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Air-pressure in the thoracic cavity of the deep diving whale (A theoretical biomechanical approach)

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Summary

With the aid of the physical conceptions of compressibility and stiffness, and the histological conceptions of structure and collagenous fibres, and the absence of free gas in the tissue a balloon model of the thoracic cavity of the whale has been constructed.

Computing of the internal air-pressure in two balloons with a different radius came out in the range 1.4 to 1.9 atmospheres.

It is concluded that the maximum air-pressure in the thoracic cavity in deep diving whales—300 m—will not exceed 1.9 atmospheres.

Introduction

Old and recent recordings concerning the air-pressure in the trachea and lung in deep diving whales, confirm the already accepted assumption that it is equal to the pressure of the sea level plus the water-pressure, according to the depth. However, experiments concerning this pressure in whales have never been carried out.

An investigation in the Weddell seal in a high pressure tank (Kooyman, Hammond and Schroeder: 1970) doesn't lead to a final conclusion about the pressure in the trachea and the lungs during deep dives. Harrison and Tomlinson (1963) suggest that the investigation of the effects on the performance of frogmen, divers, submarines and underwater projectiles of an outer casing of blubberlike substance or foam may well give fruitful and even startling results in this field of research. Mellink (1951) states that the blubber layer in a whale functions as a resistance against water-pressure. He made a comparison with rubber vacuum tubes.

The authors inspiration to this study started during a casual observation of the three dimensional course of cordlike collagenous fibres (non-elastic vide infra) in the blubber layer of a white beaked dolphin (*Lagenorhynchus albirostris*, Gray 1846) in a fresh as well as in preserved material. A histological study (Knospe: 1986) corroborated this observation.

Since experience is not practical the aim of this study is to compute the air-pressure in the thoracic cavity of the deep diving whale by means of a biomechanical model.

Methods

In the biomechanical model the following conceptions will be used:

A. from physics:

1. compressibility, which depends on: a. the presence of open or closed gas (air) cells; b. the size of the closed gas cells and c. the thickness of the layer of cells;
2. elasticity, it is the property of matter to change its shape under pressure or when stretched (note: the volume remains equal); grades in elasticity; strong elasticity, for instance in a sphere of glass and weak elasticity in a sphere of rubber;
3. stiffness of the matter, it depends on: the grade of gliding of its molecules over each other. In every kind of matter compressibility elasticity and stiffness are related closely.

B. from histology:

1. structure, that means the components and their manner of arrangements in constituting the whole;
2. fibrous tissue, it means in this model the ordinary connective tissue of the body, made up largely of yellow and/or white fibres, cells and matrix. two types of fibres are important: white or collagenous fibres. They are strong elastic (Young's modulus 10^8) (vide supra) (Gray's Anatomy, 1973) and yellow fibres, which are weakly elastic.
3. living healthy animal structure without direct contact with the open air is free from gas or gascells and is not compressible.

The shape depends on: elasticity, stiffness of the basical matter and the state (condition) of the living subject.

C. Computing figures.

1. Balloon: surface is $4\pi R^2$, constant is $4/3\pi R$;
2. pressure: gram cm^{-2} or 1 atmosphere = 1000 gram cm^{-2};

Figure 1.

3. the law of Avogrado (P1/P2 = V2/V1) will be used by the computing of the gas-pressure in the model.

During the diving of the whale the shape is dependent on: a. elasticity, b. compressibility; c. stiffness of the matter and d. size of the subject.

Results

Acceptance of the conceptions above lead to a statement about the whale: 1. the skin, blubber- and muscle/bone-layer (the bodywall) are incompressible; 2. the elasticity of this structure is strong, caused by a three dimensional course of the cords of the collagenous fibres; 3. the stiffness of this structure is relative high (Berzin, 1972) and 4. the shape may display some slight variations, especially in the direction of the long axis of the subject.

The thoracic cavity of the whale is cone shaped with the base on the cranial side and the top on the caudal one. For the model this cone is reduced to a balloon with a diameter equal to the base of the cone. The physical data of the cone are much more favourable for a pressure-model than those of a balloon, but the calculations are rather more complex however.

The external as well as the internal diameter of the balloon is taken from a diagram of the transverse section of a whale (Slijper, 1962) (Figure 1).

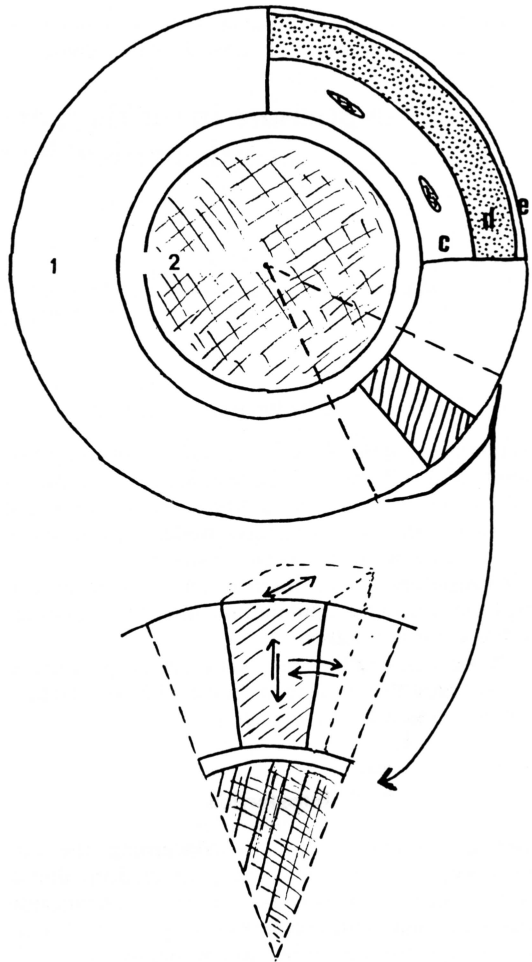

Figure 2. Transverse section of a whale.
1 + 2 external diameter
1 thickness of the wall
2 radius of the thoracic cavity
a. lung; b. heart; c. muscle/bone-layer; d. blubber-layer; e. skin; → dorsal side; ↠ ventral side; ⇆ course of the collagenous fibres.

A second reduction is the assumption of an empty thorax. This is acceptable since we know, that there is a pleural cavity between the parietal and visceral pleura in healthy animals.

The scheme of Slijper is redesigned to the ideal balloon model (Figure 2). The diameter of the thorax is three metres, the thickness of the wall is two metres. A cone (Figure 2) taken from the balloon is sketched in a three dimensional way, the arrows display the course of the collagenous fibres.

By assumption there may be a reduction of 10%

Table 1 Balloon model/computing

Internal radius	before driving	3 m
	during driving	2.7 m (−10%)
		2.4 m (−20%)
Internal volume	before diving	112.6 m^3
4/3 r^3	during diving	82.1 m^3
		57.9 m^3
Gas pressure	before diving	1 atm
P1/P2 = V2/V1	during diving	1.4 atm
		1.9 atm

or 20% of the radius. It must be accepted that the reductions are caused by equal pressures on the surface of the outer side of the model.

Table 1 displays the results of the computing.

Comment

The assumptions concerning the reduction of the inner radius of the balloon model by water-pressure are in contradiction with the strong elastic character of the collagen fibres (cords, vide supra). Nevertheless these assumptions lead to an acceptable indication of the air-pressure inside the thoracic cavity of the range being from 1.4 to 1.9 atmosphere.

A lot of questions arise however. What about the equal pressure on the skin of the diving whale? By calculation one may find a difference in water-pressure between the back and the under side of the whale at 300 metres under the surface, of 0.6 atm. This figure may be taken up in the risk of the assumptions and falls within the variations of the diagrams.

The skin of the whale is not smooth but shows wave-like ridges in the long axis of the animal. A rather complex computing model, in which this property of the skin is demonstrated, will display these ridges reinforcing the resistance against pressure (A well known principle in techniques).

Another question is the mechanism of breathing during diving. During diving to 300 metres under the water surface the water-pressure increases, but the ratio between the difference in the pressure on the back and the under side of the whale and the water pressure decreases (from 0.12 till 0.02). So there will be much more possibility for changing the shape of the thorax by breathing in shallow water than in deep water. In deep water the external breathing movements will stop, the internal breathing—by sphincters in the bronchioles—takes over (van Nie, 1985).

In case of inflammation of both the pleurae, fibrous bridges and plaques will be formed between these pleurae. The acceptance of an open thoracic cavity is no longer viable in these cases. Although these structures influence the breathing negatively, they reinforce the bodywall. Their main consequences are the disturbance of the buoyancy and so deep diving will be impossible.

A rather difficult question arises about the stiffness of the wall related to its thickness, since we don't know the exact relation between these data. However, it is possible to compare this relation with practical examples taken from daily observations. The balloon model may be compared with a tennis ball, a tractor tyre, a vacuum tube and with the nylon cord reinforced hoses of the fire-brigade. In all these cases the relation between stiffness and thickness plays an important role in protecting the inside or outside against high pressure.

It is the author's opinion, that much more study has to be carried out to solve the presented problem in any part. Without the aid of technical specialists—in theory and practice—this study will not be successful. The challenge to such a study is formulated in the.

Conclusion

Starting from conceptions in physics and histology, both introduced in a balloon model, the statement is made: The air-pressure in the thoracic cavity in the deep diving whale—300 metres under the water surface—lies between 1.4 and 1.9 atmospheres.

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