Oxygen exchange through the maxillary ostium in man

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SUMMARY

The oxygen exchange through the maxillary ostium in living humans has been investigated. Twenty-five healthy persons were used in the experiments. The change in pO_2 in the sinus was continuously measured with a small pO_2 electrode placed in the sinus. The experiments started with filling the investigated sinus with nitrogen and the exchange for air was followed. The volume of the sinus was measured roentgenographically and the size of the maxillary ostium manometrically. In 4 persons the absorption of oxygen through the maxillary mucosa was also measured after tamponade of the ostium.

There was found a direct relationship between the ostial exchange and the functional cross sectional area of the maxillary ostium and an inverse relationship between the exchange and the volume of the sinus. The oxygen exchange through the ostium was twice as fast during nasal respiration as during oral breathing with blocked nostrils.

An interaction between mucosal absorption, ostial exchange and antral pO_2 seems to occur and the result is dependent principally on the size of the ostium. According to a previous paper (Aust and Drettner, 1974c) there is a relative insufficiency for oxygen exchange when the ostium is smaller than 5 mm^2. The pO_2 of the sinus is then depressed due to the absorption through the mucosa and this affects the driving oxygen pressures over the ostium and over the mucosa, in a way faciliating a greater ostial exchange and a smaller absorption, i.e. giving a feed back system.

THE ventilation of the maxillary, as well as the other paranasal sinuses, takes place partly through the ostium of the sinus and partly through the mucosa.

The exchange through the ostium has been discussed and investigated by different authors. Proetz (1953) calculated theoretically that one promille of the sinus volume was exchanged during each breath and that the exchange was due only to fluctuations in nasal breathing pressure. With a respiratory frequency of 16 breaths per minute, the exchange would take more than one hour. Doiteau (1955) and Flottes et al. (1960) performed gas analyzes of samples taken from the

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frontal sinuses of dogs. They calculated that 90% of the gas would be exchanged in 16 minutes, and found that the gas exchange through the ostium was principally due to diffusion and to a much lesser extent respiratory pressure changes in the nose.

Model experiments for investigation of the oxygen exchange through the maxillary ostium into the maxillary sinus have been performed (Aust and Drettner, 1974a). These experiment showed that the exchange through the ostium of the maxillary sinus was dependent on the size of the ostium, the volume of the sinus and the respiratory work in the nose, i.e. the product of the respiratory pressure and the airflow in the nose. The oxygen tension in the sinus is related to the size of the ostium which has been shown in a series of investigated subjects (Aust and Drettner, 1974c).

The aim of this work is:

1. to analyze the oxygen exchange through the maxillary ostium in man in relation to the exchange through the maxillary mucosa at different pO_2-values;
2. to correlate the oxygen exchange through the ostium to the size of the ostium;
3. to correlate the oxygen exchange through the ostium to the volume of the maxillary sinus and,
4. to study the oxygen exchange through the ostium in relation to nasal respiratory work.

MATERIAL

Twenty-five healthy persons were investigated concerning the exchange of oxygen through the maxillary ostium. They all had normal rhinoscopy and there was no pathological conditions seen roentgenographically in the nose or sinus. In 19 persons the oxygen exchange, the sinus volume and the ostial size were successfully investigated. In 3 subjects the oxygen exchange during nasal respiration was too rapid to be reliably measured with the present equipment and in 3 of the investigated persons the ostial size was not measured because of technical errors. In 4 of the patients in this series of experiments the absorption of oxygen through the mucosal lining of the sinus was measured.

METHODS

The oxygen exchange was registrered with a small pO_2 electrode introduced into the maxillary sinus through the inferior nasal meatus after anaesthesia of the nasal mucosa with Xylocain aerosol spray^R Astra. The experiments started with the introduction of the pO_2 electrode into the sinus and registration of the initial pO_2 in the sinus. Subsequently, the patency and size of the ostium were manometrically measured through two cannulas introduced into the sinus at the same place as the pO_2 electrode (Aust and Drettner, 1974b). One of the cannulas was then withdrawn and the other was used for filling the sinus with water vapour saturated, preheated (36°C) nitrogen. When the sinus was filled with

nitrogen ($pO_2 = 0$) the cannula for the nitrogen was closed and the examined person was asked to breath through his nose with closed mouth. The oxygen pressure rise from zero to steady state, which normally was reached at the same level as the initial pO_2 of the sinus, was continuously recorded by the pO_2 electrode and its recording equipment.

When the pO_2 had reached steady state the sinus was once again filled with nitrogen, prepared as previously stated, and the nostrils of the examined person were blocked with cotton. The persons were asked to breathe through the mouth and the oxygen exchange was registered.

Four of the subjects were there after examined with respect to the absorption of oxygen through the antral mucosa after tamponade of the ostium (Aust and Drettner, 1974d).

The investigated persons were roentgenographically examined for the determination of the sinus volume (Aust and Helmius, 1974).

The subjects were grouped with respect to ostial size and antral volume, and the oxygen exchange at oral breathing was compared with that at nasal breathing in order to get some information of the effect of nasal respiration on antral gas exchange.

MATHEMATICAL ASPECTS

The recordings of the oxygen pressure increase in the maxillary sinus after the air in the sinus had been experimentally exchanged for nitrogen have an exponential course. The curves obtained in the experiments are illustrating the combined effect of the oxygen exchange both through the mucosa and the ostium of the maxillary sinus. The equations for these exchanges have been described in an earlier paper (Aust and Drettner, 1974a). The absorption of oxygen through the mucosa of the maxillary sinus Q_1 follows the equation, when there is no exchange through the ostium,

$$p^t - {}^b p = (p^0 - {}^b p) \quad e^{Qit} \tag{1}$$

where p^0 and p^t are the partial pressure of the oxygen at the time 0 and t and ${}^b p$ is the partial pressure of oxygen in the blood passing the mucosa. The exchange of oxygen through the maxillary ostium Q_2 follows the equation,

$$p^t - p' = (p^0 - p' \setminus \quad e^{-Q_2 t} \tag{2}$$

where p^0 is the partial pressure of oxygen in the sinus at time 0, p' is the partial pressure of the oxygen in the nasal cavity and p^t is the partial pressure in the sinus at time t.

The graph obtained in the experiments in this investigation are thus a combination of Q_1 and Q_2 and is called Q,

$$Q = Q_1 + Q_2 \tag{3}$$

The exponents Q and Q_1 were obtained by curve fitting using a Hewlett Packard Calculator B 9100. In the 4 subjects where both Q and Q_1 were obtained, the exponent Q_2 was calculated.

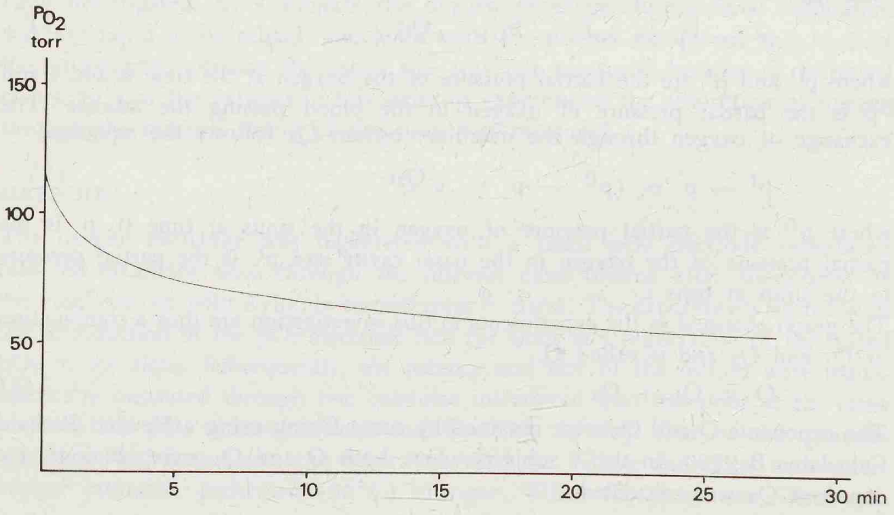
RESULTS

In 4 of the persons in whom the oxygen exchange through the maxillary ostium had been examined, the absorption of oxygen in the mucosa of the maxillary sinus after tamponade of the maxillary ostium was also examined. The mathematical expressions Q and Q_1 were calculated for each subject and from these values the Q_2 was also achieved by using equation (3).

The values for these 4 persons are presented in Table I. As seen in the table the mean Q_1 is about 6.7% of the mean Q_2.

Subject number 4 is used as an example and is illustrated in Figure 1. The absorption of oxygen in the mucosa Q_1 of the sinus was examined and the result is illustrated in Figure 1a. This graph was obtained by measuring the absorption of oxygen in the maxillary sinus after experimental blocking of the ostium (Aust and Drettner, 1974d). The mathematical expression Q_1 for this absorption-graph is 0.049. Figure 1b illustrated the oxygen exchange through the ostium in an experiment where the sinus initially was filled with nitrogen. The graph is obtained by measuring the rise in pO_2 due to the exchange through the maxillary ostium. The graph Q in Figure 1b is the graph obtained in the experiment, and contains both the exchange through the ostium and the absorption through the mucosa. In this experiment $Q = 0.681$. The exchange through the ostium without influence of the absorption of oxygen through the mucosa Q_2 is obtained by subtracting the absorption through the mucosa from the graph Q, illustrating the combined effect of exchange through the ostium and through the mucosa. $Q_2 = Q - Q_1$. In this experiment $Q_2 = 0.730$.

In the example in Figure 1b steady state of graph Q is reached at pO_2 112. At this steady state the inflow of oxygen through the ostium must be equal to the oxygen leaving the sinus through the mucosa.



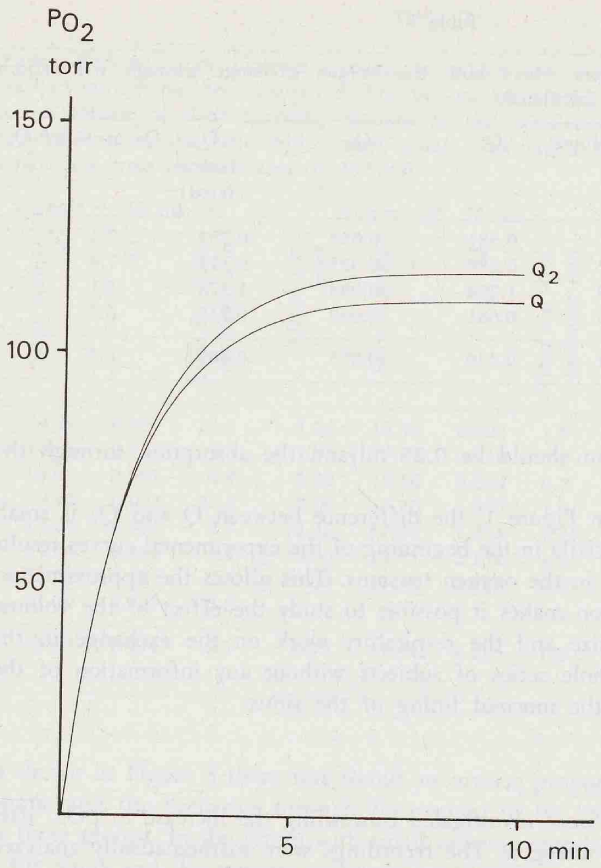


Figure 1. The oxygen exchange in the maxillary sinus of one healthy person. a. The absorption of oxygen in the mucosa of the maxillary sinus Q_1 obtained in an experiment in which the maxillary ostium was experimentally occluded. b. The registered oxygen exchange through the maxillary ostium Q obtained in an other experiment in which the maxillary sinus was filled with N_2 and the person who had a patent maxillary ostium was breathing through his nose. The graph Q_2 is the calculated oxygen exchange through the maxillary ostium without the influence of the absorption in the maxillary mucosa.

Differentiation of Q_1 and Q_2 at the point where they reach pO_2 112 gives an absorption of oxygen in the mucosa of 0.087 ml/min and a diffusion through the ostium of 0.084 ml/min.

For the 4 persons in this series the mean Q was 0.736, the mean Q_1 0.053 and the mean Q_2 0.789. The mean steady state at nasal breathing was 131 torr and the mean end value for the absorptions curves Q_1 was 40 torr.

If the absorption of oxygen in the mucosa and the exchange of oxygen through the ostium were calculated at pO_2 116.5 torr, which is the mean pO_2 in normal maxillary sinuses with patent ostia (Aust and Drettner, 1974c), the inflow of

Table I

Results obtained in 4 subjects where both the oxygen exchange through the ostium and through the mucosa was calculated.

Pat. No.	Ostial size mm_2	Sinus volume ml	Q	Q_1	Q_2 (calculated)	Q_1 as % of Q_2
1	1.43	10.1	0.381	-0.054	0.735	7.3
2	2.46	21.2	0.288	-0.025	0.313	7.9
3	—	14.9	1.294	-0.084	1.378	6.1
4	$\geqq$ 20.0	22.2	0.681	-0.049	0.730	6.7
Mean	7.96	17.1	0.736	-0.053	0.789	6.7

oxygen through the ostium should be 0.25 ml/and the absorption through the mucosa 0.10 ml/min.

As seen in Table I and in Figure 1, the difference between Q and Q_2 is small (mean 6.7%) which especially in the beginning of the experimental curves results in a negligable difference in the oxygen tensions. This allows the approximation $Q \simeq Q_2$. This simplification makes it possible to study the effect of the volume of the sinus, the ostial size and the respiratory work on the exchange in the maxillary sinus in the whole series of subjects without any information of the absorption of oxygen in the mucosal lining of the sinus.

EFFECT OF OSTIAL SIZE

Nineteen healthy persons were investigated concerning the increase in pO_2, after the sinus was filled with nitrogen. The recordings were mathematically analyzed and expressed as Q. The examined persons are presented in Table II.

The investigated subjects were placed into three groups depending on their sinus volume.

Figure 2 illustrates the relationship between the oxygen exchange Q and the ostial size. When the three groups were analyzed mathematically concerning Q and ostial size, there was found a direct proportionality between the ostial cross-sectional area and the Q in alle three groups. The mean time needed for exchange of 90% of the gas in the sinus was 4.9 min. The same type of relationship between the ostial size and the oxygen exchange through the maxillary ostium was found in the model erperiments performed prior to this investigation (Aust and Drettner, 1974a).

EFFECT OF SINUS VOLUME

The effect of the sinus volume on the oxygen exchange in the maxillary sinus was studied by arranging the subjects into three groups according to the ostial size. The three groups are presented in Table IV. One of the persons did not fit into any group.

Table II.

Results obtained from nineteen persons in which the oxygen exchange through the maxillary ostium has been registered. The persons are placed into three groups depending on the volume of their maxillary sinuses. In the calculation of the mean ostial cross sectional area of the ostia within each group ostia larger than 20 mm² was regarded as having a cross sectional area of 20 mm².

Volume 9 - 16 ml				Volume 16 - 20 ml				Volume 20 ml and larger			
Ostial size mm²	Sinus volume ml	Q	Time for 90% exchange min	Ostial size mm²	Sinus volume ml	Q	Time for 90% exchange min	Ostial size mm²	Sinus volume ml	Q	Time for 90% exchange min
0.15	14.27	0.207	13.1	1.26	18.50	0.902	1.5	2.46	21.21	0.228	9.7
0.27	16.93	0.082	3.6	1.95	17.87	0.130	5.8	6.60	21.45	0.274	8.8
1.43	10.9	0.681	4.8	5.22	16.50	0.264	0.7	≧ 20.00	22.22	0.681	0.3
1.45	9.90	0.073	21.2	7.00	15.20	1.997	1.0	≧ 20.00	23.05	0.466	6.9
4.26	13.04	0.993	2.7	12.26	17.96	1.354	1.75				
4.75	14.96	0.961	3.5	≧ 20.00	16.45	2.152	1.1				
7.00	15.59	1.474	2.4	≧ 20.00	17.78	2.200	0.85				
≧ 20.00	11.00	4.007	0.6								
4.9 (5.0)	13.10	1.494	6.5	9.71	17.44	1.286	1.8	12.58	21.98	0.407	6.4

As shown in Figure 3 there was found an inverse proportional between the sinus volume and the exchange through the ostium in the maxillary sinus in two of the three groups. In the group with small ostia no correlation between the volume of the sinus and the oxygen exchange was found.

In the other two groups there was, as shown in Table IV, the same inverse proportional between the exchange and the sinus volume in both groups.

EFFECT OF RESPIRATORY WORK IN THE NOSE

The respiratory work in the nose is the product of the respiratory nasal air flow and the nasal respiratory pressure. There was seen in the model experiments that there was an increased ventilation of the maxillary sinus with increasing nasal respiratory work. The nasal respiratory airflow and respiratory pressure variations could not be reliably measured in the present experiments due to the electrode and the cannula being placed in the nose during the measurements of the oxygen in the maxillary sinus. To get an idea of the defect of the nasal respiration on the oxygen exchange in the sinus, experiments were performed on six persons with similar antral volumes, first during nasal breathing, then during oral breathing with the nostrils blocked with cotton.

The resulting curves from the oxygen exchange measurements were analyzed and the Q for the types of experiments were plotted in a diagram in relation to

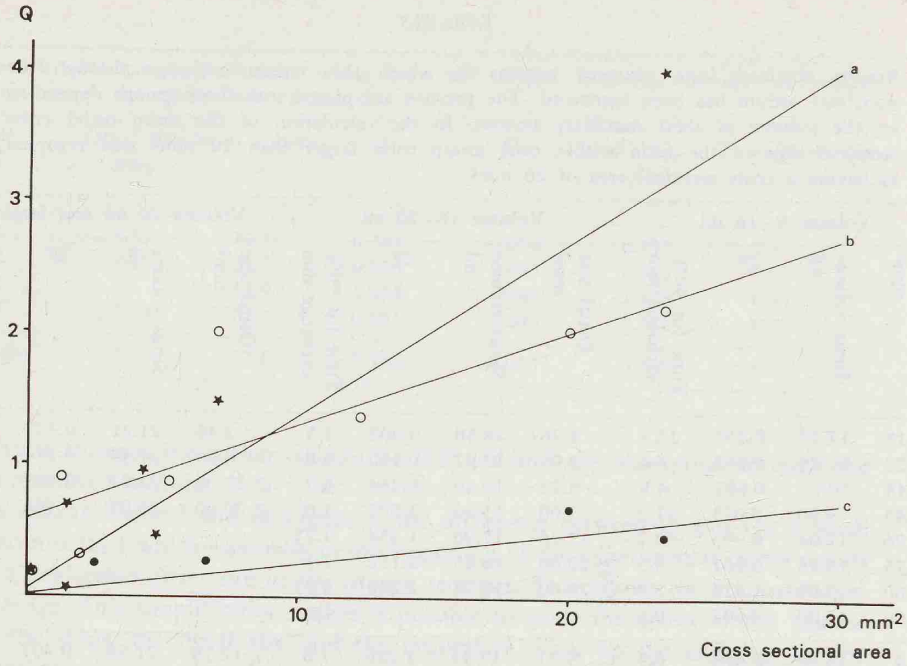


Figure 2. The relationship betwee the oxygen exchange Q in the maxillary sinus and the size of the maxillary ostium. The three lines represent three groups with different sinus volumes. Mean sinus volume a. 13.10 ml (9—16 ml) b. 17.44 ml (16—20 ml) and c. 20.0 ml.

the ostial size. There was also here found a linear relationship between ostial size and the Q within the two types of experiments. It was also seen that the Q for the experiments with nasal breathing were about twice as large as for oral breathing (Figure 4), which means that the exchange of oxygen through the ostium was twice as rapid during nasal respiration as during oral respiration with blocked nose.

DISCUSSION

The present investigation appears to be the first in which the oxygen exchange in the maxillary ostium has been studied for a relatively large group of human subjects. The method used in this investigation probably contains fewer errors than the earlier, much more complicated, methods. The use of pO_2 electrode has enabled continuous recordings so that both the absorption of oxygen in the sinus mucosa and the oxygen exchange through the ostium can be studied, even during rapid exchange.

It has been shown that in the extensively investigated sinuses in the series of 4 persons, the exchange of oxygen through the ostium is sufficient to counteract the absorption of oxygen in the mucosa at the pO_2 occurring in normal healthy

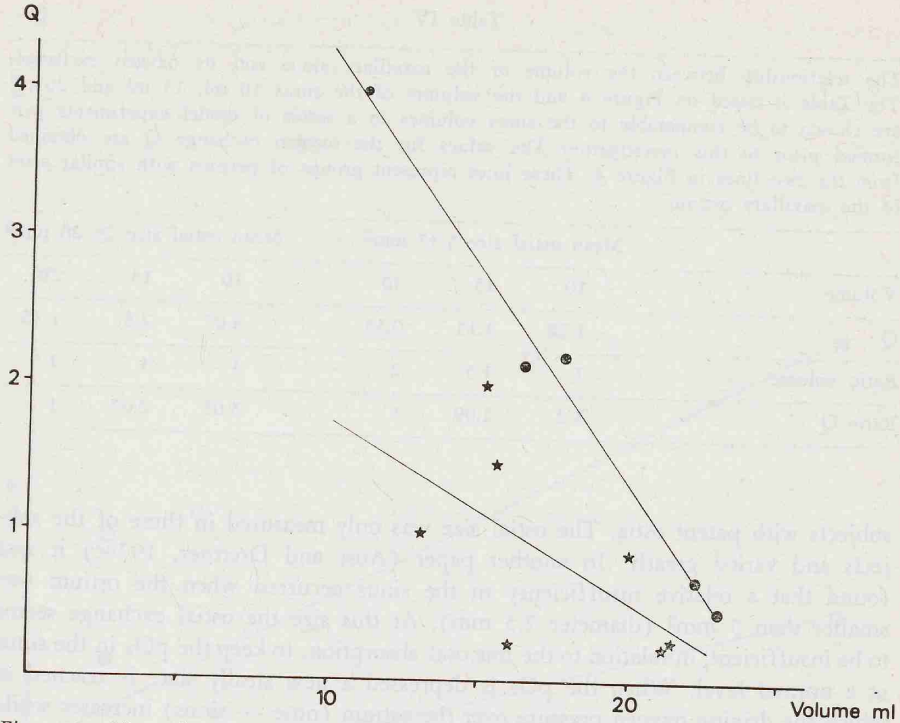


Figure 3. The relationship between the oxygen exchange Q in the maxillary sinus and the volume of the sinus. The two lines represent 2 groups with different ostial sizes. Mean ostial size a. 5.37 mm² (4—7 mm²) and b. 20 mm². The results obtained in cases with ostia smaller than 4 mm² are not included in the figure (see text).

Table III

Results obtained from eighteen persons in which the oxygen exchange through the ostium was measured. The persons are placed into three groups depending on the size of their maxillary ostia.

Ostial size 0.1 - 2 mm²			Ostial size 4.0 - 7.0 mm²			Ostial size 20 and more		
Sinus volume ml	Ostial size mm²	Q	Sinus volume ml	Ostial size mm²	Q	Sinus volume ml	Ostial size mm²	Q
9.90	0.46	0.073	13.04	4.26	0.993	11.1	> 20	4.007
10.9	1.43	0.681	15.20	7.0	1.997	16.45	20	2.152
14.27	0.15	0.207	15.59	7.0	1.474	17.78	> 20	2.200
16.93	0.27	0.082	16.05	5.55	0.246	22.22	20	0.681
17.87	1.95	0.130	19.96	4.75	0.961	23.05	> 20	0.466
18.05	1.26	0.902	21.21	2.46	0.228			
			21.45	6.6	0.274			
Mean 14.51	0.92	0.346	17.5	5.37	0.880	18.10	≧ 20	1.901

Table IV

The relationship between the volume of the maxillary sinus and its oxygen exchange. The Table is based on Figure 4 and the volumes of the sinus 10 ml, 15 ml and 20 ml are chosen to be comparable to the sinus volumes in a series of model experiments performed prior to this investigation The values for the oxygen exchange Q are obtained from the two lines in Figure 4. These lines represent groups of persons with similar sizes of the maxillary ostium.

	Mean ostial size 5.37 mm^2			Mean ostial size $\geq$ 20 mm^2		
Volume	10	15	20	10	15	20
Q	1.78	1.15	0.55	4.07	2.8	1.35
Ratio volume	1	1.5	2	1	1	1.5
Ratio Q	3.2	2.09	1	3.01	2.07	1

subjects with patent ostia. The ostial size was only measured in three of the subjects and varied greatly. In another paper (Aust and Drettner, 1974c) it was found that a relative insufficiency in the sinus occurred when the ostium was smaller than 5 mm^2 (diameter 2.5 mm). At this size the ostial exchange seems to be insufficient, in relation to the mucosal absorption, to keep the pO_2 in the sinus at a normal level. When the pO_2 is depressed a new steady state is reached at which the driving oxygen pressure over the ostium (nose — sinus) increases while the driving oxygen pressure (sinus — blood) decreases. A feed back system thus seems to occur.

In model experiments performed prior to this investigation (Aust and Drettner, 1974a), the oxygen exchange through the maxillary ostium was found to be directly proportional to the cross-sectional area of the ostium. The same relationship between the oxygen exchange and the ostial size was found in the human experiments. This means that only a small change in the diameter of the ostium caused by mucosal swelling has a dramatic effect on the exchange of oxygen in the maxillary sinus.

In the model experiments there was also found an inverse proportionality between the sinus volume and the antral oxygen exchange. This inverse proportionality was also found in human experiments in sinuses with large ostia. However, no such relationship was found in sinuses with small ostia probably dus to the effect on the pO_2 in the sinus which, as mentioned, also influences the exchange through the ostium and mucosa.

In the experiments on human subjects it was found that the oxygen exchange through the maxillary ostium is twice as rapid during nasal breathing as during oral breathing with blocked nostrils. The model experiments showed a relationship between the nasal respiratory work and the oxygen exchange through the maxillary ostium. This is in contrast to Proetz (1953), who suggested that the gas exchange in the ostia of the paranasal sinuses was only a result of the respiratory pressure variations in the nose, and Doiteau (1955) and Flottes et al.

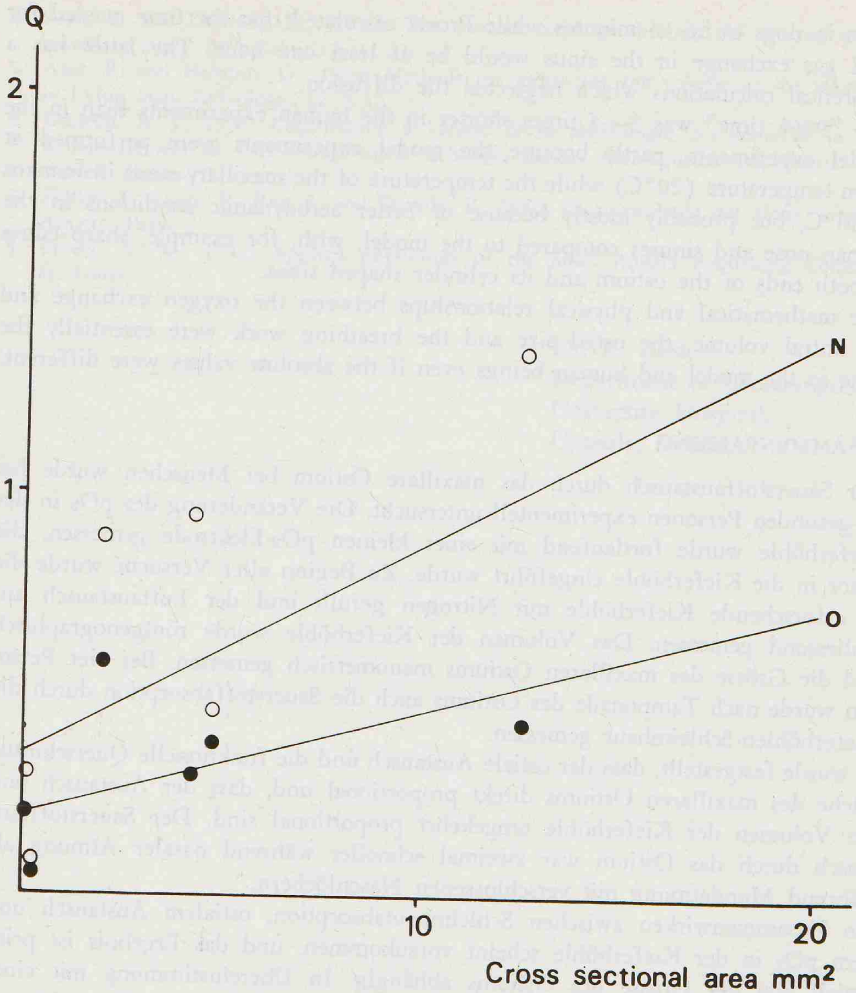


Figure 4. The oxygen exchange Q in the maxillary sinus during nasal N and oral respiration O with blocked nostrils, respectively. The same subjects in both lines.

(1960), who claimed that the exchange was principally due to diffusion and to a lesser extent to pressure change. In the presented experiments and in the model experiments, it was found that exchange of oxygen in the maxillary ostium is dependent both on diffusion and on the respiratory work in the nose. This respiratory work is the produkt of the respiratory airflow and the pressure changes in the nose.

The mean time for 90% exchange in the maxillary sinus was found to be 4.9 minutes with large variations depending on the ostial size. The "90% time" in these experiments are considerably shorter than reported by other authors. Doiteau and Flottes at al. calculated the time for the 90% exchange of gas in the frontal

sinus in dogs to be 16 minutes while Proetz calculated that the time needed for total gas exchange in the sinus would be at least one hour. The latter has a theoretical calculations which neglected the diffusion.

The "90% time" was 3—4 times shorter in the human experiments than in the model experiments, partly because the model experiments were performed at room temperature (20°C) while the temperature of the maxillary sinus in humans is 36°C, but probably mostly because of better aerodynamic conditions in the human nose and sinuses compared to the model, with, for example, sharp edges at both ends of the ostium and its cylinder shaped sinus.

The mathematical and physical relationships between the oxygen exchange and the antral volume, the ostial size and the breathing work were essentially the same in the model and human beings even if the absolute values were different.

ZUSAMMENFASSUNG

Der Sauerstoffaustausch durch das maxillare Ostium bei Menschen wurde bei 25 gesunden Personen experimentell untersucht. Die Veränderung des pO_2 in der Kieferhöhle wurde fortlaufend mit einer kleinen pO_2-Elektrode gemessen, die zuvor in die Kieferhöhle eingeführt wurde. Zu Beginn aller Versuche wurde die zu erforschende Kieferhöhle mit Nitrogen gefüllt und der Luftaustausch anschliessend gemessen. Das Volumen der Kieferhöhle wurde röntgenographisch und die Grösse des maxillaren Ostiums manometrisch gemessen. Bei vier Personen wurde nach Tamponade des Ostiums auch die Sauerstoffabsorption durch die Kieferhöhlen-Schleimhaut gemessen.

Es wurde festgestellt, dass der ostiale Austausch und die funktionelle Querschnittsfläche des maxillaren Ostiums direkt proportional und, dass der Austausch und das Volumen der Kieferhöhle umgekehrt proportional sind. Der Sauerstoffaustausch durch das Ostium war zweimal schneller während nasaler Atmung als während Mundatmung mit verschlossenen Nasenlöchern.

Ein Zusammenwirken zwischen Schleimhautabsorption, ostialem Austausch und dem pO_2 in der Kieferhöhle scheint vorzukommen, und das Ergebnis ist prinzipiell von der Grösse des Ostiums abhängig. In Übereinstimmung mit einer früheren Publikation gibt es eine relative Unzulänglichkeit im Sauerstoffaustausch, wenn das Ostium kleiner ist als 5 mm^2. Der pO_2 der Kieferhöhle wird dann durch die Schleimhautabsorption herabgesetzt. Dies wirkt auf die treibenden Sauerstoffdrücke über dem Ostium und über der Schleimhaut in einer Art, die einen grösseren, ostialen Austausch und eine geringere Absorption fördert, d.h. es gibt ein „feed back system".

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