Upsala J Med Sci 79: 177–186, 1974

Experimental Studies of the Gas Exchange through the Ostium of the Maxillary Sinus

RUDOLF AUST and BÖRJE DRETTNER

From the Department of Otolaryngology, University Hospital, Uppsala, Sweden

ABSTRACT

Model experiments were performed in order to investigate the gas exchange in the maxillary sinus. The exponent Q_2 in the equation illustrating the gas exchange through the maxillary ostium was analysed in relation to the volume of the maxillary sinus, the size of the ostium, the nasal ventilation, the nasal respiratory pressure and the respiratory work. The experiments showed that the gas exchange, expressed as the exponent Q_2, is inversely proportional to the size of the maxillary sinus, and principally directly proportional to the cross-sectional area of the ostial canal. It is also principally directly proportional to the nasal ventilation and positively correlated to the nasal respiratory pressure but estimations of the effect of these two parameters are difficult to perform separately. The relation between antral gas exchange and respiratory work has been analysed more thoroughly and a linear correlation was obvious although not directly proportional, since the diffusion of gas through the ostium will occur also when the respiratory work is zero. The correlation between respiratory work and antral gas exchange is different for different sizes of the ostium. A formula for the antral gas exchange including the sinus volume, the size and length of the ostial canal, the respiratory work and the diffusion has been elaborated.

INTRODUCTION

Two different opinions about the ventilation of the paranasal sinuses have been presented in the literature.

1. Proetz (16) concluded theoretically that about 1/1 000 of the volume of the sinus is exchanged during each breath and the exchange was supposedly due only to the fluctuations in breathing pressure. With a respiratory frequency of 16 breaths per minute, more than one hour would be required for complete exchange if there were no intermingling between the gas entering the sinus and leaving the sinus. In practice, this time would therefore be considerably longer.

2. Doiteau (8) and Flottes et al. (12) performed gas analyses of samples from the sinuses of dogs after the gas in the sinuses had been replaced by another gas. It was calculated that 90% of the total air volume in the frontal sinus of dogs was replaced in about 16 minutes. The time required for exchange was found to be directly correlated to the volume of the sinus. The exchange was considered to be due principally to diffusion and the effect of the respiratory pressure was found to be small.

A new method for studies of the gas exchange in human maxillary sinuses has been described previously (2, 3). A small electrode for pO_2-measurements is introduced into the maxillary sinus and a continuous recording of the oxygen content in the sinus is performed after the gas in the sinus has been replaced for nitrogen through another cannula also introduced into the maxillary sinus.

Factors influencing gas exchange of the sinuses

The following factors may at least theoretically have a bearing on the exchange of gases in sinuses with patent ostia:

1. Volume of the sinus,
2. Size of the ostial canal,
3. Nasal air flow,
4. Nasal respiratory pressure,
5. Size and shape of the nasal cavity,
6. Composition of the air in the nose and sinus,
7. Absorption of gases through the mucosa of the sinus.

Ad 1. The normal volume of the maxillary sinus is considered to be about 15 ml with the extreme values of 2 ml to 30 ml (19). Flottes et al. (12) reported a mean volume of 10 ml.

Ad 2. The maxillary ostium is actually a canal with a length of 6–7 mm measured on cadavers (17, 12), and a diameter of 3–6 mm (12, 19). Diameters as small as 1 mm have been reported

(15). One or two, and in rare cases, three accessory ostia may be present (15, 1, 17, 18).

Ad 3. A tidal volume of 500 ml and a respiratory frequency of 16 per minute gives a minute volume of 8 l. If the two nasal cavities have the same patency, 4 l/min. will pass through each nasal cavity. This volume passes in and out through the nasal cavity every minute. Effects on the respiratory gas volumes due to changes in temperature, humidity or respiratory quotient are disregarded in this paper.

Ad 4. The respiratory pressure changes in the nose and sinuses are identical when the ostia are patent and amount to about ±5 to ±10 mm H_2O when respiration occurs through both nasal cavities.

Ad 5. The size and shape of the nasal cavities differ in different persons. Furthermore the size of the two nasal cavities in each individual generally varies from one moment to another due to the nasal cycle. Fischer (11) reviewed the literature concerning the sizes of the nasal cavities and reported a cross-sectional area of 0.20–0.60 cm^2 at the limen nasi of each nasal cavity and cross-sectional areas in the middle and posterior part of the nose of 1.0–3.0 cm^2 and 1.0–2.5 cm^2, respectively. Van Dishoeck (7) reported a mean cross-sectional area of 0.54 cm^2 in the valve region.

Ad 6. The concentration of oxygen and carbon dioxide in the final position of the expiratory air is about 15% and 5.5%, respectively. These values change to those of atmospheric air during inspiration.

Ad 7. Diffusion of gases through a mucosa in an air-filled cavity is dependent of the difference in partial pressure in each particular gas between the gas solved in the blood in the mucosal vessels and the gas in the cavity. Each gas diffuses independent of the others. This means a transportation of oxygen from the air in the sinus to the blood in the mucosal vessels when the oxygen concentration in the sinus is higher than in the blood. Carbon dioxide usually passes in the opposite direction (12).

Mathematical and physical aspects

The gas composition in the sinus is dependent on the exchange through the ostium and mucosa. The change of the gas quantity per time unit is equal to the sum of the gas quantities passing through the ostium and those diffusing through the mucosa.

$$\frac{dn_i}{dt}=-(I_{1i}+I_{2i}) \tag{1}$$

where n_i is the number of moles in the total sinus volume and I_{1i} and I_{2i} are the number of moles passing the time unit (t) through the mucosa and ostium respectively.

The general gas equation is:

$$p_i=n_i\frac{RT}{S} \tag{2}$$

where R is the gas constant, T is temperature (K), S the volume of the sinus and p_i the partial pressure of the gas (i).

Differentiation with respect to time gives

$$\frac{dp_i}{dt}=\frac{dn_i}{dt}\cdot\frac{RT}{S} \tag{3}$$

Insertion of (1) in (3) gives

$$\frac{dp_i}{dt}=\frac{RT}{S}(I_{1i}+I_{2i}) \tag{4}$$

Fick's equation for gas obsorption gives

$$I_{1i}=\frac{Q_{1i}\,(p_i-{}^bp_i)\,S}{RT} \tag{5}$$

where ${}^bp_i$ is the partial gas pressure in the blood passing through the mucosa, and

$$Q_{1i}=\frac{\alpha_i D_i F}{\xi}\cdot\frac{RT}{S} \tag{6}$$

where α_i is the absorption coefficient for the tissue, D_i the diffusion coefficient, ξ the thickness for the absorbent layer and F the surface area of the sinus. Q_1 and Q_2 are the mathematical expressions of the gas exchange through the mucosa and ostium, respectively.

The relation for I_{2i} can be expressed:

$$\frac{dp_i}{I_{2i}}=-Q_{2i}\,(p_i-p_i') \tag{7}$$

where p'_i is the partial pressure of the gas in the nasal cavity or the mean partial pressure during one breathing cycle (p_i). The differential equation for gas pressure change is thus:

$$\frac{dp_i}{dt}=-Q_{1i}\,(p_i-{}^bp_i)-Q_{2i}\,(p_i-p'_i) \tag{8}$$

which can be solved to

$$p^t_i-B_i=(p^0_i-B_i)\cdot e^{-k_it} \tag{9}$$

where $B_i=\dfrac{Q_{1i}\cdot{}^bp_i+Q_{2i}\,p_i}{Q_{1i}+Q_{2i}}$.

$Q_i=Q_{1i}+Q_{2i}$

and p^0_i is the partial pressure at the time=0.

Q_{2i} is an expression of the exchange through the ostium and it can be determined in model experiments. When there is no diffusion through the mucosa Q_{1i} is 0 and eq. (9) can be simplified to

$$p^t_i-p'_i=(p^0_i-p'_i)\cdot e^{Q_{2i}t} \tag{10}$$

Another special case is when there is no exchange through the ostium as after tamponade or ostial obstruction. Q_2 is then 0 and eq. (9) becomes

$$p^t_i-{}^bp_i=(p^0_i-{}^bp_i)\cdot e^{Q_{1i}t} \tag{11}$$

The purpose of the present study is to perform model experiments to analyse eq. (10), i.e. to investigate the gas exchange through the maxillary ostium in relation ot the volume of the maxillary sinus, the size of the maxillary ostium, the nasal airflow and the nasal respiratory pressure. Furthermore, the nasal respiratory work has been utilized as a parameter including nasal airflow and nasal respiratory pressure. The exchange has been analysed as regards oxygen.

METHOD

A model was used for investigation of the oxygen exchange through an ostium, simulating the maxillary ostium. The model consisted of a rubber nose moulded from a cadaver. The cross-sectional area of the limen nasi was 0.72 cm² and the corresponding areas in the middle and posterior parts of the nose were 3.0 cm² and 1.7 cm², respectively. The nasal patency ($\dot{V}_{10}$), expressed as the expiratory airflow at a differential pressure of 10 mm H_2O between nasopharynx and nasal opening (9), measured in the investigated nasal cavity of the model by breathing through a tube attached to the nasopharyngeal part of the model, was 22 l/min. The other nasal cavity of the model was blocked during this measurement.

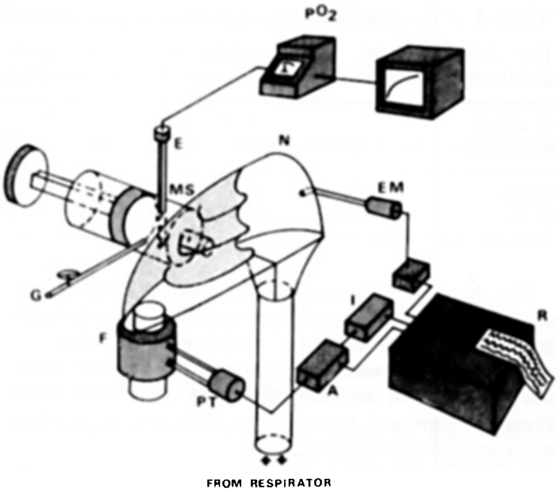

Fig. 1. Schematic drawing of the equipment for model experiments of the gas exchange in the maxillary sinus. One nasal cavity of a nasal model (*N*) is connected via the middle meatus to a syringe corresponding to the maxillary sinus (*MS*). The size of the connection which represents the maxillary ostium, can be changed. A to-and-fro airflow is led through the model and the flow is measured by a pneumotachograph (*F*), a pressure transducer (*PT*) and an amplifier (*A*) connected to a recorder (*R*). The flow is also integrated, by (*I*), and recorded as a volume. The nasal pressure, actually measured as the pressure difference between nasopharynx and the nostrils, is measured by an electromanometer (*EM*) and recorded. The syringe is filled by nitrogen through *G* at the beginning of the experiment. The oxygen content in the syringe is analysed by a small P_{O_2}-electrode (*E*) connected to an instrument for P_{O_2}-measurements, and a recorder.

A syringe was connected to the nasal model into the middle meatus (fig. 1). The syringe corresponded to the maxillary sinus and its volume could be varied. The connection between the nasal model and the syringe simulated the ostium with a length of 6 mm and a variable inner diameter of 2 mm, 4 mm, or 6 mm. Two holes were made in the wall of the syringe, one for insufflation of nitrogen or other gases and the other for a small P_{O_2}-electrode in a cannula. The electrode was introduced through an air-tight fitting. The recording of P_{O_2} with this P_{O_2}-electrode has been described in a previous paper (3).

The air stream through the nasal model was generated by a respirator and the respiratory frequency was 16/min in all model experiments. The flow was measured with a Fleisch pneumotachograph, a pressure transducer (EMT 32, Elema-Schönander, Stockholm) and an amplifier (EMT 31). By using an RC-integrator unit (EMT 40 and 41) the flow of air passing the nose model was converted to volume. A time constant of 40 sec was generally used at the integration.

Table I. *Calculations of the exponent Q_2 at 10–90 % of full deflection in 18 recordings*

The deviations of the Q_2-values from the mean Q_2 in each recording were expressed in per cent and the means and standard deviations of these percentage values are given in the table

% of full deflection . . .	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %
Mean	−0.3	+0.5	+0.3	−1.4	+0.2	−1.0	−1.0	+0.3	−0.2
S. D.	±8.7	±6.4	±6.7	±6.1	±5.2	±9.1	±5.0	±7.8	±7.4

The pressure changes in the nasal cavity of the model were measured as the pressure difference between the nasopharynx and the attachment between the nostril and the pneumotachograph. A pressure transducer (EMT 33) and amplifier (EMT 32) were used. Pressure, flow and volume were recorded on a galvanometer recorder (Mingograph 81).

Calibration of flow and volume was performed with a special pneumotachograph calibrator (14) which produces a known airflow and volume.

Calibration of the P_{O2}-electrode and measurements were all performed at room temperature (+22°). All experiments started with filling the sinus, i.e. the syringe, with nitrogen. The to-and-fro air stream through the nasal model was generated by the respirator. The exponential increase of P_{O_2} was recorded continuously.

RESULTS

Validity of equations

In order to study the validity of eq. (7) and (10), nine values of Q_2 were calculated from each of altogether 18 recordings of model experiments in which the sinus volume, the size of the ostium, the nasal airflow and the nasal pressure varied. These nine values were obtained at 10, 20, 30, 40, 50, 60, 70, 80 and 90% of full deflection. The mean Q_2 for each recording was also calculated. The deviation of each single measurement from the mean Q_2 of each recording was expressed in per cent of the actual mean Q_2 value. Table I shows the mean and standard deviation of these percentage values for 10, 20, 30, 40, 50, 60, 70, 80 and 90% of full deflection calculated from the 18 recordings. These mean deviations were close to zero at all calculated points of the recordings, i.e. the eq. (7) and (10) are valid for the oxygen exchange through the ostium. Q_2 can thus be used to express this exchange.

Each Q_2-value, discussed later in this paper, is the mean of nine measurements (10–90% of full deflection in each recording).

Effect of sinus volume

Model experiments were performed in order to investigate the effect of changes of the volume of the sinus. The volumes 5 ml, 10 ml and 15 ml were used. Fig. 2 and Table II show the result when the ostial diameter, the nasal ventilation and the respiratory pressure were kept konstant. With a ratio for the sinus volumes of 1 : 2 : 3 the ratios for the times for 90% exchange were 1.0 : 1.5 : 2.8 and the ratios for Q_2 2.6 : 2.0 : 1.0, respectively, when the ostial diameter was 2 mm. When the latter was 4 mm the time ratios were 1.0 : 1.5 : 2.6 and the Q_2-ratios 3.1 : 2.0 : 1.0. The oxygen exchange in the sinus is thus inversely proportional to the sinus volumes at these ostial diameters.

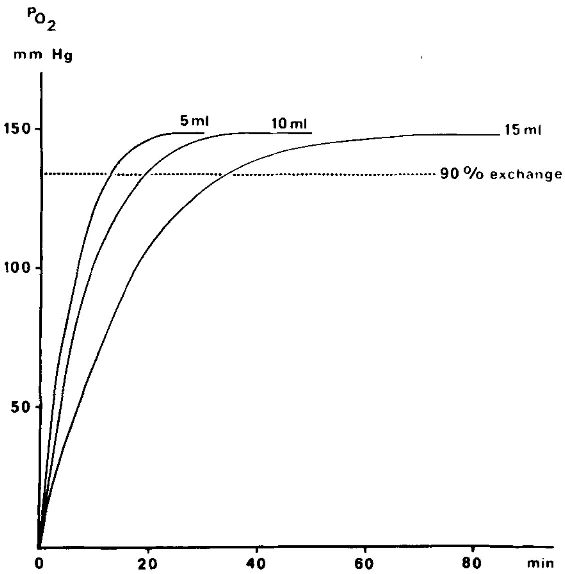

Fig. 2. Recordings of the increase in P_{O2} in the model of the maxillary sinus after the gas in the sinus was replaced by nitrogen. Three different sinus volumes 5 ml, 10 ml and 15 ml. Nasal ventilation 4.0 l/min, respiratory pressure ±20 mm H_2O, ostium diameter 2 mm. The exponent Q_2 in the equation mentioned in the text is calculated from each recording as the mean of nine values, obtained at 10 to 90 % of full deflection.

Table II. *Oxygen exchange in the sinus model in relation to variations of the sinus volume*

Nasal minute ventilation 4 litres
Nasal breathing pressure ±10 to ±20 mm H_2O

	Ostial diameter, 2 mm			Ostial diameter, 4 mm		
Sinus volume (ml)	5	10	15	5	10	15
Ratio of sinus volume	1	2	3	1	2	3
Time for 90 % exchange (min)	12.5	18.5	34.0	2.8	4.2	7.3
Ratio of time	1	1.5	2.8	1	1.5	2.6
Q_2	0.16	0.12	0.06	0.68	0.44	0.22
Ratio of Q_2	2.6	2.0	1	3.1	2.0	1

Effect of ostial diameter

Table III shows the exchange in relation to the ostial diameter. When the diameters were 2 mm, 4 mm and 6 mm, i.e. the cross-sectional areas had the relationship 1:4:9, the ratios for the times for 90 % exchange were 10.2:3.0:1.0 and the Q_2-ratios 1.0:3.6:9.8, respectively. The latter were thus principally directly proportional to the cross-sectional areas.

Effect of nasal ventilation

Studies of the effect of changes in the nasal ventilation per minute are impossible to perform without some changes in nasal respiratory pressure. Table IV shows results concerning the antral oxygen exchange with nasal ventilation of 4, 6, and 8 litres per min. The intranasal pressure was within ± 30 mm H_2O. When the ratios for nasal minute ventilation were 1.0:1.5:2.0, the ratios for the times for 90% exchange had the relationship 1.6:1.1:1.0 and the Q_2-ratios 1.0:1.4:2.2. The latter values are thus principally directly proportional to the nasal ventilation.

Table III. *Oxygen exchange in the sinus in relation to variations of the diameter of the maxillary ostium*

Sinus volume, 15 ml
Nasal minute ventilation, 4 litres
Nasal breathing pressure, ±10 to ±20 mm H_2O

Ostial diameter (mm)	2	4	6
Ratio of diameters	1	2	3
Ostial cross-sectional area (mm^2)	3.14	12.56	28.26
Ratio of cross-sectional area	1	4	9
Time for 90 % gas exchange (min)	24.90	7.40	2.45
Ratio of time	10.2	3.0	1.0
Q_2	0.097	0.35	0.96
Ratio of Q_2	1	3.6	9.8

Effect of intranasal pressure

The intranasal pressure produced by the respirator was more peak-shaped than the normal sinusoidal respiratory pressure curve. Higher pressures than those corresponding to a normal nasal respiration had therefore to be used for each nasal minute ventilation.

The interrelationship between intranasal pressure and nasal minute ventilation mentioned above does not exclude changes in the maximal intranasal pressure with a constant nasal ventilation. Table V shows the results of experiments with maximal intranasal pressures of ± 14.5, ±23.5, and ± 49.0 mm H_2O with a constant nasal ventilation of 4 l/min. The relationship for the pressures were 1.0: 1.6: 3.4, for the time ratios 2.0: 1.3: 1.0 and for the Q_2-ratios 1.0: 1.2: 2.1. The latter ratios were thus correlated to the maximal intranasal pressures but not directly proportional.

Effect of respiratory work

The experiments just described were obtained by keeping the maximal nasal ventilation within a certain level when the nasal respiratory pressure was increased. The pattern of the pressure and flow recordings was therefore not identical.

Table IV. *Oxygen exchange in the sinus in relation to variations of the nasal ventilation*

Sinus volume, 15 ml
Ostial diameter, 2 mm
Nasal breathing pressure, ±10 to ±20 mm H_2O

Minute ventilation (l/min)	4	6	8
Ratio of nasal ventilation	1	1.5	2
Time for 90 % gas exchange	34.0	23.0	22.0
Ratio of time	1.6	1.1	1
Q_2	0.06	0.10	0.14
Ratio of Q_2	1	1.4	2.2

Table V. *Oxygen exchange in the sinus in relation to variations of the nasal breathing pressure*

Sinus volume, 15 ml
Ostial diameter, 2 mm
Nasal minute ventilation, 4 litres

Nasal pressure (mm H_2O)	±14.5	±23.5	±49.0
Ratio of nasal pressure	1	1.6	3.4
Time for 90 % gas exchange (min)	34.0	23.0	17.4
Ratio of time	2.0	1.3	1
Q_2	0.06	0.078	0.14
Ratio of Q_2	1	1.2	2.1

The respiratory work may in this connection be a more reliable parameter than respiratory pressure and nasal ventilation since respiratory work in principle is pressure times air volume for each moment of a breath. The equation for the mechanical work of breathing is

$$W=k\cdot\int_{V_2}^{V_1} P\cdot dV \qquad (12)$$

where W is work in kpm, V is volume in litres and P pressure in cm H_2O. The constant (k) is 0.01 with these expressions. The respiratory work was obtained by putting a series of corresponding values of pressure and air volume from one breath in a coordinate system. Both these values were recorded during the experiments. The volume is the integrated flow. Fig. 3 gives an example of such a pressure-volume diagram. The area within this loop was measured by planimetry in which way the respiratory work, expressed in kpm/breath was obtained for inspiration and expiration. Since no elastic work is included in model experiments in contrast to measurements during ordinary respiration (5), the total area was planimetrically calculated, which means the sum of non-elastic work for inspiration and expiration. From the value of the work per breath, the work per minute was easily calculated, since the respiratory frequency always was 16 per minute.

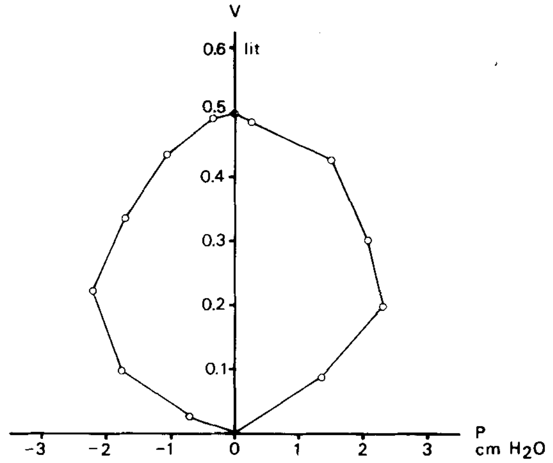

Fig. 3. Pressure-volume diagram obtained from plottings of corresponding values of pressure and air volume during one breath. Values at inspiration to the left of the ordinate and values at expiration to the right. Nasal ventilation 8 l/min. Planimetry gave a total respiratory work of 0.16 kpm/breath=2.56 kpm/min.

Table VI and Fig. 4 show the connection between oxygen exchange in the sinus and the respiratory work. The results in Fig. 4 are given for the ostial diameter of 2, 4, and 6 mm. For the latter, only measurements with small respiratory work could be performed due to recording difficulties with very rapid exchange. The results with rapid exchange have not the same confidence level as those with slower exchange, and the results for the 6 mm ostium are therefore not as reliable as those with smaller ostia. The lines

Table VI. *Oxygen exchange in the sinus in relation to variations of nasal breathing work*

Sinus volume, 15 ml

	Ostial diameter, 2 mm			Ostial diameter, 4 mm		
Nasal breathing work (kpm/min)	1.51	3.86	6.75	0.54	1.78	3.95
Ratio of breathing work	1	2.6	4.5	1	3.3	7.2
Time for 90 % gas exchange (min)	24.9	9.2	7.3	9.5	7.4	4.0
Ratio of time	3.4	1.3	1	2.3	1.9	1
Q_2	0.10	0.15	0.20	0.23	0.35	0.71
Ratio of Q_2	1	1.5	2.0	1	1.5	3.1

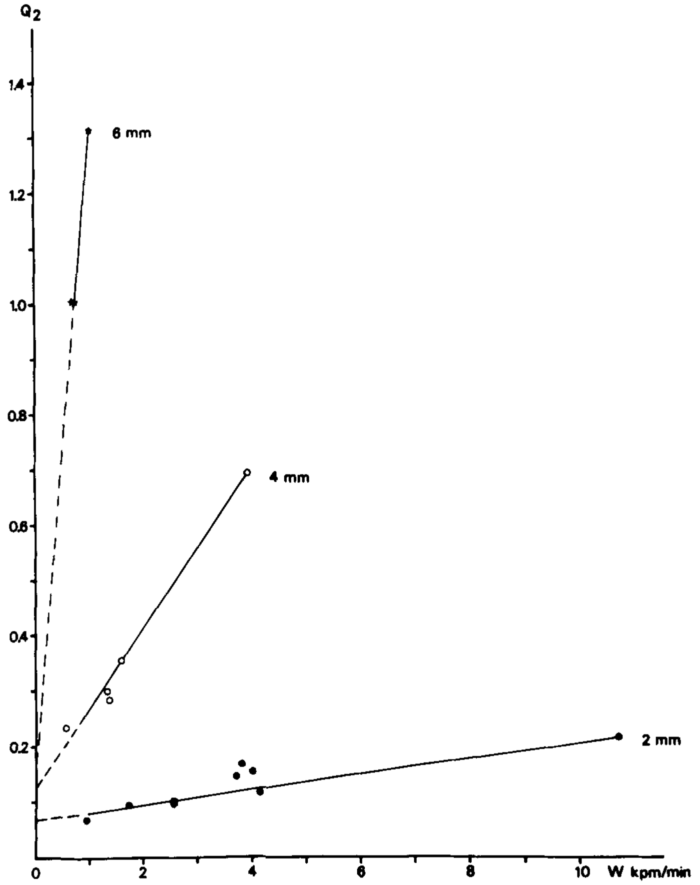

Fig. 4. The relation between the exponent Q_2, expressing the gas exchange in the sinus model, and the respiratory work with the ostium diameters 2, 4 and 6 mm. Measurements for 6 mm ostium were possible for low work only, due to too-rapid exchange at greater work. The lines have been extrapolated to the ordinate. Sinus volume 15 ml. For further interpretation see text.

are not parallel which means there is a different relationship between Q_2 and work (W) at different ostia.

The relationship can mathematically be expressed

$$Q_2=k\cdot W+1 \qquad (13)$$

in analogy to the equation for a straight line $y=k\cdot x+1$. By introducing symbols showing the diameter of the ostium, the following equations are obtained from Fig. 4:

$$Q_{2-2}=0.0145\,W_2+0.065 \qquad (14)$$

$$Q_{2-4}=0.150\,W_4+0.120 \qquad (15)$$

$$Q_{2-6}=1.140\,W_6+0.175 \qquad (16)$$

When the ratio Q_{2-4}/Q_{2-2} is analysed in Fig. 4 in points with identical work, the ratio 4 : 1 is obtained in at least the higher ranges of work. In the lower range of the work the ratio is somewhat lower.

At a respiratory work of 1 kpm/min the three Q_2 at the ostial diameters 2, 4 and 6 mm, have a relationship of 1 : 4 : 13.

DISCUSSION

The nasal model used in the present investigation was moulded from a cadaver. According to published measurements (7, 11) the nasal model had a size at the upper range of the variation of a normal nasal cavity. However, as stressed by Fischer, it is impossible to define a normal nasal cavity since the anatomical and physiological variations are almost unlimited. The patency ($\dot{V}_{10}$) of the investigated nasal cavity of the model, measured as the expiratory flow rate at a pressure difference of 10 mm H_2O, was 22 l/min. The normal value in adults with bilateral nasal breathing is 42 l/min (9). The nasal cavity in the model had thus a patency very close to that of a normal nasal cavity in a living person.

In the present investigation no studies have been performed concerning the effect on antral ventilation of changes of the size and shape of the nasal cavity. Such a study is postponed until more basic knowledge of the ventilation of the sinuses is obtained. It seems likely that a narrowing of the nasal cavity with a constant nasal ventilation will have a similar effect as an increase of the flow rate in a constant nasal cavity, assuming the shape of the cavity is unaltered.

This investigation shows that the antral oxygen exchange through the ostium is inversely proportional to the volume of the sinus and principally directly proportional to the cross-sectional area of the ostial canal.

No experiments have been performed in which the length of the ostial canal have been varied. This has been neglected partly because the anatomical variations seem to be small (12, 15, 17) and partly because the air resistance in an orifice is more dependent on changes in the diameter than in length. It seems reasonable to assume that the exchange is inversely proportional to the length of the canal.

If the actual parameters, i. e. the sinus volume, ostial size, nasal ventilation, respiratory pressure, and respiratory work, are examined, some new facts about the gas exchange through the ostium become apparent.

1. The exchange is inversely proportional to the volume of the sinus (S). It thus follows that

$$Q_2=k_1\frac{1}{S} \tag{17}$$

2. The exchange is principally directly proportional to the cross-sectional area (A) of the ostial canal, i. e. to the square of the diameter. The equation will thus be

$$Q_2=k_2\cdot A \tag{18}$$

3. The exchange is also probably inversely proportional to the length of the ostial canal:

$$Q_2=k_3\frac{1}{L} \tag{19}$$

When the three equations are combined, the following relationship is obtained

$$Q_2=\frac{k_4CA}{SL} \tag{20}$$

in which (C) is the conduction.

The equation shows that the ostial exchange is directly proportional to the conduction. This conduction is dependent on, among other things, the molecular motion of the air in the ostium, i.e. the kinetic energy in the air which increases with an increase in nasal respiratory work, for example by an increase in air velocity.

Thus, (C) in eq. (20) can partly be substituted for the nasal respiratory work (W). A diffusion through the ostium also takes place when there is no respiratory work in the nose and this »basic» ostial diffusion (d) has to be added to the exchange caused by the nasal respiratory work.

4. The exchange has thus a linear correlation to the respiratory work.

Thus it follows that,

$$Q_2=k_5\cdot(W+d) \tag{21}$$

which means that there is an exchange also when there is no respiratory work.

The equation is different for different ostial sizes. The lines have a greater slope (Fig. 4), for a 4 mm ostium than a 2 mm ostium, i. e. k_5 in the equation above, which represents the tangent of the angle between the line and the abscissa increases with an increasing ostial size. From Fig. 3 and eqs. (14) and (15) it can also be seen that in experiments with no respiratory work, Q_2 may be assumed to be about 0.06 and 0.12, at ostial diameters of 2 mm and 4 mm, respectively. This will also be the magnitude of the exchange which is caused only by diffusion. Flottes et al. (12) discussed the diffusion and found it to be of greater importance for the exchange than the respiratory pressure. As can be seen from Fig. 4 this seems to be especially true for small ostia. Fig. 4 also shows that the relative distance from the abscissa for each of the lines principally corresponds to a relationship of 1 : 4 which therefore further illustrates the relationship between the cross-sectional area of the canals.

5. The relation between gas exchange and nasal ventilation, on the one hand, and nasal respiratory pressure, on the other, can hardly be defined exactly since the latter two parameters cannot be varied independently. Both these parameters are exactly defined in the respiratory work. It seems logical that the gas exchange in principle has a similar relationship to nasal

ventilation and respiratory pressure as it has to respiratory work, i. e. an exchange will occur also when there is no nasal ventilation or no respiratory pressure changes.

6. A combined equation in which the respiratory work (W), sinus volume (S), length (L), the diffusion (d) and cross-sectional area (A) of the ostial canal are regarded, can therefore be expressed:

$$Q_2=\frac{KA(W+d)}{SL} \tag{22}$$

The composition of the air in the nose and sinus is of importance for the ventilation time of the sinuses. However, the exponent Q_2 in eq. (10) will still be the same as it includes the partial pressure of the gas at time 0 and time t, and also the partial pressure of the gas in the nasal cavity. Q_2 is thus a better expression for the ventilation than the time for exchange, since the latter is dependent on the initial gas concentrations in the nose and sinus. The value of Q_2 for the gas, e.g. oxygen, is thus valid for all initial concentrations. The oxygen concentration in the nose is 20.93 % at inspiration and about 15 % at the end of expiration (6). The oxygen concentration in the sinus with a patent ostium is about 16.3% (4). A decrease in the oxygen concentration in the sinus will theoretically occur when the ventilation through the ostium is lower than the absorption of oxygen from the mucosa. When the ventilation through the ostium is sufficient to compensate for the mucosal absorption of oxygen there will be a steady state oxygen concentration in the sinus.

The results in this investigation only concern oxygen, or more precisely, the inflow of oxygen through the ostium to a sinus filled with nitrogen. In man there is also a transportation of nitrogen and carbon dioxide through the ostium. The diffusion of each gas occurs independent of other gases and is inversely proportional to the square root of the densities of the gases (Graham's law). The relative rates of diffusion for O_2, N_2 and CO_2 is thus 1.0 : 1.1 : 0.9 when the gases are under the same conditions. Direct measurements of the exchange of carbon dioxide in the maxillary sinus have so far not been possible to perform due to difficulties in manufacturing a small P_{CO_2}-electrode.

ACKNOWLEDGEMENT

This work was supported by grants from the Swedish Medical Research Council (B 73-17X-749-08).

Mathematical equations 1 to 11 have been elaborated by Thorvald Forsner, Ph. D.

REFERENCES

1. van Alyea, O. E.: The ostium maxillare. Arch Otolaryng (Chic.) *24:* 555, 1936.
2. Aust, R. & Drettner, B.: Ventilatory studies of the maxillary sinus. Int Rhinology *9:* 69, 1971.
3. – Investigation of oxygen exchange in human paranasal sinuses with a small P_{O_2}-electrode. Upsala J Med Sci *77:* 208, 1972.
4. – Oxygen tension in the human maxillary sinus during normal and pathological conditions. In press, 1974.
5. Butler, J.: The work of breathing through the nose. Clin Sci *19:* 55, 1960.
6. Comroe, J. H., Forster, R. E., Dubois, A. B., Briscoe, W. A. & Carlsen, E.: The Lung. Clinical physiology and pulmonary function tests. Year Book Medical Publ. Corp. Inc., Chicago, 1970.
7. van Dishoeck, H. A. E: Some Remarks on Nasal Physiology. University Press, Leiden, 1957.
8. Doiteau, R. J.: Contribution à l'étude de la physiologie des sinus de la face. Renouvellement de l'air intrasinusien. Echanges gazeux permuqueux. Imprimerie Sammarcelli Frères, Bordeaux, 1955.
9. Drettner, B.: Vascular reactions of the human nasal mucosa on exposure to cold. Acta Otolaryng, Suppl. *166*. 1961.
10. Dubois, A. B.: Resistance to breathing. Handbook of Physiology, Sect. 3: Respiration, Vol. 1 (ed. W. C. Fenn & H. Rahn), American Physiological Society, Washington, D. C. 1964.
11. Fischer, R.: Die Physik der Atemströmung in der Nase. Hausdruckerei des Klinikum Steglitz der Freien Universität, Berlin, 1969.
12. Flottes, L., Clerc, P., Riu, R. & Devilla, F.: La physiologie des sinus. Librarie Arnette, Paris, 1960.
13. Handbook of Respiration. National Academy of Sciences. Saunders & Co., London and Philadelphia, 1958.
14. Herzog, P. & Nordlander, O. P.: Präzisions-Instrument für die Eichung von Pneumotachographen. Der Anaesthesist *15:* 168, 1966.
15. Myerson, M. C.: The natural orifice of the maxillary sinus. Arch Otolaryng (Chic.) *15:* 80, 1932.
16. Proetz, A. W.: Applied Physiology of the Nose. Annals Publishing Company, St. Louis, 1953.
17. Simon, E.: Anatomy of the opening of the maxillary sinus. Arch Otolaryng (Chic.) *29:* 640, 1939.
18. Takahashi, R., Onmyoji, S., Ikeda, K., Shimada, K. & Chiba, T.: Studies on the natural orifice of the maxillary sinus. *In* A Collection of Ear, Nose and Throat Studies, p. 153. Kyoya Co., Ltd., Tokyo, 1971.

19. Wagemann, W.: Anatomie, Physiologie und Untersuchungen der Nase und der Nebenhöhlen. *In* Hals-Nasen-Ohrenheilk., Band 1 (ed. J. Berendes, R. Link & F, Zöllner). Georg Thieme Verlag, Stuttgart, 1964.

Received December 23, 1973

Addresses for reprints:
R. Aust, M. D.
Department of Otolaryngology
University Hospital
S-750 14 Uppsala
Sweden