extravasation of blood, a process com-

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[2] Fennology is herein defined as that branch of science in which practical problems are explained in terms of physical and physiological mechanisms (FENN, 1931, 1957).

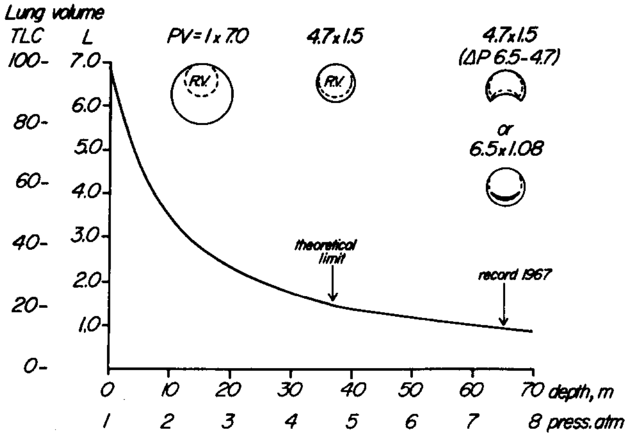

Fig. 1. Pressure volume relationships during breath hold diving. The ordinate indicates lung volume as % TLC or as liters for a hypothetical diver whose TLC is 7.0 litres. The theoretical limit as indicated by an arrow is defined by the RV: TLC. At the depth of the present record 2 alternatives are considered. One indicates the development of a transthoracic pressure difference of 1.8 atm, which would kill the diver, the other further gas compression by blood.

monly known as "the squeeze". If the diver descends to a depth at which the lung volume is less than the non-compressible space, it is predicted that he would experience a "thoracic squeeze" which might result in hemoptysis. These considerations are shown graphically in fig. 1.

According to these ideas it is apparent that the maximal depth of a breath hold dive would be 40 m for a subject whose RV was 20% of the TLC.

This depth in meters can be defined as $\{(\mathrm{P_B} \times \mathrm{TLC/RV}) - \mathrm{P_B}\}10$ where PB is expressed in atmosphere and 10 represents the depth equivalent in sea water of 1 atmosphere. Table 1 indicates that for a number of years breath hold divers have been going to depths at which the lung gas volume must have been less than what would be considered normal for RV. The physiologist finds himself in the embarrassing position of being proven wrong by the sports divers.

A solution to this dilemma was indirectly suggested by FENN (1960). He reminds us that "every problem, I have found, is basic if the investigator puts some basic thinking into it."

Assuming, then that Boyle's law applies, the relationship between gas volume and depth as illustrated in fig. 1 must obtain. As the diver descends, the size of the thoracic volume can change with compression of the thoracic cage and elevation of the diaphragm. This mechanism of pressure equalization can account for the diver's ability to go to a depth at which the air volume would equal the RV. Below this depth the RV is virtually non-compressible. We have been unable to express more than 200 cc of air either by external pressure to the chest, abdomen, or both simultaneously after a subject has expired maximally.

TABLE 1

Year	Diver	Depth, meters	Gas vol., % surface volume
1951	Falco and Novelli	35	22.2
1952	Bucher	39	20.4
1956	Falco and Novelli	41	19.6
1960	Santarelli	43	18.9
	Maiorca	45	18.2
	Santarelli	46	17.9
	Maiorca	49	16.9
1966	Mayol	60.4	14.2
1967	Croft	64.8	13.4

Another mechanism which might account for further gas compression in the thorax is a shift of blood from the peripheral to the central circulation. If, as the diver continues his descent the gas volume is not compressed by a change in the thoracic volume, the intrathoracic pressure would become less than the ambient pressure. As the other parts of the body are completely fluid systems, the pressure in the peripheral circulation follows the ambient pressure. Therefore, there would be a pressure gradient which would shift blood from the peripheral to the central circulation.

In order to test this idea, it was necessary to prove that a diver could go deeper than can be accounted for by the RV: TLC without incurring changes in transthoracic pressure which might result in hemoptysis. With the facilities and the subjects available it was not feasible to conduct dives to 40–64 m. However, it was possible to start the dive after the subject had expired maximally to his RV. If the transthoracic pressure differences were independent of depth, pressure compensation must have occurred by a mechanism other than further compression of the thorax.

Methods and results

The RV of the subject used in these experiments had been measured by the 3 breath method (Rahn, Fenn and Otis, 1949) on numerous occasions in air and in water over a period of at least 2 years and was known to be 2.0 litres (BTPS). Transthoracic pressure was measured as the pressure difference between a balloon strapped to the lateral thoracic wall 20 cm below the level of the 1st thoracic vertebral spine and an esophageal balloon. The pressure at each site was recorded. The difference in the output of each pressure transducer was also recorded directly on the third channel of a polygraph.

Before each dive the subject hyperventilated and breathed 100% O_2 during the last 3–4 breaths. These procedures were necessary as the breath holding time at RV is considerably less than the 30 sec which was desired for the dive (Mithoefer, 1965). In addition, if the subject had started after breathing room air, the $P_{A_{O_2}}$ would have

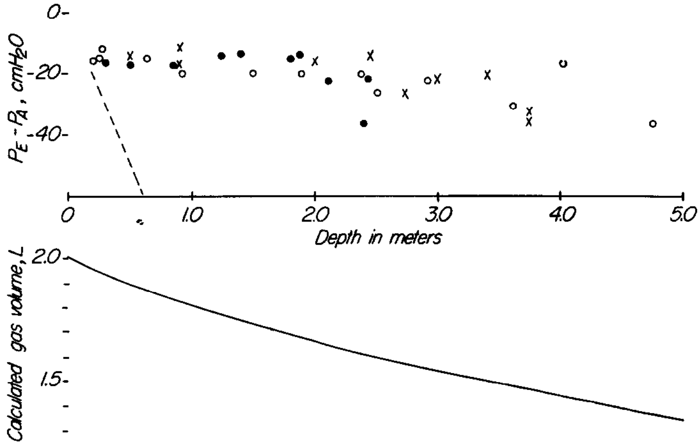

Fig. 2. Observed transthoracic pressure differences during three different series of dives are shown in the upper part. The circles indicate dives performed in two different pools, the crosses in a lake. PE indicates esophageal pressure, PA ambient pressure as measured in the external balloon. In the lower part the calculated change in gas volume in this subject whose lung volume at the beginning of the dive was RV and equal to 2.0 litres is indicated.

been dangerously low at the end of the dive (CRAIG, 1961a, b; LANPHIER and RAHN, 1963).

Each dive was made feet first to avoid the complication of the effect of changing position on the pressures measured (HONG, TING and RAHN, 1960). Descent was assisted by holding weights.

Several series of experiments were carried out. At first the dives were performed cautiously in the laboratory tank the depth of which was only 1.5 m. As no pressure differences at this depth with very rapid descents were noted, the equipment was moved to a swimming pool. Here it was possible to descend to 2.5 m, and as indicated in fig. 2, the transthoracic pressure difference was independent of depth. By using another pool it was possible to dive to 3.75 m, and in a local lake to 4.75 m.

Again the pressure differences were independent of depth. If gas compression had not occurred, the pressure difference would have varied with the depth as indicated by the dashed line in this figure. If gas compression could occur to a limited degree but no further, transthoracic pressure differences would still be described by the slope of the dashed line but it would move to the right on the abscissa.

The actual records from two dives are shown in fig. 3. The upper half of each record indicates the pressure in the external balloon which is also a measure of the depth. The lower part shows the pressure difference between the two balloons. Before the dive these pressure differences reflected the respiration. The pen failed to record the pressure during the maximal expiration which preceded the dive but quickly indicated the negative intrathoracic pressure as expected with relaxation (RAHN *et al.*, 1946). The pressure differences were the same whether the diver was at 1 m as shown in the top record or 3.75 m as in the bottom one. The small fluctuations during the dive re-

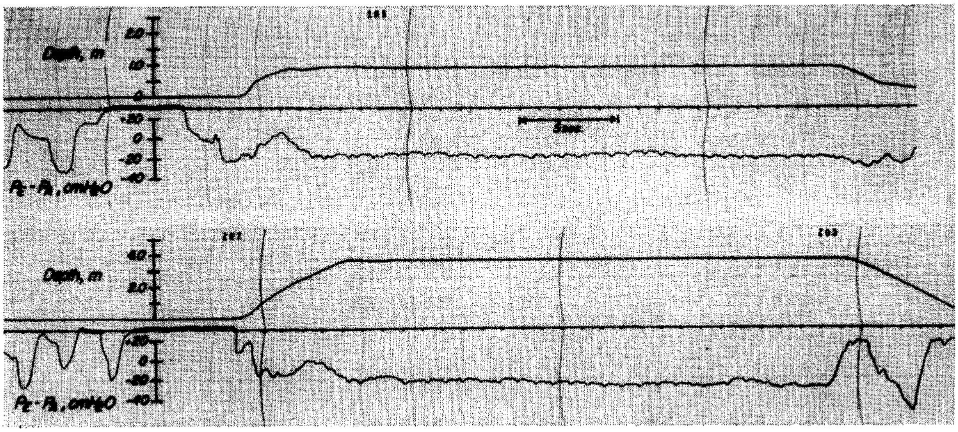

Fig. 3. Direct photographs of 2 records during dives. The upper half of each shows the pressure (expressed as depth) in the balloon strapped to the lateral thoracic wall. The lower part is the record of the pressure difference between the outer and the esophageal balloon.

flected pressure changes secondary to cardiac action (BLAIR, WEDD and HARDWICKE, 1942). The calculated change in gas volume during these dives in which there was no change in transthoracic pressure with different depths is indicated in the lower half of fig. 2. At 4.75 m the beginning gas volume of 2.0 litres must have been compressed to at least 1.4 litre, a difference of 600 cc. This calculation neglects the possibility that the gas volume was probably even less as the V_{O_2} leaving the alveoli would be greater than the V_{CO_2} exchanged during this time (LANPHIER and RAHN, 1963; CRAIG and HARLEY, 1968).

Discussion

Fig. 4 illustrates the implications of a gas compression of 600 cc below the RV in a diver whose TLC is 7.0 litres and whose RV is 1.5 litre. To descend from 37 m where the gas volume would be equal to RV to 64 m which is the present depth record (NEW YORK TIMES, Feb. 9, 1967) would require a shift of 570 cc of blood from the peripheral to the central circulation. From another point of view our diver who went to 4.75 m starting at RV was "physiologically" deeper than the present record.

The present demonstration that the gas volume in the lungs can be compressed to considerably less than the RV does not in itself prove that the mechanism is a blood shift. On the other hand such changes in blood volume between the peripheral and the central circulation seem the most likely explanation.

OSHER (1950) noted that the vital capacity decreased transiently as the subject went from the erect to the supine position. In some individuals this amounted to as much as 530 cc and was probably due to a sudden shift of blood from the dependent portions of the body. FENN *et al.* (1947) calculated that during positive pressure breathing blood could be displaced from the lungs. In their tallest subject, identified as RAHN, as much as 830 cc entered the lower part of the body.

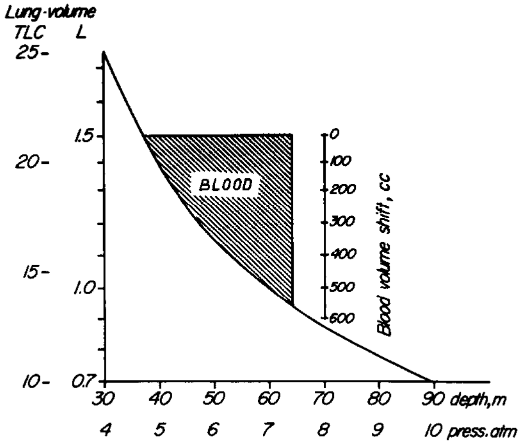

Fig. 4. The cross hatched area indicates the blood volume shift which would be required to maintain pressure equalization assuming that the diver started from the surface after inspiring maximally. Gas exchanges have been neglected.

Sudden changes in intrathoracic pressure can also produce movement of blood. If after a maximal inspiration the recumbent subject performs a brief Valsalva, he can readily inspire another 300 cc of air (Bahnson, 1952). Presumably the pressure has displaced a similar volume of blood from the central to the peripheral circulation. In five seated subjects we have shown that an average of 250 cc could be expired after the subject had breathed out maximally and had developed -20 cm H_2O airway pressure for 10 sec (unpublished data). With exercise central blood volume also appears able to increase with very little increase in pulmonary vascular pressure. Yu *et al.* (1967) indicate a change in pulmonary vascular volume of about 260 cc with mild leg exercise in the supine subject. Their measurements included the blood volume between the pulmonary artery and the left atrium. It would be expected that the large veins and the ventricles could also serve as a reservoir.

From these considerations it would appear that the capacity of a diver to compress the air volume by fluid changes might be the major limiting factor in the depth of the dive. If as much as 1 liter of blood could move from the peripheral to the central circulation, a diver might go as deep as 140 m. To obtain these depths he obviously faces other problems.

During a dive to depths of 10 m and greater, CO_2 would leave the alveoli and enter the circulation (Lanphier and Rahn, 1963; Craig and Harley, 1968). A very significant decrease in the lung volume will be due to the removal of O_2. Therefore, the O_2 uptake from the alveoli of a breath hold diver would also be a major determinant of depth (Craig and Medd, 1968). The gas volumes lost by exchange must be replaced by blood volume shifts if the thoracic cage cannot be compressed. If a diver went to a depth which demanded gas compression to less than RV and remained there, a "thoracic squeeze" would occur as O_2 is consumed. This train of events probably explains why "thoracic squeezes" occur relatively slowly (Schaefer, personal communication, 1967) and not suddenly as predicted from considerations based solely on RV: TLC and depth.

The mechanism of shifting fluid parts of the body to provide pressure compensation is not unknown. RAHN (1965) has shown that the soft tissues (and perhaps blood) around the eyeball can impinge on the air space of diving goggles. The divers from the Tuamotu Archipelago do not use pressure compensating bulbs on their goggles yet they descend as deep as 40 m without experiencing conjunctival hemorrhage. The air space in the goggles is very small, and the soft tissues in the orbit can move forward enough to compress the air.

It has also been postulated that the complex network of venous channels and sinuses in the middle ear of sea lions and seals could fill with blood and thus provide pressure compensation across the tympanic membrane (ODEND'HAL and POULTER, 1966; MØHL, 1967). Unfortunately, it has not yet been demonstrated that such events actually take place in the ear. It would be very interesting to observe if the air volume in the middle ear did decrease as negative pressure was applied to this animal's external auditory canal.

It is also tempting to extend the present observations to the problems faced by diving mammals. During an extensive study of the elephant seal (ELSNER *et al.*, 1964), two "dives" to 300 m were made by one large male (890 kg). The animal was contained in a cargo net and lowered to the desired depth by the ship's winch. He suffered no apparent adverse effects either immediately or during his subsequent life in the zoo.

Although the beginning gas volume was not known, a dive to this depth would result in compression of the gas in air containing spaces to 3.32% of the surface volume. Despite the fact that the elephant seal's ribs are completely cartilagenous it is difficult to conceive of a mechanical change to this extent.

If one assumes that the TLC of this animal was approximately 80 litres (TENNEY and REMMERS, 1963) and that the RV was 10%, he would have reached this latter volume at 90 m. From that depth to 300 m the gas volume must have been compressed by another 5.4 litres. Could this have been accomplished by a transfer of blood from the abdomen to the thorax?

In another large male elephant seal it was observed at autopsy that the inferior vena cava contained about 20 litres of blood (ELSNER *et al.*, 1964). Such a reservoir would provide more than adequate blood for transfer and gas compression. In fact, even if this diver started with half his TLC, he would have to shift only 6.7 litres from the inferior vena cava as he went from 40 to 300 m. Such calculations imply that the ability of the diving mammal to reach great depths may be relatively independent of his beginning gas volume. It has been observed that many diving mammals probably expire before a dive (ANDERSEN, 1966). This maneuver has the advantage of decreasing buoyancy and making descent easier. If there is an adequate mobile blood reservoir in non-air containing spaces at the beginning of the dive, there would be little problem of gas compression to meet the absolute necessity for pressure compensation between the tissues and the environment.

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