THE ACTION OF ADIABATIC EFFECTS ON THE COMPLIANCE OF AN ARTIFICIAL THORAX

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SUMMARY

The pressure, volume, and temperature conditions obtaining in an artificial thorax are discussed. It is shown that isothermal conditions can be more nearly realized if the vessel is filled with copper wool. In any case it is desirable that the characteristics of an artificial thorax should be known.

When intermittent positive pressure ventilation is used to inflate the lungs of a patient, the positive pressure has to force the inflating gas in against the elastic forces of the lungs and thorax. The slope of the line that results from plotting the external force (pressure) against the resulting increase in volume gives a measure of the stiffness or distensibility of the lungs and thorax. The slope of the graph gives a measure of the “total compliance” of the chest wall and lungs (Comroe et al., 1956). Compliance is defined (Mushin, Rendell-Baker and Thompson, 1959) as “the volume increase produced by each unit pressure increase in the alveoli”. It is normally measured in terms of litres per centimetre of water pressure (l./cm H\(_2\)O). Mushin, Rendell-Baker and Thompson take a typical value for the total compliance (chest wall plus lungs) to be 0.05 l./cm H\(_2\)O.

It is possible to simulate the compliance of the chest wall plus lungs in the laboratory by the use of a rigid vessel of suitable capacity. Elastic forces are not involved, but a definite increment of pressure applied to the vessel will force into it a definite increment of gas volume. A graph can be plotted for the vessel of volume increment against pressure increment, and the slope is a measure of the effective “compliance” of the vessel. It will be shown that this “compliance” is proportional to the volume of the vessel. This can be chosen so that the compliance of adults, children or neonates is simulated as desired.

THEORY

Consider a given mass of gas contained in a volume V at a pressure P. Assuming that the temperature stays constant (isothermal conditions), we have the Boyle’s Law relationship, that P \(\times\) V is a constant, i.e. P.V = C. Differentiating both sides of the equation gives

\[ P \cdot dV + V \cdot dP = 0. \]

Hence the compliance of the system

\[ \frac{dV}{dP} = - \frac{V}{P}. \]

It is assumed that the inflation pressure dP is small compared with the barometric pressure P. dV is the tidal volume. The compliance is directly proportional to the volume of the vessel. Assuming a barometric pressure of 76 cm Hg, a vessel of 51.7 l. capacity would give a compliance of 0.05 l./cm H\(_2\)O. In the Research Department of Anaesthetics, a 10-gallon oil drum has been used as an artificial thorax. It is better to use a glass carboy rather than an oil drum because of its rigidity.

In using a simple Boyle’s Law calculation to deduce the compliance of a vessel, the fundamental assumption is made that conditions are isothermal. In general, when a gas is compressed, its temperature is raised since energy has been imparted to the system. To produce an isothermal change, the compression must take place very slowly in order to allow the heat developed to be taken up by the walls of the vessel.
An adiabatic compression is said to occur if no heat is lost from the gas during compression. The temperature of the gas will thus increase as a result of its compression. Under these conditions the equation

\[ P.V^\gamma = K \]

is obeyed, where \( K \) is a constant, and \( \gamma \) is the ratio of the specific heats of the gas at constant pressure and constant volume. For air \( \gamma \) can be taken as 1.4. Differentiating \( P.V^\gamma = K \), we have

\[
V\,dP + \gamma P.V^{\gamma-1} \,dV = 0,
\]

and the compliance is

\[
\frac{dV}{dP} = -1 \cdot \frac{V}{P} \gamma.
\]

If the changes in the artificial thorax were adiabatic rather than isothermal, a compliance smaller by a factor of 0.71 would be obtained.

When used for comparing artificial ventilators, the glass vessel is provided with an aneroid pressure manometer scaled plus or minus 30 cm H\(_2\)O. Assuming a value of the vessel's compliance from Boyle's Law, it is possible to calibrate the pressure gauge in terms of the volume actually delivered to the vessel. If a rapid response electrical manometer is used, this overcomes problems encountered when using anemometer-type volume meters with a peaky ventilator waveform. If, in fact, the changes were adiabatic, it might appear that the ventilator was incapable of providing the desired tidal volume at a given inflation pressure. It was thus a matter of practical importance to determine whether at normal respiratory rates the compressions were of an isothermal or adiabatic nature.

It is possible to calculate the order of temperature rise to be expected in an adiabatic compression. The Characteristic Equation of a Perfect Gas is:

\[ P.V = m.r.T \]

where \( m \) gm is the mass of gas, \( r \) is the gas constant per gram of gas and \( T \) is the temperature of the gas in degrees absolute. Raising each side to the power \( \gamma \):

\[ (P.V)^\gamma = (m.r.T)^\gamma \]

Dividing by \( P.V^\gamma = K \):

\[ P^{\gamma-1} = \frac{(m.r.T)^\gamma}{K} \]

Re-arranging:

\[ \frac{P^{\gamma-1}}{T^\gamma} = \frac{(m.r)^\gamma}{K} = K' \]

Because \( \frac{P^{\gamma-1}}{T^\gamma} \) is constant, it is possible to calculate the rise in temperature. Differentiating:

\[ (\gamma - 1)P^{\gamma-2}T^{-\gamma}dT + (\gamma - 1)P^{\gamma-1}T^{\gamma-2}.dT = 0. \]

\( dT \) is the temperature rise, \( T \) the ambient temperature in degrees Absolute, and \( P \) the ambient pressure.

\[ dT = dP \frac{(\gamma - 1)}{P} \frac{T}{\gamma} \]

This is independent of the volume of the vessel. For a 15 cm H\(_2\)O rise in pressure the adiabatic temperature increase should be 1.2°C.

**EXPERIMENTS USING AN EMPTY GLASS VESSEL**

As part of the evaluation programme for a ventilator designed for use with small children, it was required to know the characteristics of a bottle of 6.16 l. capacity. An electrically controlled piston and cylinder pump (Hill, Hook and Bell, 1961) was used to deliver a fixed tidal volume of 63 ml into a glass bottle of 6,160 ml capacity. The pressure changes occurring within the bottle were...
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recorded by means of a Vickers capacitance pressure transducer, this was regularly calibrated against a water manometer. As a check, a clamped all-glass syringe was also used to deliver a 100-ml tidal volume, the rate being set by a metronome.

With the 6,160-ml volume bottle, if Boyle's Law is obeyed, a volume increment of 63 ml should produce a pressure rise of 10.6 cm H₄O. For an adiabatic compression, the pressure rise should be 14.8 cm H₂O. Figure 1 shows that at respiratory rates greater than four per minute, conditions are within 5 per cent of adiabatic. Figure 2 shows that similar results were found with a bottle of 6,700 ml capacity and a tidal volume of 130 ml.

![Figure 1](image1.png)

**Fig. 1**
The effect of adding copper wool to a 6.7-litre bottle, and copper gauze to a 50-litre bottle.

**The use of a heat absorber.**

It is desirable for reproducibility that the conditions in the artificial thorax should be isothermal under the conditions of use, and this can be aided by filling the bottle with copper gauze to act as a heat absorber. The effect of adding 1.3 kg of copper wool to the 6,700-ml bottle is shown in figure 2. It is seen that with the tidal volume of 130 ml, conditions are now completely isothermal up to 30 b.p.m.

To simulate the compliance of an adult patient, a glass carboy of 50 l. volume was used. From figure 2 it is seen that, with the carboy empty, conditions are approximately within 10 per cent of adiabatic. Compared with the smaller vessel, there is now a larger surface area to take up heat. The effect of adding 1.3 kg of copper gauze to the 50-litre bottle is also shown in figure 2. Up to 15 b.p.m., conditions are now within 5 per cent of isothermal. The copper gauze used was of a coarse mesh, and more nearly isothermal conditions would have been obtained by using fine copper wool as in the smaller vessel. Some experiments have been carried out using steel wool, and similar results were obtained as when copper wool was used.

Figure 3 shows a bottle of volume 1,175 ml empty, containing 35 ml of copper gauze. It pos-

![Figure 2](image2.png)

**Fig. 2**
The effect of adding copper wool to a 6.7-litre bottle, and copper gauze to a 50-litre bottle.

![Figure 3](image3.png)

**Fig. 3**
A small artificial thorax designed for use in testing an infant’s ventilator.
A large artificial thorax designed for evaluating adult ventilators.

It is evident that the use of copper wool can greatly help in the production of isothermal conditions in an artificial thorax, but whether wool is used or not, it is desirable that the characteristics of any artificial thorax be carefully established.

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REFERENCES


L'ACTION DES EFFETS ADIABATIQUES SUR LA COMPLIANCE D'UN THORAX ARTIFICIEL

On expose les conditions de pression, de volume et de température pour obtenir un thorax artificiel. On montre que l'on peut se rapprocher davantage des conditions isothermes si le réservoir est rempli de laine de cuivre. En tout cas, il est désiré que les caractéristiques d'un thorax artificiel soient connues.

DIE AUSWIRKUNG DES ADIABATISCHEN EFFEKTEN AUF DIE REAKTIONSFAHIGKEIT DES KÜNSTLICHEN THORAX