The oxygen exchange through the mucosa of the maxillary sinus

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SUMMARY

The absorption of oxygen from the maxillary sinus in normal persons and in persons with acute sinusitis or allergic rhinitis was examined with a small pO_2 electrode introduced into the maxillary sinus. The maxillary ostium was blocked with a tampon in the healthy subjects, while the patients had spontaneously obstructed ostia. The antral gas was experimentally exchanged for atmospheric air in all of the pathological cases and in two of the normal subjects. The blood flow of the antral mucosa was measured plethysmographically in 2 of the healthy subjects.

There was found an oxygen absorption in the normal sinus of 0.117 ml/min corresponding to an absorption of 0.002 ml/min · cm² mucosa when the oxygen tension in the sinus was 116.5 torr, which in a previous study was found to be the mean oxygen tension in normal cases with patent ostia. This absorption is considerably greater than previously reported by other authors.

There is a slightly faster decrease in the oxygen content in diseased sinuses.

The blood flow was found to be insufficient to transport all the absorbed oxygen from the mucosa. There was found a remainder of 0.1 ml/min which the blood would not be able to bind. This amount is considered to represent the oxygen consumption in the mucosa.

There is thus a perfusion-limited oxygen absorption by the mucosa in the maxillary sinus and probably no diffusion-limitation in the normal sinus. However, a diffusion-limitation in pathological cases cannot be excluded since such a limitation may be possible if the absorbent layer is thick.

INTRODUCTION

THE gas exchange in the paranasal sinuses takes place via two routes, namely through the ostium and mucosal lining. The diffusion through the ostium obeys, as has been shown in model experiments (Aust and Drettner, 1974a) and will be illustrated by experiments on living humans (Aust, 1974), simple physical laws and is dependent on the size of the ostium, the volume of the sinus and the respiratory work in the nose.

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The gas oxygen exchanges through the antral mucosa is more complicated, and has been subject of a number of investigations. Doiteau (1955) and Flottes et al. (1960) performed measurements of the gas content in frontal sinuses of dogs in which the naso-frontal duct had been blocked. Samples were taken out at different periods of times and analyzed. There was found an absorption of oxygen from the sealed sinus and a decreasing oxygen content, to about 9% after 3 hours (Doiteau, 1955), and an increase of CO_2 to about 4.5%—5%. The oxygen absorption was calculated to be 0.003 cm^3/min in a sinus with a volume of 6 cm^3 (Flottes et al., 1960). Measurements of the pressure changes showed an initial pressure increase, caused by a rapidly increasing CO_2, followed by a progressive pressure decrease caused by oxygen absorption but counteracted by mucosal swelling and transudation. After 5 hours the pressure was about 30 mm H_2O (2 mm Hg) below the atmospheric pressure.

The absorption of oxygen from the sinus is thought to be an important factor in the pathogenesis of sinusitis (Flottes et al., 1960; Naumann, 1964). Furthermore, the opinion that symptoms of vacuum sinus are due to a negative pressure in the sinus (Sluder, 1927; Söderberg, 1934; Ballenger & Ballenger, 1952) has by other investigators (Flottes et al., 1960) been replaced by a theory in which a low oxygen content is essential. A series of investigations of the pO_2 in the maxillary sinus of patients with sinusitis and pain in the forehead or over the maxillary sinus showed that pain could be present at various pO_2 levels in the maxillary sinus but was most prevalent at a low pO_2 value (Aust & Drettner, 1974b).

Measurements of gas exchange in subcutaneous gaspockets (Rahn and Canfield, 1955) and closed cavities (Loeschcke, 1956) have provided the basic knowledge also for gas exchange in middle ears and paranasal sinuses. The existing partial pressure of each separate gas regulates the diffusion of the gases. The total pressure of the dry gas in a tissue is 58 mm Hg below that of atmospheric air. This is the driving pressure which hypothetically should be able to cause a negative pressure of 58 mm Hg in a sealed cavity with rigid walls, even if such a value never has been measured experimentally.

Rahn & Canfield (1955) collected from the literature results from several hundred measurements in various types of closed pockets in man including pneumothorax and occluded bronchi. The oxygen tension in these varied between 0 and 100 mm Hg with the majority between 20 and 40 mm Hg while the carbon dioxide values varied between 35 and 90 mm Hg with a prevalence for 40 to 50 mm Hg.

The blood flow and the composition of the blood in the walls of a sealed gas cavity must be of importance for the changes in gas concentrations. Experiments concerning the exchange in the frontal sinus of cats were performed by Loring and Tenney (1973). They analyzed the question of whether gas absorption principally is diffusion-limited or perfusion-limited and found the latter to be of greatest importance. This is in agreement with the results of Flottes et al. (1960), but in contrast to reports in literature concerning subcutaneous gas pockets where

a principally diffusion-limited absorption has been found (Piiper et al., 1962). No direct measurements of the oxygen exchange through the mucosa of the human paranasal sinuses have been found in the literature.

The purpose of this work is to analyze the oxygen absorption in the mucosa of the maxillary in living man by directly recording the antral pO_2. The results will be divided between those obtained from healthy persons and those from patients with diseases of the paranasal sinuses. Furthermore, the oxygen exchange will be analyzed in relation to the blood flow of the mucosa, measured with a recently described method for plethysmography of the antral mucosa (Drettner and Aust, 1974c).

MATERIAL

Altogether 20 persons were examined. Ten of these were healthy subjects with normal rhinoscopy and normal X-rays of the paranasal sinuses. Ten were patients with diseases of the nose and/or sinuses. In altogether 8 of the persons the experimental procedure could not be performed due to incomplete tamponade of the ostium or to electrode trouble. These 8 consisted of 4 healthy and 4 non-healthy persons. The final material consists of 6 healthy and 6 non-healthy persons.

METHODS

The oxygen tension was continuously recorded during the experiments with a pO_2 electrode in a cannula introduced into the sinus through the lower nasal meatus (Aust and Drettner, 1972).

The patency of the ostium in the investigated sinus was examined with a cannula introduced into the sinus and a catheter in the nasal cavity, both being connected to an electromanometer (Drettner, 1965).

The blood flow of the mucosa of the maxillary sinus was studied plethysmographically in two of the normal persons with a method described in another paper (Drettner and Aust, 1974c).

All experiments were performed with the persons in a semi-recumbent position. The person who participated in the experiments were later examined roentgenographically for diagnosis and for calculation of the volume and surface area of the mucosa in the investigated sinus (Aust and Helmius, 1974).

PROCEDURE OF THE EXPERIMENTS

The persons were investigated according to two different procedures depending on the patency of the ostium.

1. *Patients with nasal or paranasal diseases*

After the initial pO_2 in the sinus had been measured and when the manometric studies showed that the ostium was obstructed, a third cannula was introduced in addition to the one with the electrode and the one connected to the manometer. Through the cannula connected to the manometer, preheated (36 °C) and water

vapour saturated air was blown into the sinus to flush out the old gas in the sinus through the cannula. When the antral gas had been exchanged for air, the two cannulas for gas exchange were withdrawn leaving the pO_2 electrode to measure the change of the antral oxygen tension. Experiments in living man showed that the holes from the two cannulas would not permit leakage of air if the pressure difference between the sinus and the nasal cavity was below 10 cm H_2O.

2. *Normal persons*

In healthy persons with patent ostia, the ostium was experimentally blocked with gauze moistened with otoguttae Terracortril cum polymyxin B (Pfizer) and the effect of the tamponade was checked with the equipment for study of the patency of the ostium. Xylocain aerosol spray (Astra) was used as anaesthesia. In some patients the tampon had to be replaced a few times before the ostium was completely obstructed.

When the ostium was blocked the cannula connected to the manometer was withdrawn and the electrode with its cannula introduced into the sinus. From the beginning of the tamponade there was a time delay before the ostium was sufficiently occluded and the electrode introduced into the sinus. The initial phase of the oxygen absorption was therefore lost. In order to study also this phase, atmospheric air was blown slowly through the cannula into the sinus and out through another after tamponade of the ostium and after introduction of the pO_2 electrode. The complicated procedure and the requirement of having a tampon which resisted the excess pressure in the sinus during blowing prevented the use of the procedure in all experiments. This procedure was used successfully in only two of the normal persons.

MATHEMATICAL ASPECTS

In a previous paper (Aust and Drettner, 1974a) the oxygen exchange in the maxillary sinus has been mathematically analyzed both concerning the exchange through the ostium and mucosa. When the ostium is occluded the exchange through the ostium is abolished and only exchange through the mucosa is relevant. The following equation was given for the mucosal exchange for occluded ostia.

$$p^t - b_p = (p^0 - b_p) \cdot e^{Q_1 t},$$

where p^t and p^0 are the oxygen tensions at the times t and 0 in the experiments, b_p is the oxygen pressure in the blood passing through the mucosa and Q_1 expresses the absorption of oxygen by the mucosa and is mathematically defined as

$$Q_1 = \frac{\alpha \, D \, F}{\zeta} \cdot \frac{RT}{V}$$

In this equation α is the absorption coefficient for the tissue. D the diffusion coefficient, ζ the thickness of the absorbent layer, F the surface area of the mucosa, R the gas constant, T the temperature (K°) and V the volume of the sinus.

RESULTS

Six normal persons were investigated successfully according to the described procedure. In two of them the sinus was filled with atmospheric air while in the remaining four the registration of the decrease in pO_2 was performed without changing the gas in the sinus experimentally.

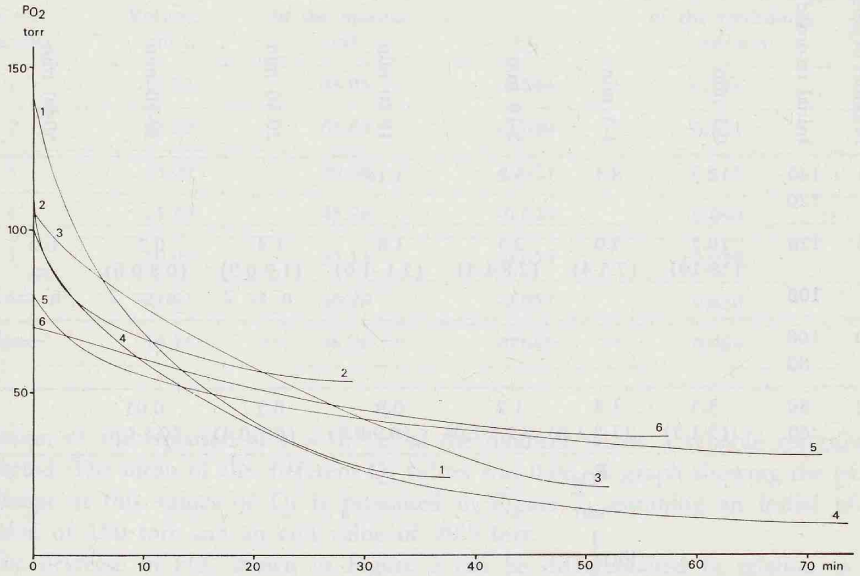

Figure 1. Recordings of the decrease in pO_2 of the maxillary sinus in 6 normal subjects after experimental obstruction of the maxillary ostium. In subjects number 1 and number 2 the gas in the sinus was also experimentally exchanged for air immediately before the recordings.

Figure 1 shows the results of these measurements. The recordings of the oxygen absorption for different persons formed a family of curves of essentially similar appearance. All absorption curves closely followed the theoretically calculated equation and when the absorption curves were analyzed mathematically with curve fitting to the theoretical equation, the mean correlation coefficient between the curves and the equation was found to be 0.99. The curve fittings were performed with a Hewlett Packard 9100 B calculator.

The mean end pO_2 in the experiments was found to be 29.5 torr. The decreases in pO_2 per minute during different periods of recordings are presented in Table I and the values are given in relation to the recorded initial pO_2 after tamponade and introduction of the electrode. The decrease per minute is, as seen, related both to the time of the experiment and the initial value.

Table II shows the results of the calculations regarding the volume of the sinus, the mucosal surface, the value of Q_1 and the absorption of oxygen per minute in the initial moment of the recordings. The latter value was obtained by differen-

Table I

The mean and the ranges of the decrease of the antral pO_2 in torr/minute during different time periods of the experiments in 6 normal persons with tamponade of the maxillary ostium. The values are presented in relation to the initial recorded pO_2 of the sinus.

Number of persons	Initial recorded pO_2	0-1 min	1-5 min	5-10 min	10-20 min	20-30 min	30-50 min	50-90 min
1	140 120	12	8.5	3.2	1.16			
3	120 100	10.5 (18-10)	5.0 (7.5-4)	2.5 (2.8-1.4)	1.8 (2.1.-1.0)	1.4 (1.9-0.9) n = 2	0.7 (0.8-0.6) n = 2	0.2 = n = 1
0	100 80	—	—	—	—	—	—	—
2	80 60	3.3 (5-1.5)	1.4 (1.8-1.0)	1.2 (1.3-1.0)	0.9 (0.9-0.8)	0.5 (0.7-0.4)	0.05 (0.5-0)	

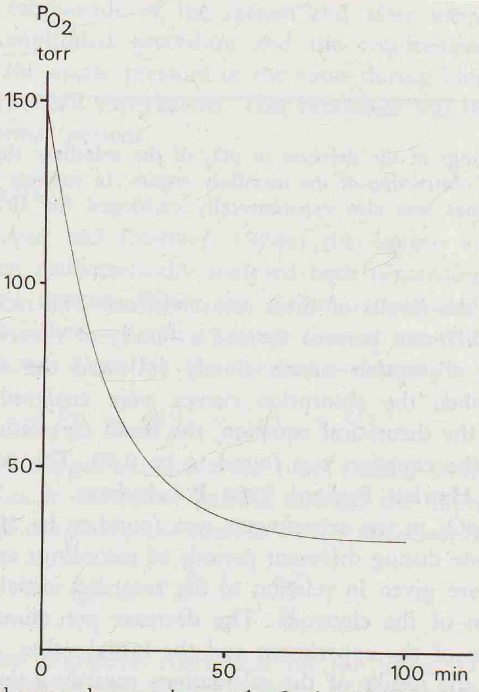

Figure 2. The calculated mean decrease in antral pO_2 in the normal subjects. The graph is constructed from the mean Q_1 of all these subjects. Assumed initial value 150 torr, i.e. the oxygen tension of water vapour saturated air at 760 torr.

Tabel II

The oxygen absorption in the six normal subjects at the beginning of the recordings. Subjects number 1 and number 2 were filled with atmospheric air at the beginning of the recordings.

Case number	Volume ml	Surface area of of the mucosa cm^2	Q_1	Absorption of oxygen in the sinus at the beginning of the recordings ml/min
1	14.93	43.95	-0.084	0.193
2	22.22	63.64	-0.049	0.131
3	13.09	39.68	-0.074	0.115
4	15.39	45.98	-0.046	0.090
5	10.09	35.13	-0.054	0.030
6	21.21	60.29	-0.052	0.030
Mean	16.16	48.06	-0.060	0.089

tiation of the equation at $t = 0$ i.e. at the moment where a reliable recording started. The mean of the different Q_1 values was 0.06. A graph showing the pO_2 change at this values of Q_1 is presented in Figure 2, assuming an initial pO_2 value of 150 torr and an end value of 29.5 torr.

The decrease in pO_2 shown in Figure 2 can be differentiated in relation to a decrease in volume. Figure 3 shows the result of such a differentiation with a volume of the sinus of 16.2 ml which was the mean volume of the investigated sinuses in the series of healthy persons. In this graph, which is obtained by differentiation of the graph in Figure 2, it is seen that the mean absorption of oxygen at a pO_2 of 116.5 torr was 0.117 ml/min corresponding to an absorption of oxygen of 0.002 ml/min · cm^2 mucosa in the sinus, since the mean mucosal surface area was 48.1 cm^2. The value 116.5 torr was chosen as it was the mean pO_2 in a series of normal sinuses with patent ostia presented in an earlier paper (Aust and Drettner, 1974b).

In two of the subjects in this series the blood flow in the mucosa was measured plethysmographically and the results are presented in Table III. The blood flow in the whole antral mucosa in these two subjects was 0.89 ml/min and 0.28 ml/min and the oxygen absorption 0.193 ml/min and 0.131 ml/min, respectively.

Patients with nasal or paranasal diseases

Six patients, all with spontaneously occluded ostia, were examined. Three of them had acute sinusitis with swollen mucosa seen roentgenographically. Air was seen roentgenographically in the sinus but the volume of the air-filled spatium was not examined.

The remaining three patients had allergic rhinitis with swollen mucosa partly

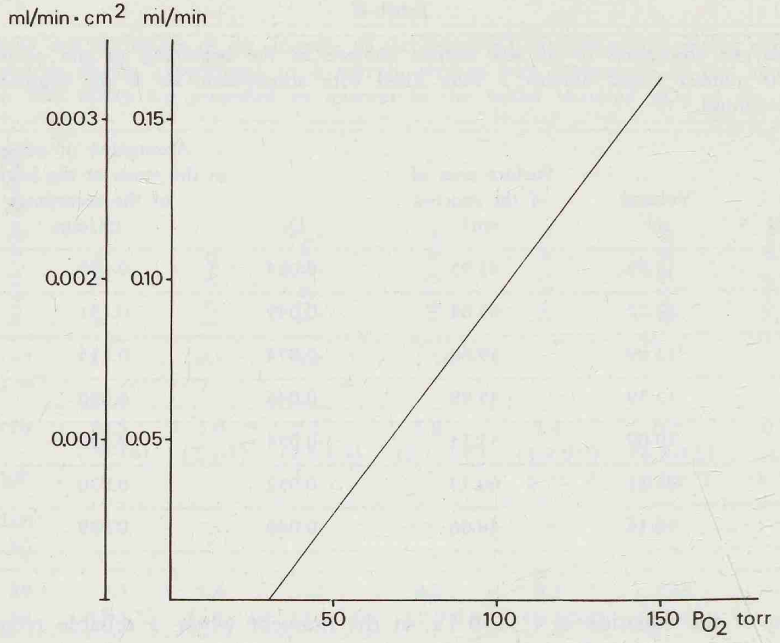

Figure 3. The mean oxygen absorption in ml/min and ml/min · cm^2 in normal maxillary sinus in relation to the pO_2. The graph is obtained by differentiation of the graph in Figure 2.

Table III

Results obtained in the two normal subjects who were investigated concerning oxygen absorption and mucosal blood flow.

Case number	Volume of sinus ml	Surface area of mucosa cm^2	Q_1	Oxygen absorption at the beginning of recording		Blood flow	
				per total mucosa ml/min	per surface area ml/min · cm^2	per total mucosa ml/min	per surface ml/min · cm^2
1	14.93	43.95	-0.084	0.193	0.004	0.89	0.02
2	22.22	63.64	-0.049	0.131	0.002	0.28	0.004

with polyps in the nose. X-ray of the maxillary sinuses showed air in the sinuses but the volume was not measured.

The results of the measurements of the decrease in oxygen tension in the sinuses are presented in Table IV. Mathematical analyses of the results showed that there was a somewhat more rapid decrease in the pathological cases than in the normal

persons. The mean Q_1 for the patients with sinusitis was 0.065 (correlation coefficient 0.99) and that for patients with allergic rhinitis 0.095 (correlation coefficient 0.88. As the surface area was not known in these cases a calculation of the absorption per cm² could not be performed.

Table IV

Mean and ranges of the decrease of the antral pO_2 torr/min during different time periods in 3 patients with acute sinusitis (S) and with allergic rhinitis (A). All had spontaneously occluded maxillary ostia. The values are presented in relation to the initial recorded pO_2 of the sinus.

Number of patients	Initial pO_2 torr	0-1 min	1-5 min	5-10 min	10-20 min	20-30 min	30-50 min	50-90 min
S 2	150	S : 6.0 (8.0-4.0)	S : 5.1 (6.7-3.5)	S : 3.0 (3.6-2.4)	S : 1.9 (2.1-1.6)	S : 1.4 (1.4-1.3)	S : 0.4 (0.5-0.3)	
A 1	130	A : 3.0	A : 2.5	A : 1.6	A : 0.9	A : 0.8	A : 0.2	
S 0	130							
A 1	110	A : 3.0	A : 3.0	A : 2.0	A : 1.4			
S 0	110							
A 0	90							
S 1	90	S : 2.0	A : 1.5	A : 0.6	A : 0.6	S : 0.4		
A 0	70							
S 0	70							
A 1	50	S : 2.0	S : 1.0	S : 1.0	S : 6.0	S : 0.3	S : 0.1	S : 0.1

DISCUSSION

Previous methods used for studies of the absorption of oxygen in the paranasal sinus have been complicated and offered only possibilities to analyze samples of gas removed from the investigated sinus at sertain intervals. Doiteau (1955) and Flottes et al. (1960) used a system for examination of the gas exchange in the frontal sinuses of dogs which contained a pump and a gas analyzer. Samples of gas were pumped from the sinus to the analyzer every 20th minute but it must have been difficult to keep the sinuses and system as an air-tight closed circuit even when the pump worked. Furthermore, this technique made it impossible to follow fast changes in gas tensions in the intial phase of their experiments. They found an oxygen absorption of 0.003 ml/min in the frontal sinus with a volume of 6 ml.

In our experiments we used a small pO_2 electrode placed in the investigated sinus giving a continuous measurement of the oxygen tension in the sinus.

In our experiments we found a mean oxygen absorption of 0.117 ml/min or 0.002 ml/min per cm² mucosa, which is considerably greater than found by

Doiteau and Flottes et al. in the sealed frontal sinuses of the dogs. When the difference in volume between the human maxillary sinus and the frontal sinus in dogs is taken into consideration, the absorption per surface area was found to be about 15 times greater according to our investigation than in that by Flottes et al. Our result is in this comparison taken as the mean absorption at an oxygen tension of 116.5 torr in the sinus.

However, the findings of Flottes et al. cannot be directly compared with our values since their result is based on the decrease in oxygen content during the first 20 minutes. If the graph in Figure 2 is read in a similar way starting at 130 torr and extrapolating 20 minutes forwards, the total decrease is found to be 73 torr which means an absorption of 0.08 ml/min.

When the differences in volumes are taken into consideration, again our result will still be 10 times greater than that reported by Flottes et al. It is thus obvious that he difference between our values and those of Flottes et al. can only partly be explained by the fact that they only could measure after a period of 20 minutes. A real underestimation of the absorption in the latter investigation seems probable and can be referable to the differences in methods. However, no direct comparison can be performed between the human maxillary sinus and the frontal sinus in dogs, especially since the dogs also were under general anaesthesia.

The presented results can also be analyzed concerning the problem of a diffusion-limitation to the absorption of oxygen. Flottes et al. found that a theoretical oxygen absorption only limited by diffusion should be 30 times greater than that really found, or 0.004 ml/min · cm^2. This value is only slightly greater than our value 0.002 ml/min · cm^2. It thus seems probable that a diffusion-limitation is not generally present but may occur sometimes.

Flottes et al. assumed a thickness of the absorbent layer of 0.1 mm in their calculations. Since the whole mucosa is said to be 0.125 mm thick (Loring and Tenney, 1973), the absorbent layer is probably thinner which would increase the theoretically calculated absorption before a diffusion-limitation can occur. Another factor of importance is the diffusion coefficient which was assumed to be the same as that in water by Flottes et al., while that in tissues is lower (Handbook of Respiration, 1958). The importance of the thickness of the absorbent layer is, however, greater and since this is unknown the problem concerning a diffusion-limitation cannot be answered directly from the results of the oxygen absorption but must be considered in relation to the blood flow. Only one of the factors, diffusion-limitation or perfusion-limitation can generally be present simultaneously. From our results it seems likely that a diffusion-limitation may occur if the absorbent layer is thick which is conceivable in cases with mucosal swelling. The present investigation cannot illustrate these questions since the absorption per mucosal surface area in the pathological cases could not be calculated. However, the decrease in pO_2 was somewhat more rapid in the diseased sinuses than in the normal ones. The relative importance of different effects in these cases cannot be judged, e.g. mucosal thickness and surface area, blood flow, oxygen consumption in the mucosa and in an exsudate, etc.

The blood flow in the mucosa was studied plethysmographically in two of the healthy patients together with the absorption of oxygen. These results provide a possibility to analyze the question of perfusion-limitation. The blood flow in the whole mucosa was 0.89 ml/min and 0.28 ml/min, respectively. These values are at each end of the range in material published in another paper (Drettner and Aust, 1974c). If the available oxygen saturation of haemoglobin is assumed to be 45% (based on a pO_2 in venous blood of 30 torr, i.e. an oxygen saturation of 55%), and using an oxygen capacity of 0.2 ml O_2/ml blood, the maximal uptake of oxygen by the blood in these two subjects should be 0.08 ml/min and 0.026 ml/min, respectively. The first subject had a total oxygen absorption of 0.193 ml/min and the second 0.131 ml/min. The additional oxygen not taken up by the blood was 0.11 ml/min in both cases. The oxygen capacity of the blood was thus not sufficient to take up all the oxygen which was absorbed by the mucosa. This means, that there is a perfusion-limitation for the oxygen absorption and also that the rest must be used for oxygen consumption in the mucosa. With such a relatively great remaining portion it seems probable that the perfusion-limitation dominates in the normal maxillary sinus and there is usually no diffusion-limitation of importance.

The rest of the oxygen is thus assumed to be used for consumption. An oxygen consumption of 0.155 ml/min per g dry tissue has been published for gastric mucosa (Handbook of Biological data, 1966). When considering that dry tissue may be 1/3 of wet tissue and that this result is obtained in vitro giving an oxygen consumption of about half of that in vivo (Artursson, 1974), our value of 0.1 ml/min for the total antral mucosa of about 0.5 cm^3 seems reasonable. The plethysmographic method has several errors involved (Drettner and Aust, 1974) which all work in the direction of giving too low values. If the blood flow is greater than measured, the rest of oxygen available for consumption would be less. However, the blood flow can hardly be considerably greater than the measured values, since already the recorded values mean that the antral mucosa has a blood flow which is great in comparison with that of other organs of the body. These errors can thus not change the obtained values about the blood flow to such an extent that the oxygen capacity in the blood should not be completely utilized.

ZUSAMMENFASSUNG

Die Sauerstoffabsorption in der Kieferhöhle gesunder Personen und Patienten mit akuter Sinusitis oder allergischer Rhinitis wurde mit einer kleinen pO_2-Elektrode untersucht, die in die Kieferhöhle eingeführt wurde. Bei gesunden Personen wurde das Kieferhöhlenostium tamponiert, während es bei Patienten krankheitsbedingt verschlossen war.

Das Gas der Kieferhöhle wurde experimentell gegen atmosphärische Luft bei den sechs pathologischen Fällen und bei zwei der sechs gesunden Personen ausgetauscht. Der Blutfluss der Kieferhöhlenschleimhaut wurde bei zwei gesunden Personen plethysmographisch gemessen.

In der normalen Kieferhöhle wurde eine Sauerstoffabsorption von 0.117 ml/Min. festgestellt, was einer Absorption von 0.002 ml/Min. · cm^2 Schleimhaut entspricht, wenn der Sauerstoffbereich im Sinus 116.5 torr war. In einer vorhergehenden Studie wurde festgestellt, dass dies der durchschnittliche Sauerstoffbereich bei normalen Fällen mit offenem Ostium ist. Diese Absorption ist beträchtlich grösser als bei anderen Autoren gefunden wurde.

Bei kranken Kieferhöhlen nahm der Sauerstoffgehalt etwas schneller ab.

Es wurde festgestellt, dass der Blutfluss nicht ausreicht den gesamten, von der Schleimhaut absorbierten Sauerstoff weiterzutransportieren. Ein Rest von ungefähr 0.1 ml 0_2/Min. wurde gefunden, den das Blut nicht binden konnte. Dieser Rest wird als die Menge Sauerstoff angesehen, die die Schleimhaut verbraucht. Es gibt daher eine Perfusionsbegrenzung der Kieferhöhlenschleimhaut und wahrscheinlich keine Diffusionbegrenzung bei normalen Kieferhöhlen. Aber eine Diffusionsbegrenzung bei pathologischen Fällen kann nicht ausgeschlossen werden, weil eine solche möglich sein kann, falls die absorbierende Schicht dick ist.

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