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Research Article

A Mathematical Model of Middle Ear Ventilation. Controlled Valvular Tympanostomy Tube

Fücsek M [1*], Molnárka GY [2]

[1] Petz Aladár University Teaching Hospital 9023 Győr, Vasvári Pál u. 2-4. HUNGARY.

[2] Széchenyi István University, Győr 9026 Győr, Egyetem tér 1.

***Corresponding Author:** Mihály Fücsek, 9022 Győr, Árpád u. 77 / B. 2nd em. Door 4. HUNGARY.

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Abstract

BAKGROUND

The middle ear (tympanic cavity and mastoid process) is a closed cavity. It is filled with a special gas mixture and at the same pressure as atmospheric air, the composition of the gas is similar to the surrounding tissues. Its change in pressure is compensated by the occasional opening of the Eustachian tube. If the tube does not open, a persistently high negative pressure develops in the middle ear, the clinical consequences of which are well known. The negative pressure is eliminated by a tympanostomy tube implanted in the tympanic membrane. Inserting the tube instead of one abnormal condition (permanently closed middle ear) creates another abnormal condition (permanently open middle ear). Prolonged insertion of the tube may cause irreversible damage. / eardrum atrophy, tympanosclerosis, permanent perforation, auditory bone damage, cholesteatoma.

AIM

We are looking for a solution that is similar to the original, i.e. the middle ear should be closed and open from time to time.

METHOD

We studied middle ear ventilation based on literature data, our own research, and our computer model.

RESULTS

We concluded that the original function can be restored with the valve tube. In our case, the opening and closing of the valve is controlled by a change in volume caused /diethyl ether/ by a change in body temperature.

CONCLUSION

A more advanced solution would be a nanotechnology valve controlled by a change in total pressure, a partial pressure change in oxygen or carbon dioxide. However, a valve that can be opened at different intervals or even individually adjusted is conceivable.

Key words: middle ear ventilation; mathematical model; gas diffusion; valvular tympanostomy tube; tympanostomy tube

Introduction

The middle ear /ME/ is a closed, special gas mixture filled cavity.[1-6] Closing is passive. The pressure changes of the ME are compensated by the actively opening Eustachian tube /ET/.

Otitis media is a common disease in childhood. Permanently decreased in middle ear pressure caused by ET dysfunction is one of the fundamental factors in the pathology of otitis media.

The ME / tympanic cavity and mastoid process / pressure is provided by gas diffusion and ET function. Gas diffusion between the surrounding tissues /ST/ and the ME takes place in accordance with the laws of physics (bidirectional gas exchange), so the pressure from the diffusion in the ME, can be a maximum of 706 mmHg. (Table 1) That is, 92% of the ME pressure is provided by the gas diffusion, and 8% by the ET (Table 2).

GAS	MIDDLE EAR*	SURROUNDING TISSUES
O_2	51	40
N_2	616	573
CO_2	46	46
TOTAL	713 /-54 /	659

The data refer to dry gases

*Optimal gas composition in the middle ear

Table 1: Pressure from Gas Diffusion in the Middle Ear

Partial pressure of gases

/Hgmm/

Gas	Air	Middle ear	Surrounding tissues
O_2	158	51	40
CO_2	0,3	46	46
N_2	596	616	573
Vapor	5,7	47	47
Total	760	760	706

Table 2: In normal operation, the pressure of the ME gas is the same as the atmospheric pressure, and the gas composition is similar to the gas composition of the ST (3-5 Table).

COMPOSITION OF MIDDLE EAR GASES

GAS	PRESSURE mmHg	VOLUME ml	VOLUME %
Oxigen	51	405	7,10
Carbon dioxid	46	363	6,45
Nitrogen	616	4861	86,34
Total	713	5629	99,89

The data refer to dry gases and a 6000 ml middle ear.

Table 3

GAS COMPOSITION OF MIDDLE EAR

GAS	O2	CO2	N2
CALCULATED	51	46	616
MEASURED*	39-54	48-52	563-606

*according to several authors

Table 4

/ Partial pressure of gases in mmHg with respect to dry gases /

Gas	Air	Middle ear*		Surrounding tissues
O_2	150	$\Rightarrow$ 138	$\rightarrow$	40
CO_2	-	$\Leftarrow$ 15	$\leftarrow$	46
N_2	563	$\Leftarrow$ 570	$\leftarrow$	573
Total	713	713	/-54/	659

$\Rightarrow$ diffusion acros the tympanostomy tube
$\rightarrow$ diffusion through the mucosa
* FELDING és mtsai. /3/

Table 5: GAS DIFFUSION AFTER TUBE INSERTION

The pressure and gas composition are provided by complex active and passive mechanisms operating in harmony with each other, including the nasopharyngeal biphasic pressure wave, the mastoid process volume and the tension and elasticity of the eardrum. ME volume is an important pathological factor. Diffusion of the same quantity of gas (O_2, N_2, CO_2) causes a greater pressure change in a smaller volume middle ear.

If the ET does not open, the partial pressures of the gases / O_2, N_2 / are equalized between the ME and ST and negative pressure develops in the middle ear with well-known clinical consequences.

The importance of negative ME pressure in pathology is demonstrated by many millions of measurements / tympanometry / daily around the world. The pathological process attempts are made to prevent by inserting a tympanostomy tube.

The long-term effects of tube insertion have been analyzed in several studies [7-10].

The consequences of tube insertion

After tube insertion, the pressure in the ME is restored but the gas composition of the ME changes [11-13]. The gas composition of the ME will be more similar to air than to the gas composition of the ST. The larger lumen of the tube, the more the gas composition of ME resembles air rather than the gas composition of ST (Table 5).

Intermittent pressure equalization, which under intact conditions is the result of a dynamic process and intermittent, will be continuous and passive. This passivity can lead to structural damage.

The partial pressure of oxygen in the ME is too high, therefore the absorption of oxygen into the ST increases / hyperoxia /.

Strong, continuous diffusion of carbon dioxide begins from the surrounding tissues into the cavity of the ME, causing the ST to lose large amounts of CO_2.

The ME loses water vapor / 100% humidity in the intact middle ear / thus the mucous membrane dries out and is damaged.

Inserting the ventilation tube instead of one abnormal condition (permanently closed middle ear), does another (permanently open middle ear).

So we did not restore the original condition by inserting the tube. The ear may compensate for our therapy in the short term, but with repeated or prolonged tube insertion, side effects may occur (atrophy, scarring, tympanosclerosis, perforation of the eardrum, damage to the auditory ossicles, cholesteatoma, and hearing loss).

AIMS

We are looking for a solution that creates conditions similar to intact ventilation, i.e. the middle ear should be closed and open from time to time. We examined the ventilation of the middle ear based on known literature data and our own research. Intact middle ear ventilation was analyzed using a mathematical model.

METODS

Our calculations refer to dry gases (713 mmHg), constant outside temperature and air pressure. The diffusion constants are shown in the Table 6. Diffusion surface: A = 15 cm, middle ear volume: 9 ml. Diffusion processes are described by the Noyes-Whitney equations. Table 7. The ET performs pressure equalization every minute.

Data and methods

The calculations refer to dry gases (713 Hgmm), constant outside temperature and air pressure.

Diffusion constant: $D_{O_2} = 20 \frac{cm}{min \cdot Hgmm}$

$$D_{N_2} = 4 \frac{cm}{min \cdot Hgmm}$$

Diffusion surface: $A = 15\ cm^2$, middle ear volume: 9 ml.

The diffusion process is described by the Noyes-Whitney equations.

Table 6.

The equations

$$\frac{dP_{O_2}(t)}{dt} = D_{O_2} \cdot A \cdot \left(P_{O_2}(t) - P_{O_2\,tissue}\right)$$

$$\frac{dP_{N_2}(t)}{dt} = D_{N_2} \cdot A \cdot \left(P_{N_2}(t) - P_{N\,tissue}\right)$$

Where the temporal change in the oxigen partial pressure $P_{O_2}(t)$, the temporal change in the nitrogen partial pressure $P_{N_2}(t)$ and the partial pressure of dissolved gases in tissues $P_{O_2\,tissue}$ and $P_{N_2\,tissue}$

.

Table 7.

Basic physical concepts: The gases flow across the ET according to their percentage composition from the higher pressure point to the lower pressure point.

The gases diffuse across the mucosa according to their partial pressure difference.

The process was analyzed for O_2 and N_2 gases only.

RESULTS

The diffusion of gases at constant atmospheric pressure shows Table 8.

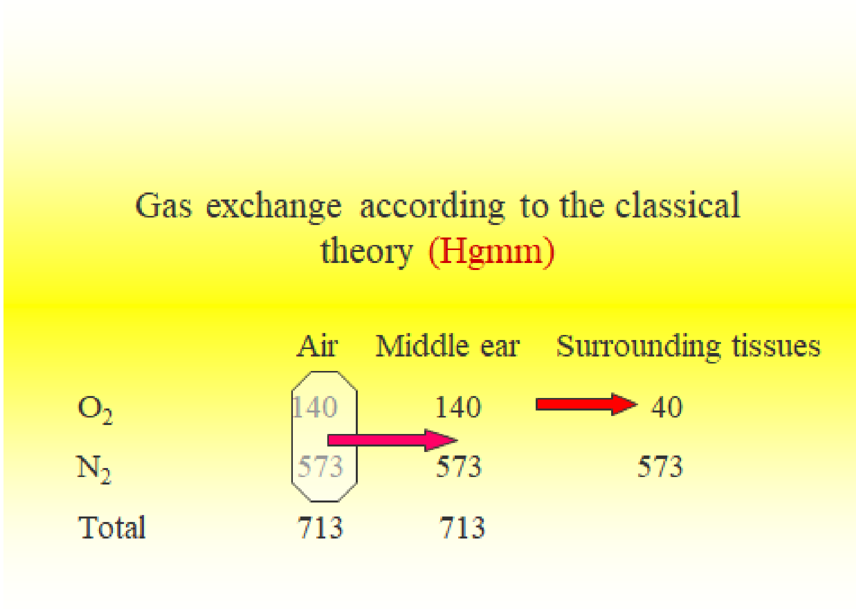

Table 8.

This is actually the classic theory. The middle ear is filled with air / 21% oxygen, 79% nitrogen /. Oxygen diffuses in the ST according to its pressure gradient, the pressure in the ME cavity decreases. The ET opens and compensates for the pressure decrease with air (21% oxygen, 79% nitrogen). Therefore, the partial pressure of oxygen decreases and that of nitrogen increases in the ME (Figure 1,2.) As a result, at one point, more and more nitrogen diffuses into the surrounding tissues (Figure 3).

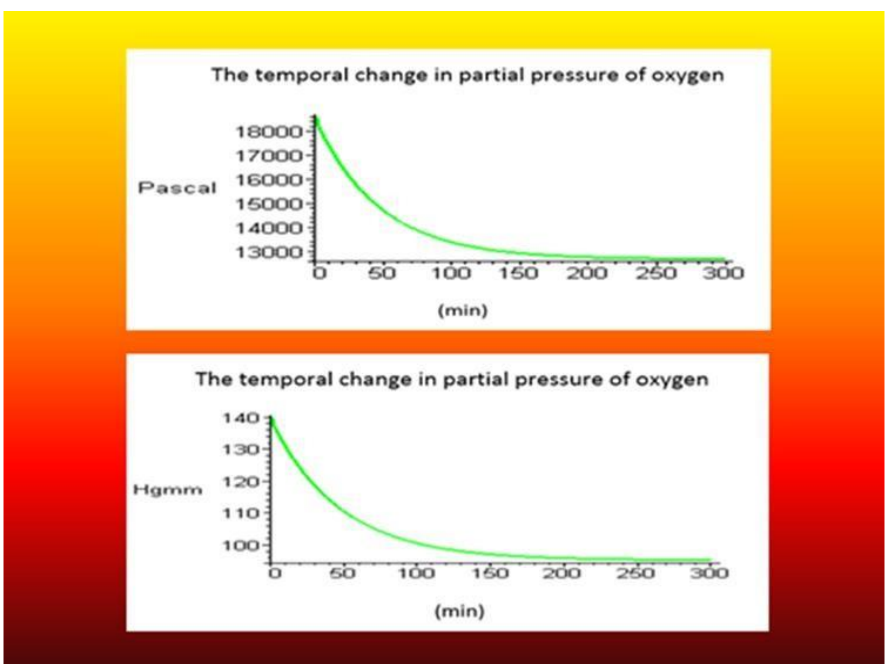

Figure 1.

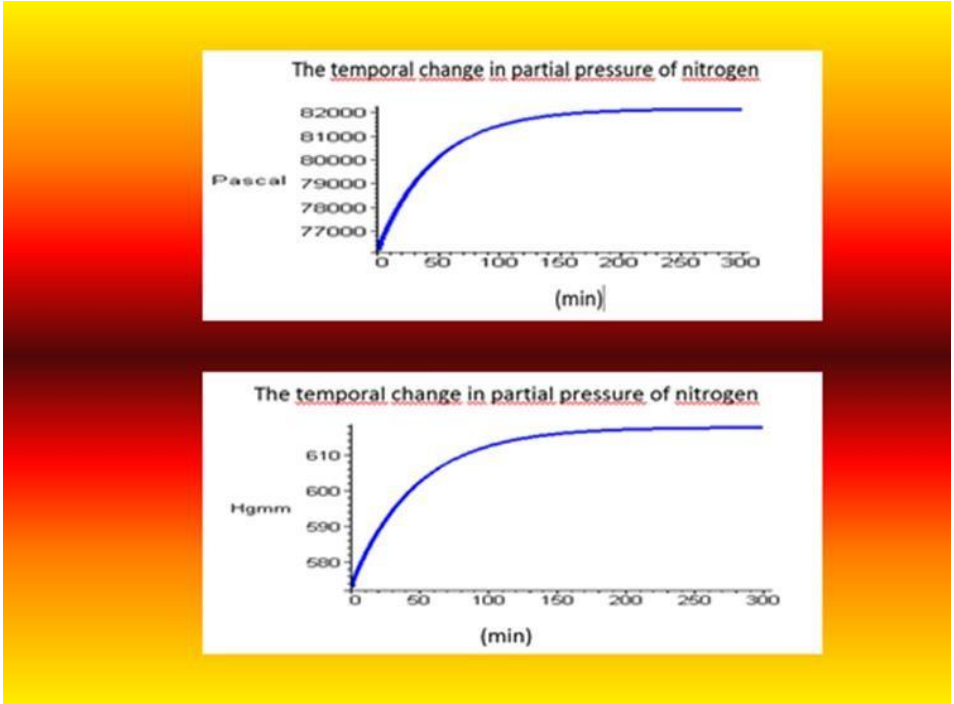

Figure 2.

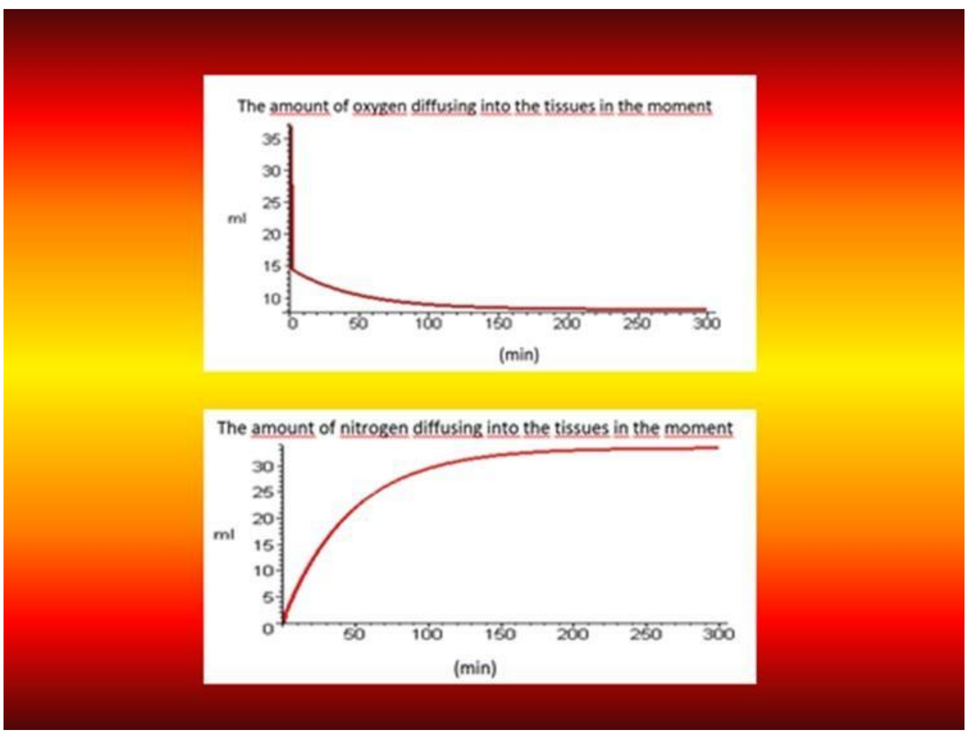

Figure 3.

If nitrogen is replaced by air, the process is reversed. The partial pressure of oxygen increases and that of nitrogen decreases. The two processes take place in parallel, then process stabilizes when the ratio of nitrogen to oxygen absorption is 21:79 as it is replaced or the same amount of gas is absorbed from oxygen and nitrogen. /Supporting information/ The partial pressure changes of O_2 and N_2 and total pressure are shown figures 4-6. Gas exchange takes place in a similar way, starting from the optimal gas composition, only the equilibrium state is reached earlier in time. (Table 2,3).

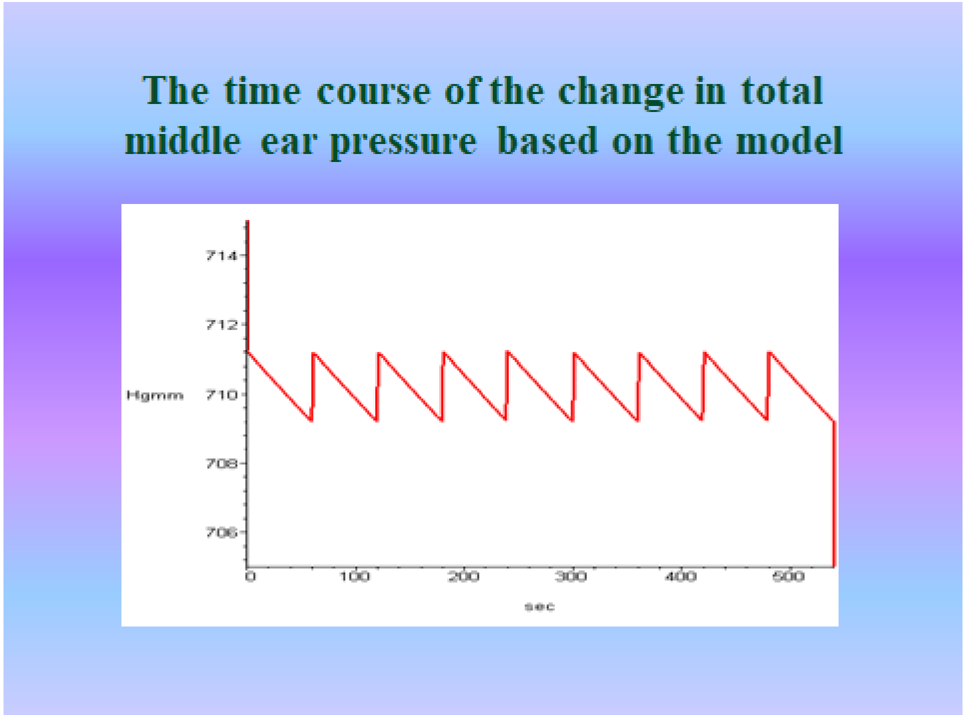

Figure 4.

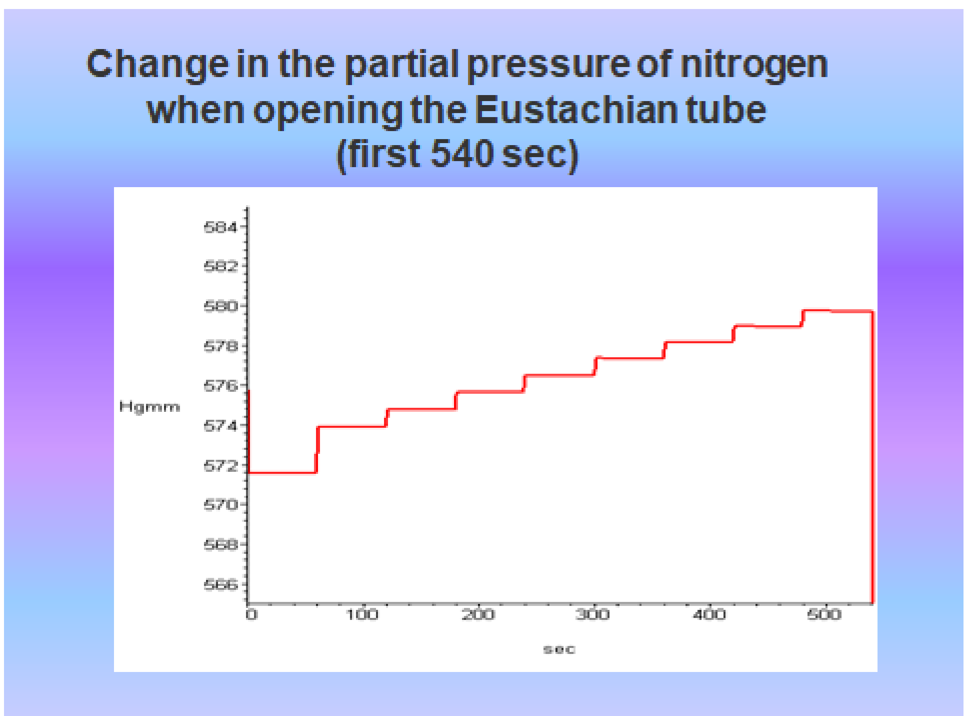

Figure 5.

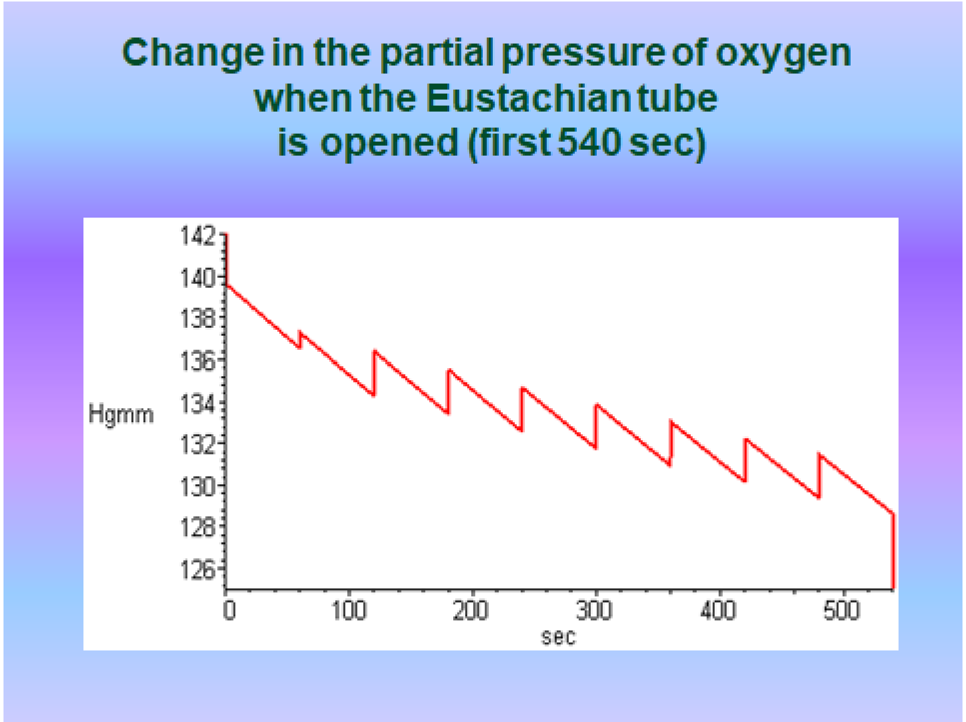

Figure 6.

A similar process takes place with increasing air pressure. When the ET opens, air flows into the middle ear. The partial pressures of O_2 and N_2 increase by 21:79, the absorption of O_2 and N_2 increases, absorption ratio changes slightly and then returns to 21:79. With constant and increasing air pressure, the partial pressure of carbon dioxide is essentially unchanged, which corresponds to the surrounding tissues.

The steady state lasts until the air pressure changes.

As the air pressure decreases, if the ET opens the gases flow outwardly through the ET according to their percentage composition and reduce the partial pressures of oxygen, carbon dioxide, and nitrogen in the ME. In the normal state, the partial pressure difference of O_2 and N_2 between the middle ear and the surrounding tissues is around 50-60 mmHg /Supporting information/. This pressure difference is sufficient to compensate for the athmospheric pressure decrease. As the diffusion coefficient of carbon dioxide is the best (20 times better than oxygen /, a slight, transient pressure increase may occur in the middle ear.

In the event of a sudden drop in air pressure greater than 50-60 mmHg, if the partial pressures of O_2, N_2, and CO_2 in the ME fall below the level of the surrounding tissues, O_2, N_2, and CO_2 may diffuse into the middle ear. This can cause a transient, two-peak pressure rise in the ME. / CO_2 faster and bigger wave, O_2 and N_2 slow, elongated curve./

Compensating for a sudden drop in air pressure is the most difficult task in middle ear ventilation.

With increasing and constant air pressure, the Eustachian tube equalizes towards the middle ear cavity, with decreasing air pressure, it equalizes towards the outside world, in which case the direction of diffusion may change according to the partial pressures differences in the middle ear.

Because diffusion and flow through the ET is a passive process, the ME ventilation is controlled by the active ET opening.

.

The ET creates, the gas diffusion equalizes for the partial pressure differences between the middle ear and the surrounding tissues.

CONCLUSIONS

THE MIDDLE EAR VENTILATION CHARACTERISTICS.

Gas flow across the ET and gas diffusion between ME and ST is a two-way process.

The ME pressure decrease is always equalized with air (21% O_2, 79%N_2)

The pressure decrease is caused by the absorption of O_2 and N_2 in the middle ear.

A pressure equalizes /air flow/ and the gas diffusion passive process

The gas diffusion continuous, the pressure equalization intermittent.

Diffusion of a certain amount of gas (O_2, N_2, CO_2) causes a greater pressure decrease in a smaller volume in the ME.

In the ME the pressure decrease due to nitrogen or oxygen absorption is always compensated by air /21% Oxygen, 79% Nitrogen/. When the absorbed oxygen or nitrogen is replaced by air, it changes the partial pressure of oxygen and nitrogen in the ME in the opposite direction.

Ventilation of the ME is the result of a complex, dynamic process controlled by the active ET opening. The ME is a closed cavity, which is opened time to time. This is the most important statement of ME ventilation.

We designed a valve tube that is closed and opens intermittently. Accordingly, we designed a tympanostomy tube that performs this task.

VALVULAR TYMPANOSTOMY TUBE

The following figures 7-10 show the structure of valve tube

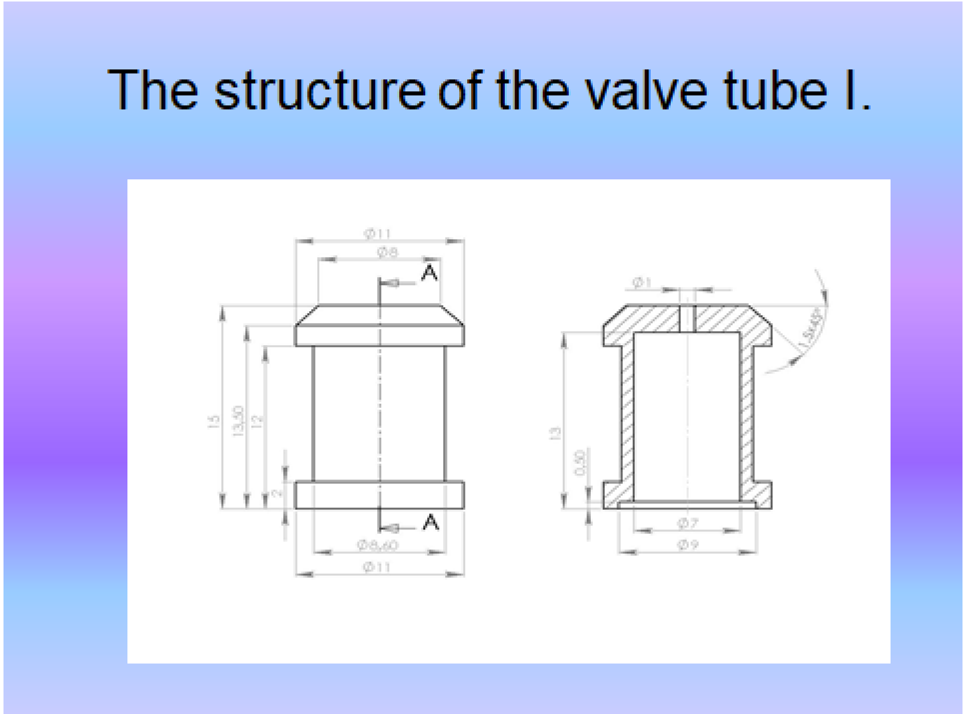

Figure 7.

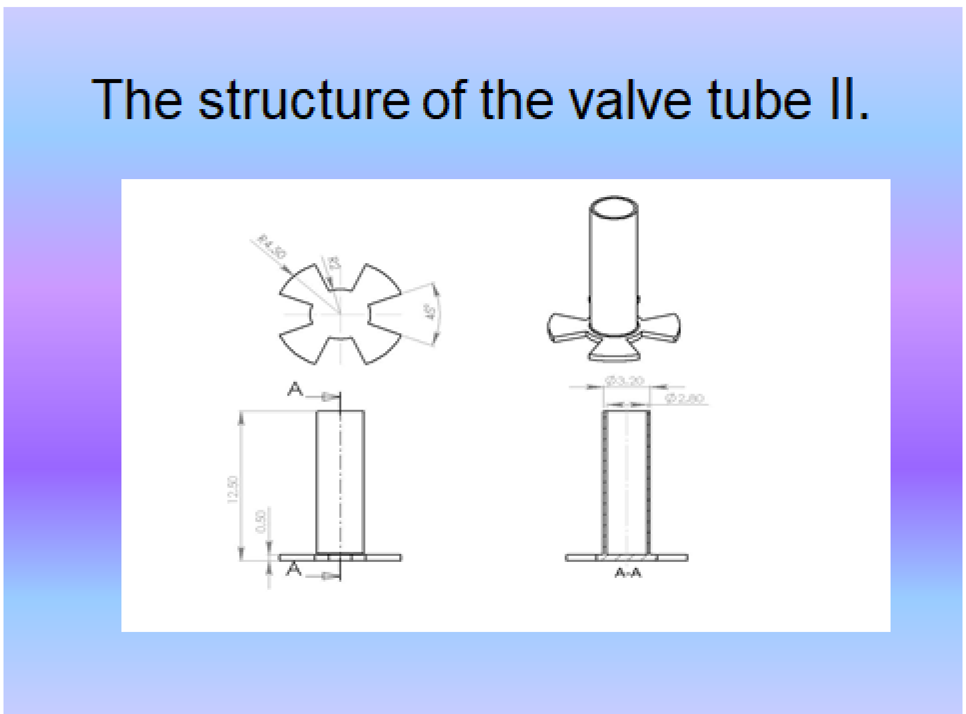

Figure 8.

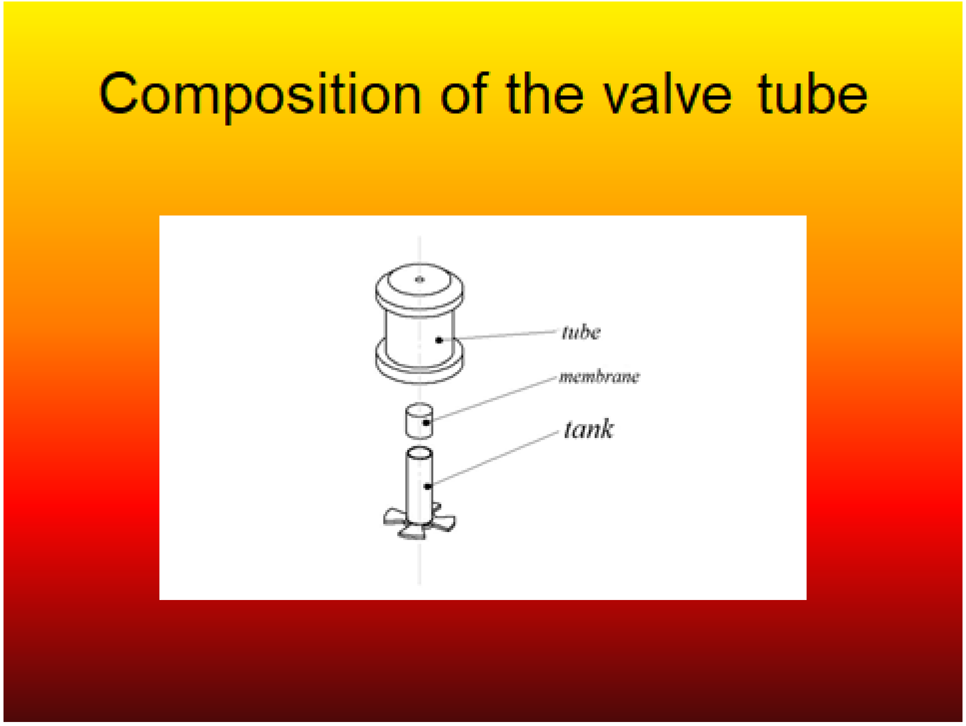

Figure 9.

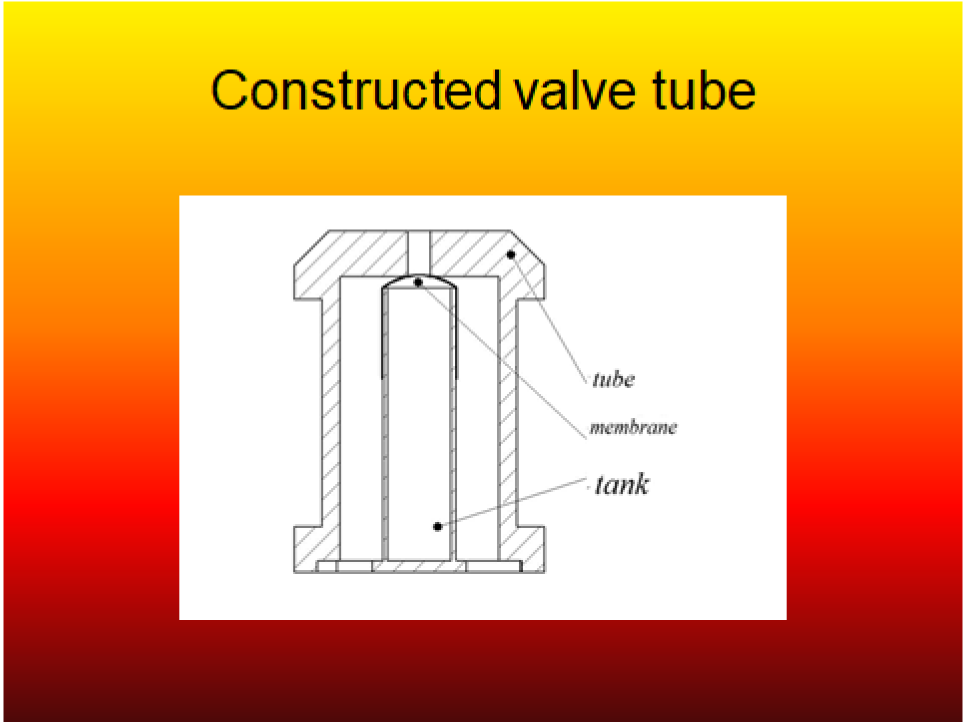

Figure 10.

The temperature of the human body can vary widely. It is known that in muscle work, body temperature can be as high as 40 degrees Celsius.
The valve container should be filled with a fluid boiling point around body temperature to move the valve diaphragm. The membrane material is flexible or flexible plastic. During physical activity, the body temperature rises and the liquid enclosed in the tank boils, expands, which closes the valve. At rest, the body's temperature decreases, the fluid cools, its volume decreases, thus opening the valve. Diethyl ether ($C_4H_{10}O$) has a boiling point of 36.4 ° C and may be suitable for valve operation (Figure 11).

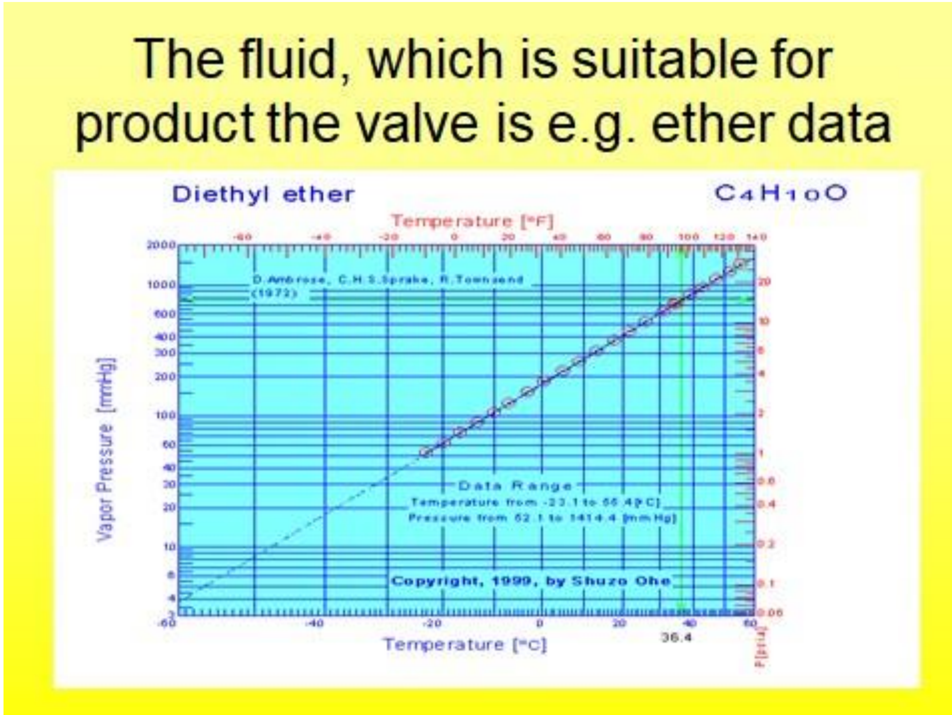

Figure 11.

DISCUSSION

Our valve tube is regulated by the volume change due to the change in body temperature, its preparation is a technical task.

The operation of the valve can be controlled by the full pressure difference, the partial pressure differences, the pulses of the chemo-mechanoreceptors. By setting the opening time, changes due to thesurface / volume ratio can also be compensated and monitored. The idea can probably be solved with nanotechnology.

Abbreviations

ET :Eustachian tube
ME :middle ear
ST :surrounding tissues
PP :partial pressure
PPD :partial pressure difference

Competing Interests

The authors declare that they have no competing interests.

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Supporting Information

Gas exchange
At constant air pressure
Equilibrium can theoretically be achieved in two forms

Steady state 1

Partial pressure difference between O_2 and N_2 in the middle ear.
The partial pressures of oxygen and nitrogen changes during pressure equalization until the same amount of gas is absorbed from oxygen as from nitrogen.
This is when the balance is reached

E.g.: 10-10 ml O_2 and N_2 is absorbed, and is replaced it with air

O_2 21% $O_2 \downarrow$ 2,1ml
$\Rightarrow$ **O_2**
N_2 79% $N_2 \uparrow$ 7,8 ml
end result = O
O_2 21% $O_2 \uparrow$ 2,1ml
$\Rightarrow$ **N_2**
N_2 79% $N_2 \downarrow$ 7,8 ml 2.

So if I replace 10 ml of absorbed oxygen with air, the partial pressure of oxygen decreases, the nitrogen increases
If I replace 10 ml of absorbed nitrogen with air, the partial pressure of oxygen increases, the nitrogen decreases. The result is zero, steady state was created.
The amount of gas absorbed is given by the product of the partial pressure differences and the diffusion coefficients.
The same amount of gas is absorbed from O_2 and N_2 when the ratio of the partial pressure between O_2 and N_2 is 1:5, i.e. 5 times. In the middle ear, the partial pressure and the total pressure do not change. The result of the gas exchange is 0 i.e. zero
For example

OXIGEN/mmHg/	Absorbed volume of O_2	NITROGEN/mmHg/	Absorbed volume of N_2
1 PPDx 20 DC=	20ml	5 PPDx 4 DC=	20ml
10 PPD x 20 DC=	200ml	50 PPD x 4 DC =	200ml
20 PPD x 20 DC=	400ml ??	100 PPD x 4 DC=	400ml ??

The last line is incorrect. There are no such partial pressure differences between the middle ear and the surrounding tissues.
The above equilibrium is reached when the partial pressure difference of oxygen is between 1-10 mmHg and that of nitrogen is between 5-50 mmHg between the middle ear and the surrounding tissues.
Partial pressure in the middle: O_2=41-50 mmHg, N_2=578-623mmHg
O_2:N_2= 1:1 absorption
O_2:N_2=1:5 partial pressure difference
Diffusion constant : O_2:N_2=20:4=5
PPD= partial pressure difference

Dc=diffusion constant
$\downarrow$ = partial pressure decrease
$\uparrow$ = partial pressure increase

Steady state 2

As much is absorbed as it is replaced
Partial pressure differences between middle ear and surrounding tissues
If the partial pressure difference between the middle ear and the surrounding tissues for O_2 and N_2 gases is 1:20, then the absorption of O_2 and N_2 takes place in a ratio of 21:79 as it is replaced by air / 21: 79 / $\approx$ 4x
For example
Partial pressure differences of O_2 and N_2 between ME and ST

OXIGEN	Absorbed volume of O_2	NITROGEN	Absorbed volume of N_2
1 Hgmm x 20 DC=	20 ml	20 Hgmm x 4 DC=	80ml
2 Hgmm x 20 DC=	40 ml	40 Hgmm x 4 DC=	160ml
2,5 Hgmm x 20 DC=	50 ml	50 Hgmm x 4 DC=	200ml
3 Hgmm x 20 DC=	60 ml ??	60 Hgmm x 4 DC=	240ml ??

The last line is incorrect. The maximum partial pressure difference for N_2 can be around 50 mmHg. This is the same as the measured and computer results measured. / 616 mmHg in the middle ear /
The absorption ratio of O_2 and N_2 is 21:79. / about 4x / As much is absorbed as it is replaced.
The steady state lasts until the air pressure changes.
O_2:N_2=21:79 ≈ 1:4 absorption
O_2:N_2=1:19 ≈20 partial pressure difference between ME and ST
This requires partial pressures of 41-42,5 mmHg, O_2 and 593-623 mmHg N_2 in the middle ear.
Steady state 1 equilibrium occurs with decreasing air pressure, steady state 2 with constant and increase air pressure.

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