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MODELLING FORUM

Flow Resistance of Airways under Hyperbaric Conditions

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Summary

Based on the known relations governing flow resistance of a tube during laminar and turbulent flow and the value of the so-called Reynold's number the following conclusions were derived: 1. The flow resistance of airways increases under hyperbaric conditions because a) the turbulent flow participates in the airways to a greater extent due to its gradual extension to minor airways, and b) during turbulent flow the flow resistance is directly proportional to the pressure of the inhaled gas. 2. If the pressure in the surrounding environment increases n-times, this has an impact on the distribution of laminar and turbulent flow in the airways and their flow resistance, similarly as if the flow rates would increase n-times under normobaric conditions. 3. Dynamic indicators of lung ventilation corresponding to higher flow rates (e.g. PEF – peak expiratory flow) are reduced under hyperbaric conditions to a greater extent than the dynamic parameters corresponding to lower flow rates (e.g. $FMEF_{25-75}$ – forced midexpiratory flow) determined usually by conditions in the minor airways, where the flow usually remains laminar or intermediate.

Key words

Hyperbaric environment – Respiratory resistance – Laminar and turbulent flow

Divers, sandhogs, some tunnelers, personnel of hyperbaric chambers and other workers may feel an increased resistance when breathing under hyperbaric conditions. Under certain circumstances, this can lead to breathlessness or restriction of their physical performance. Spirometry conducted under hyperbaric conditions showed that dynamic indicators of lung ventilation are decreased (Lord *et al.* 1966, Hogg 1977, Bennett and Elliott 1982, Burnet *et al.* 1990, Hrnčíř *et al.* 1990, 1991a,b,c). This fact has been known for more than 30 years and is taken into consideration in divers (particularly when planning physical activity in greater depths) (Lord *et al.* 1966, Bennett and Elliott 1982, King 1989). As we have not found any paper dealing with an accurate analysis and a physical explanation of the variations in respiratory resistance observed under varying surrounding pressure, we tried to solve this problem on the basis of known physical and mathematical relations.

The resistance during breathing has three components: an elastic one which is based on lung and chest elasticity, a flow component which is due to the resistance produced when the flow of gas is inhaled into the airways, and an inert component corresponding to the variations in kinetic energy in the airways, chest, abdominal organs and air in connection with respiration (Hogg 1977, Welch 1977, Paleček *et al.* 1987, Hrnčíř 1993).

The elastic and inert components of respiratory resistance do not change in a hyperbaric environment. The increase in the inert resistance due to the increased weight of compressed gas circulating in the lungs is negligible at pressures encountered in practice. Nevertheless, the flow resistance in the airways changes according to physical laws with the degree of compression of the inhaled gas. This is consistent with the mentioned decrease in the dynamic indicators of lung ventilation, e.g. one-second forced expiratory volume (FEV_1), peak expiratory flow (PEF), forced midexpiratory flow between 25 % and 75 % of the vital capacity ($FMEF_{25-75}$) and others including the inspiratory ones, found in a hyperbaric environment (Lord *et al.* 1966, Bennett and Elliott 1982, Paleček *et al.* 1987, King 1989, Hrnčíř *et al.* 1990, 1991a,b).

The inhaled gas moves in the airways either as a laminar or a turbulent flow. The type of flow depends on the inner diameter of the tube, density and dynamic viscosity of the circulating gas and the flow velocity. It can be determined on the basis of calculation of Reynold's number **Re** (Hogg 1977). It is defined by the following relationship:

$$\mathbf{Re} = 2\,r\,\delta\,v\,/\,\mu \qquad (1)$$

where: r = radius of the tube (m)
δ = density of the flowing gas ($kg.m^{-3}$)
v = velocity of the flowing gas ($m.s^{-1}$)
μ = dynamic viscosity of the flowing gas ($kg.m^{-1}s^{-1}$)
(Note that **Re** is dimensionless.)

When considering the flow in a tube circular in cross-section with smooth inner walls, it is true that if the value of Reynold's number **Re** is under 2000, the flow is laminar and if it is over 3000, the flow is turbulent. If **Re** is between 2000 and 3000, the flow is intermediate between laminar and turbulent (Hogg 1977, Hrnčíř 1993).

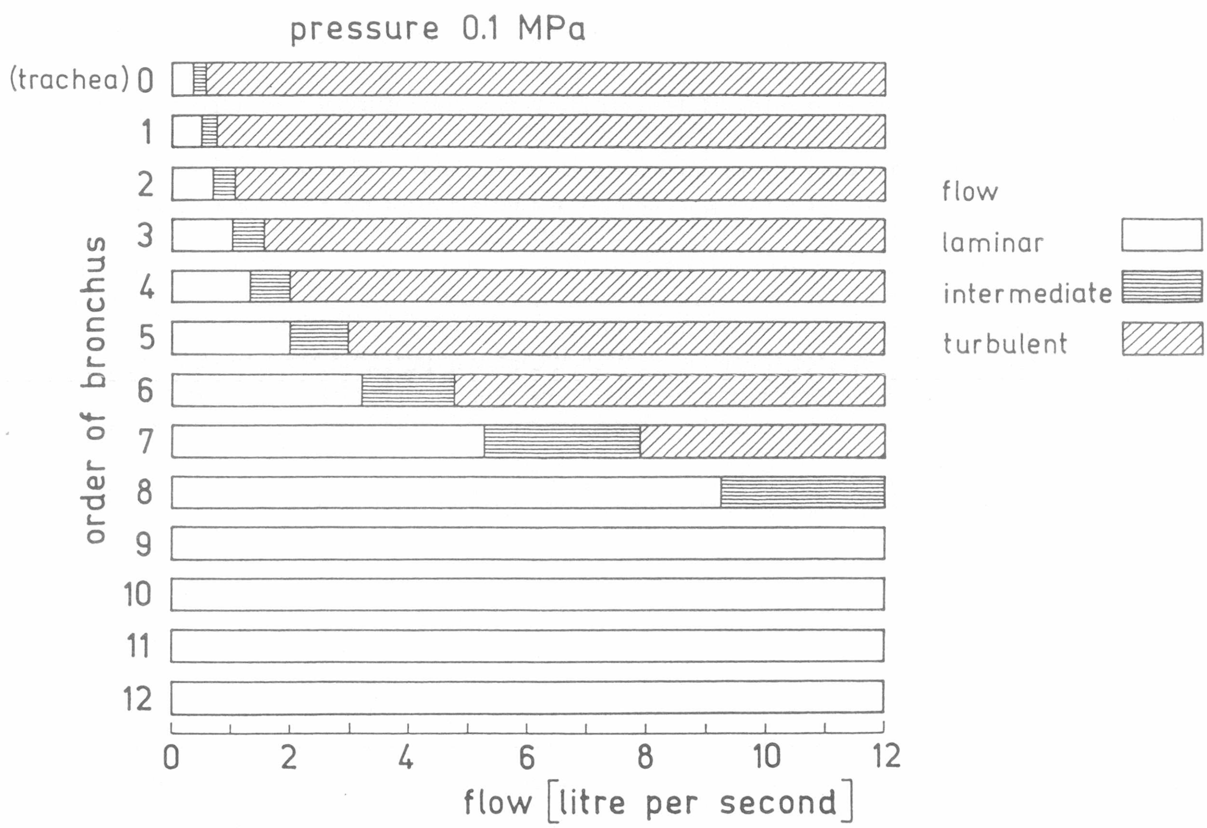

Fig. 1
Distribution of different types of flow in the airways under normobaric conditions (at 0.1 MPa)

When assuming, for the sake of simplicity, that the airways are a system of tubes with smooth inner walls and circular in cross-section, and neglecting the turbulent flow due to their bifurcations, we will be able to determine the type of flow in each individual bronchus at a given inspiratory or expiratory velocity providing that the anatomy is known. The distribution of laminar, intermediate and turbulent types of flow in the airways according to the rate of inspiratory or expiratory flow is given in Figure 1. The calculations were performed on the basis of data published by Paleček *et al.* (1987).

Table 1

Pressure (MPa)	Dynamic viscosity of air ($kg.m^{-1}.s^{-1}$)
0.1	16.96×10^{-6}
0.2	16.98×10^{-6}
0.4	17.01×10^{-6}
0.6	17.04×10^{-6}
0.8	17.07×10^{-6}
1.0	17.11×10^{-6}

Table 1 shows that with increasing pressure the dynamic viscosity of air remains almost unchanged (at least for the range of pressures that are of practical importance from the point of view of occupational medicine). Nevertheless, the density of air changes proportionally to the variations in pressure (as we can deduce from the equation of state, the density of a gas at constant temperature is directly proportional to its pressure). That is why Reynold's number **Re** in a hyperbaric environment becomes higher than under normobaric conditions (at a n-fold increase in pressure **Re** is n-times higher) and that is why the turbulent flow type in the airways participates to a greater extent. Figures 2 and 3 show what types of flow are to be expected in the airways at pressures of 0.4 MPa and 0.7 MPa depending on the rate of the expiratory or inspiratory flow. The data were calculated from those published by Paleček *et al.* (1987).

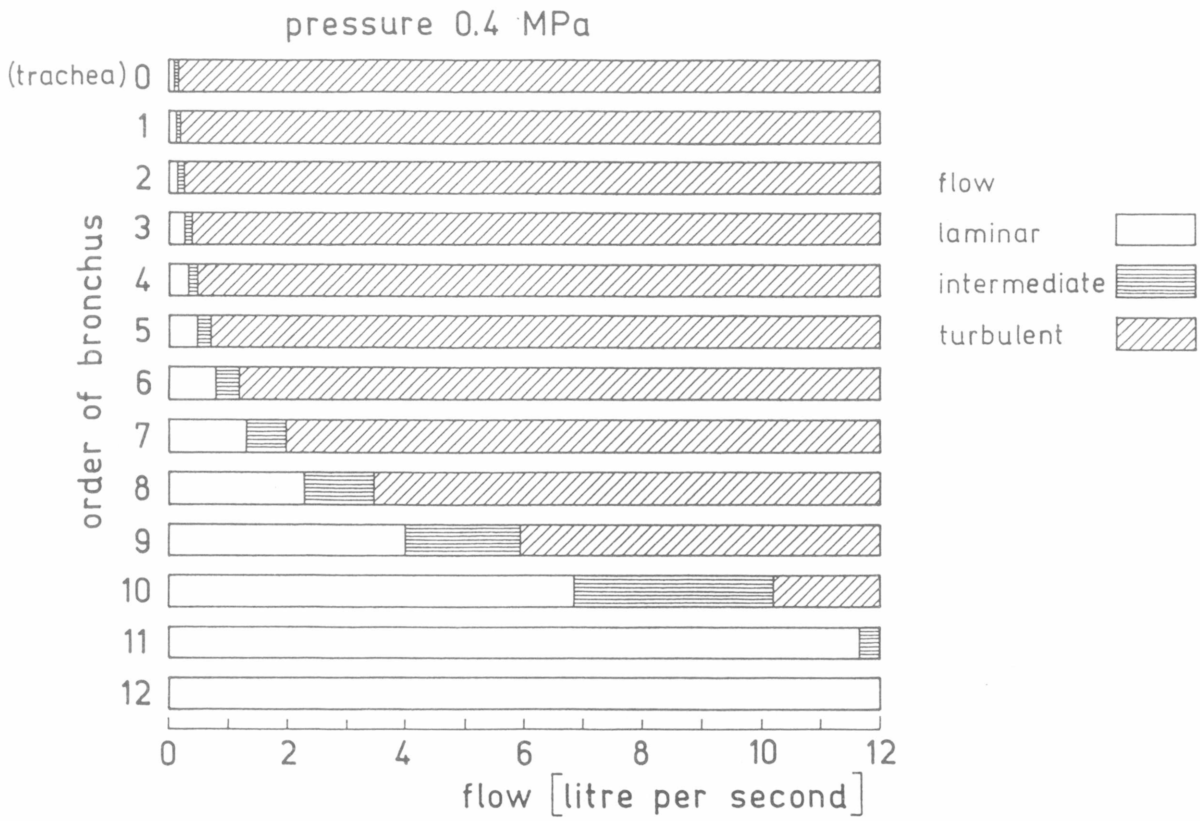

Fig. 2
Distribution of different types of flow in the airways under hyperbaric conditions (at 0.4 MPa)

The flow resistance $\mathbf{R}_{aw}$ of the tube is defined as the ratio of the difference in pressures between the ends of the tube and the flow rate:

$$\mathbf{R}_{aw} = dp / V$$

where: dp = difference in pressures between the ends of the tube (Pa), V = rate of flow ($m^3 . s^{-1}$).

For a dichotomic system of bifurcating tubes, as the airways theoretically are, the total resistance $\mathbf{R}_{aw\text{-}total}$ would be given by the sum of partial resistances at individual levels. Supposing that all i-order bifurcations have approximately an equal lumen and length, the following would hold:

$$\mathbf{R}_{aw\text{-}total} = \sum_{i=0}^{n} \frac{\mathbf{R}_{awi}}{2^i} \qquad (2)$$

where: n = number of bifurcations (trachea is a zero order tube), $\mathbf{R}_{awi}$ = flow resistance of one i order tube (bronchus).

The flow resistance of the tube during laminar flow is described by the following relationship (Hagen-Poiseuille's law) (Hogg 1977):

$$R_{aw\text{-}laminar} = 8 \mu \, l \, r^{-4} \varkappa \pi \qquad (3)$$

where:
μ = dynamic viscosity of gas ($kg.m^{-1}s^{-1}$)
l = tube length (m)
r = tube radius (m).
π = Ludolf's number (3.14159)

From this it is evident that in laminar flow the flow resistance of the tube depends on its length and lumen and dynamic viscosity of the circulating gas flow but does not depend on the velocity of the flow or on the gas pressure (at least in the range of pressures at which the dynamic viscosity is practically constant – see Table 1).

If the laminar flow in a tube changes to turbulent, its flow resistance increases significantly. The following relationship holds:

$$R_{aw\text{-}turbulent} = L \delta v \, l \, r^{-3}/4 \qquad (4)$$

where: L = coefficient of friction (dimensionless)
δ = gas density ($kg.m^{-3}$)
v = flow velocity ($m.s^{-1}$)
l = tube length (m)
r = tube radius (m)

Note that the coefficient of friction L depends on the character of the inner surface of the tube (i.e. on its "roughness") and on Reynold's number (i.e. on the flow velocity, dynamic viscosity and pressure of the circulating gas). These circumstances must be taken into consideration in case of the intermediate type of flow while in a fully developed turbulent flow the L value is approximately constant and thus does not depend on the velocity of flow and on the pressure of the gas.

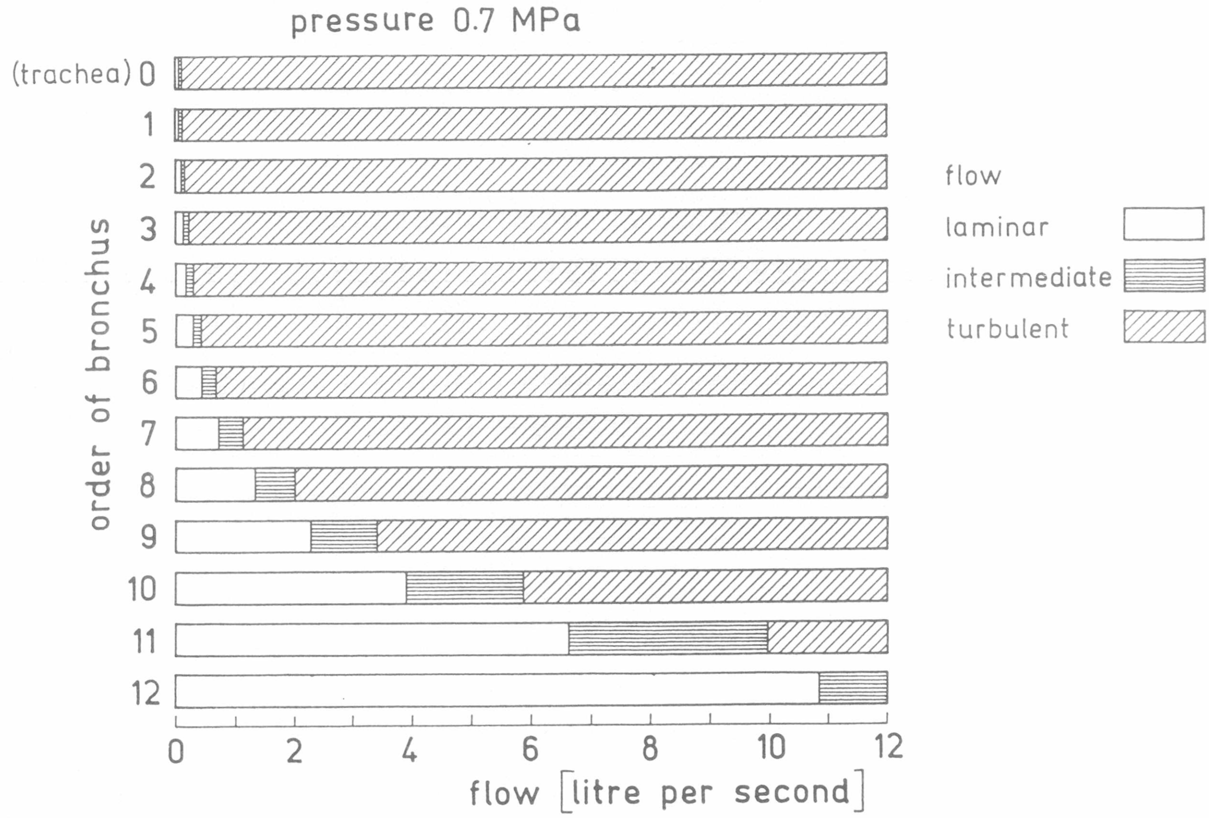

Fig. 3
Distribution of different types of flow in the airways under hyperbaric conditions (at 0.7 MPa)

The relationship (4) indicates that in turbulent flow the flow resistance of the tube is directly proportional to the density and thus to the gas pressure.

Figure 4 illustrates the variations in flow resistance of the airways in relation to the velocity of the expiration or inspiration flows under normobaric (0.1 MPa) and hyperbaric (0.4 MPa and 0.7 MPa) conditions.

It should be noted that in practice a turbulent flow cannot spread to all parts of the airways simultaneously. As can be calculated for normobaric conditions (0.1 MPa), at a flow rate of 10 litres per second the flow is turbulent only up to the 7th order bronchi, during an (unreal) flow rate of 200 litres per second the same is true even for up to the 13th order bronchi. Calculation indicates that under hyperbaric conditions (e.g. 0.7 MPa) at a flow rate of 10 litres per second the turbulent flow will also occur up to the 11th order bronchi. Laminar and partly intermediate types of flow are found in higher order bronchi.

From what has been stated, the true causes of the increased flow resistance in the airways under hyperbaric conditions may be derived:

1) In a hyperbaric environment, the turbulent flow, which is associated with a higher flow resistance compared to the laminar flow, is found in the airways to a greater extent than under normobaric conditions. The higher the pressure of the surrounding environment, the higher the number of bronchi where a turbulent flow passes in their lumina at a given flow velocity.

2) The flow resistance of a tube (and of the airways) during turbulent flow is directly proportional to the density and thus also to the pressure of the circulating gas. In these parts of the airways where the flow is turbulent the flow resistance increases proportionally to the increase in pressure of the surrounding environment.

It must be mentioned that the increase in flow resistance under hyperbaric conditions does not result from an increased viscosity of the compressed gas as is sometimes erroneously explained. As has already been stated (see Table 1), the dynamic viscosity of a gas does not change markedly with increasing pressure, its dynamic viscosity (defined as the ratio of kinematic viscosity to the density) even decreases with increasing pressure.

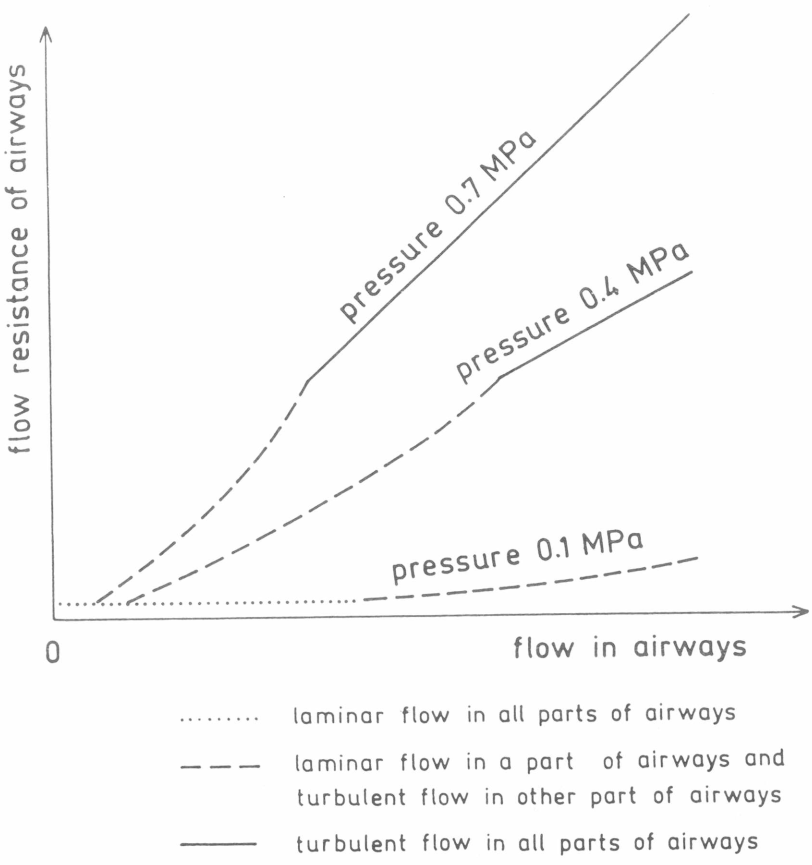

Fig. 4
Change in airway resistance in relation to different ratios of laminar, intermediate and turbulent types of flow occurring under normo- and hyperbaric conditions

It is remarkable that at the very low expiratory or inspiratory flow, when only laminar flow would be expected in all airways, according to Hagen-Poiseuille's law the flow resistance of the airways does not change with the increasing pressure (at least up to the flow rate which does not cause the development of a turbulent flow). Nevertheless, in reality turbulent flow is always present in the large airways to a certain extent even under hypobaric conditions. This is especially true at the bifurcation of the trachea and bronchi or in the presence of small irregularities on their inner surface. That is why a certain increase in the flow resistance is to be expected with an increase in the surrounding pressure even at very low magnitudes of flow velocity.

From the presented relationships (1), (3) and (4) it is clear that during turbulent flow Reynold's number and the flow resistance change proportionally to the surrounding pressure (gas density) and flow velocity, while the flow resistance during laminar flow does not depend on any of these two variables. From these facts it may be deduced that an n-fold increase in the surrounding pressure will lead, at a given flow velocity, to the same change in the distribution of laminar and turbulent flow in the airways and in the flow resistance as if the given flow velocity had increased n-times (Hrnčíř 1993).

The greater the extent of turbulent flow in the airways, the higher the increase in the flow resistance under hyperbaric conditions. Since turbulent flow is found in wider segments of the airways at greater flow velocities, under induced hyperbaric conditions the flow resistance increases more during higher expiratory or inspiratory flow compared to lower flow. This means, for instance, that the dynamic indicators of lung ventilation corresponding to higher flow velocities (e.g. PEF – peak expiratory flow) will be reduced more under hyperbaric conditions (both absolutely and relatively) than the indicators corresponding to lower flow velocities (e.g. $FMEF_{25-75}$ – forced midexpiratory flow). The results of measurements of lung functions under hyperbaric conditions are consistent with this (Bennett and Elliott 1982, Paleček *et al.* 1987, King 1989, Hrnčíř *et al.* 1990, 1991a,b).

The flow resistance of the airways during expiration as well as inspiration increases under hyperbaric conditions. During expiration, however, the lumen of the airways is somewhat reduced, so that Reynold's number during expiration is higher than during inspiration although the flow rate is similar in different parts of the airways. (The flow rate is significantly increased at the site of stenosis.) The flow resistance of the airways is thus as a rule higher during expiration than inspiration even when the flow rate is equal (even under normobaric conditions). This is one of the reasons why assessment of the so-called expiration rates is used in practice more frequently (e.g. PEF or $FMEF_{25-75}$) than the inspiration rates (e.g. PIF or $FMIF_{25-75}$). Another reason is that obstruction below the bifurcation of the trachea (e.g. in bronchial asthma or chronic pulmonary obstruction) associated with restricted flow, especially during expiration, is much more frequent than obstruction above the tracheal bifurcation which particularly restricts the flow during inspiration.

References

BENNETT P.B., ELLIOTT D.H.: *The Physiology and Medicine of Diving and Compressed Air Work.* Third Edition, Baillire Tindall, London, 1982, pp. 1–532

BURNET H., LUCCIANO M., JAMMES Y.: Respiratory effects of cold-gas breathing in humans under hyperbaric environment. *Respir. Physiol.* **81:** 413–423, 1990

HOGG J.C.: The respiratory airways. In: *Pulmonary Medicine.* C.A. GUENTER, M.H. WELCH (eds), J.B. Lippincott, Philadelphia, 1977, pp. 38–71.

HRNČÍŘ E.: Why pulmonary functions change in a hyperbaric environment (in Czech with English summary), *Stud. pneumol. phtiseol.* **53:** 58–63, 1993.

HRNČÍŘ E., HYKEŠ P., DOLEŽAL V.: Changes of some ventilation parameters in hyperbaric environment (in Czech). *Pracov. Lék.* **42:** 311–313, 1990.

HRNČÍŘ E., HYKEŠ P., DOLEŽAL V.: Indicators of forced inspiration in normobaric and hyperbaric conditions (in Czech). *Stud. pneumol. phtiseol.* **51:** 57–63, 1991a.

HRNČÍŘ E., HYKEŠ P., DOLEŽAL, V: Forced expiration and inspiration under hyperbaric conditions (in Czech). *Čas. lék. čes.* **130:** 51–53, 1991b.

HRNČÍŘ E., HYKEŠ P., DOLEŽAL V.: Influence of a hyperbaric environment on dynamic indicators of pulmonary ventilation in subjects with bronchopulmonary obstruction (in Czech). *Pracov. Lék.* **43:** 17–19, 1991c.

KING J.: Health effects of hyperbaric environments. In: *Occupational Health Practice*, Third Edition, H.A. WALDRON (ed.), Butterworths, London, 1989, pp. 415–429.

LORD G.P., BOND G.F., SCHAEFER K.E.: Breathing under high ambient pressure. *J. Appl. Physiol.* **21:** 1833-1841, 1966.

PALEČEK, F., FEITOVÁ S., FELKEL H., HERGET J., KANDUS J., KRÁL B., OUŘEDNÍK A., PACINA V., POKORNÝ J., VOJANEC V., ZAPLETAL A.: *Pathophysiology of Respiration* (in Czech), Avicenum, Prague, 1987, pp. 1–312.

WELCH M.H.: Ventilatory function of the lungs. In: *Pulmonary Medicine,* C.A. GUENTER, M.H. WELCH (eds), J.B. Lippincott, Philadelphia, 1977, pp. 72–123.

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