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DESIGN OF THE MAMMALIAN RESPIRATORY SYSTEM. V. SCALING MORPHOMETRIC PULMONARY DIFFUSING CAPACITY TO BODY MASS: WILD AND DOMESTIC MAMMALS*

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Abstract. This paper utilizes a comparative approach to establish the relationship between morphometric diffusing capacity for oxygen ($D_{L_{O_2}}$) and maximal oxygen consumption ($\dot{V}_{O_2max}$). $D_{L_{O_2}}$ and $\dot{V}_{O_2max}$ were determined on the same 21 individuals in African mammals spanning a range in body mass from 0.4 to 240 kg. We confirmed earlier findings that $D_{L_{O_2}}$ was proportional to $M_b^{0.99}$ while $\dot{V}_{O_2max}$ was proportional to $M_b^{0.79}$. Thus, the ratio of $D_{L_{O_2}}/\dot{V}_{O_2max}$ is approximately proportional to $M_b^{0.20}$. We conclude that large animals require a larger pulmonary diffusing capacity to transfer oxygen at the same rate from air to blood.

African mammals | Lung morphology
Allometry | Oxygen consumption
Alvéolar surface area | Pulmonary diffusing capacity

The pulmonary diffusing capacity for O_2, $D_{L_{O_2}}$, is the conductance for O_2 flow from air to blood in the lung, driven by the partial pressure difference between alveolar air and capillary blood (fig. 1). It is determined, in part, by some

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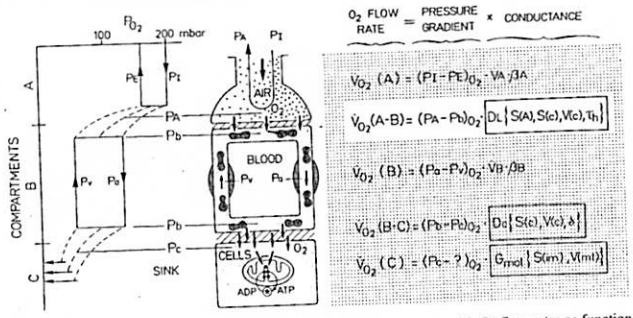

Fig. 1. Model of respiratory system subdivided into three compartments with O_2 flow rates as function of partial pressure gradients and conductances at each step. The flow rate from air to blood [$\dot{V}_{O_2(A-B)}$] depends on the pulmonary diffusing capacity ($D_{L_{O_2}}$) which is related to various morphometric lung parameters.

morphometric properties of the lung, such as the alveolar and capillary surface areas, the capillary blood volume and the thickness of the air–blood tissue barrier (Weibel, 1970/71). One would expect $D_{L_{O_2}}$ to relate closely to O_2 consumption, specifically to $\dot{V}_{O_2max}$, the O_2 flow across the lung under conditions of sustained maximal O_2 need.

There are basically two approaches to testing whether $D_{L_{O_2}}$ is matched to $\dot{V}_{O_2}$: one can compare (1) $D_{L_{O_2}}$ in animals of similar size but differing $\dot{V}_{O_2max}$, or (2) the scaling of $D_{L_{O_2}}$ and $\dot{V}_{O_2}$ over a large size range of mammals. In the first approach matching is established if mass-specific $D_{L_{O_2}}$ is proportional to mass-specific $\dot{V}_{O_2}$; this is found to be the case, for example, in comparing various species, such as horse and cow of body mass ~500 kg (Gehr and Erni, 1980; Weibel, 1979), or, in the sense of adaptation, waltzing mice with normal laboratory mice (Geelhaar and Weibel, 1971; Hugonnaud *et al.*, 1977). Thus it appears that, within a given size class, $D_{L_{O_2}}$ is closely matched to $\dot{V}_{O_2}$.

Using the comparative approach it has been found consistently that, over the size range of mammals (2 g < M_b < 1000 kg), $\dot{V}_{O_2std}$ scales with $M_b^{0.75}$ (Kleiber, 1932, 1961); in a companion paper to this study a similar relation is found for $\dot{V}_{O_2max}$ (Taylor *et al.*, 1981). This means that mass-specific $\dot{V}_{O_2}$ of a rat of 500 g is about six times higher than that of a horse of 500 kg. In comparative morphometric studies on the mammalian lung we found that $D_{L_{O_2}}$ and the alveolar surface area, S(A), one of the main determinants of $D_{L_{O_2}}$, scale approximately proportional to $M_b^{1.0}$ (Weibel, 1972, 1973, 1979). The earlier data of Tenney and Remmers (1963) for terrestrial mammals show the same relationship between S(A) and body mass;

we believe that marine mammals should be considered separately for reasons given in the discussion.

Consequently, the two approaches proposed to test whether $D_{L_{O_2}}$ was matched to $\dot{V}_{O_2}$ give paradoxical results: whereas $D_{L_{O_2}}$ is closely proportional to $\dot{V}_{O_2}$ within a size class, $\dot{V}_{O_2}$ and $D_{L_{O_2}}$ scale differently to body mass over a large size range.

It seemed possible that this paradox resulted from the fact that in the comparative studies the measurement of $\dot{V}_{O_2}$ and $D_{L_{O_2}}$ have not been done on the same animals, or not even on a homogeneous and comparable population of animals. In order to remove this the present study combines $D_{L_{O_2}}$ studied by morphometry in the lungs of the same specimens of African bovids and viverrids on which Taylor *et al.* (1981) had obtained measurements of $\dot{V}_{O_2max}$. The inclusion of wild and domesticated bovids in that study also allowed us to compare $D_{L_{O_2}}$ with $\dot{V}_{O_2max}$ for animals of similar size but different metabolic needs.

MATERIALS AND METHODS

This study was performed on 27 African mammals (15 species) ranging in body mass (M_b) from 0.42 to 251 kg as specified in table 1. The animals were recruited from viverrids (dwarf mongoose, banded mongoose, genet cat), wild bovids (suni, dik-dik, Grant's gazelle, Thomson's gazelle, wildebeest or gnu, waterbuck, eland, giraffe) and domestic ruminants (Masai goat, Masai sheep, zebu cattle, camel). Combined estimates of maximal oxygen consumption, $\dot{V}_{O_2max}$, and morphometric diffusing capacity for oxygen, $D_{L_{O_2}}$, were obtained on 22 of these animals. $\dot{V}_{O_2max}$ measurements were obtained while the animals were running on a treadmill by the method described by Seeherman *et al.* (1981). The detailed data of this part of the study are presented in the companion paper by Taylor *et al.* (1981).

After completion of the physiological studies the animals were sacrificed and their lungs fixed by tracheal instillation of a 2.5% potassium-phosphate buffered glutaraldehyde solution at a head pressure of 25 cm above the chest with the animals in supine position. The lungs were removed from the chest *in toto*, their volume estimated by a water displacement method, following which we proceeded to tissue sampling and morphometric analysis as described in detail by Weibel *et al.* (1981a). The sampling procedure adopted for this study deviated somehow from that used on the older material introduced here for comparison, but it has been shown that the new method only affects the errors and not the estimates, so that the results of the new and of the older studies remain comparable (Weibel *et al.*, 1981a).

The following physical coefficients were used together with the estimates of morphometric parameters to calculate $D_{L_{O_2}}$ after the model of Weibel (1970/71):

$$K_t = K_p = 4.1 \cdot 10^{-10}\ \text{cm}^2 \cdot \text{sec}^{-1} \cdot \text{mbar}^{-1},$$

$$\Theta_{O_2} = 1.87 \cdot 10^{-2}\ \text{ml O}_2 \cdot \text{ml}^{-1} \cdot \text{sec}^{-1} \cdot \text{mbar}^{-1}$$

These constants are expressed in SI units* yielding an estimate of DL_{O_2} in units of ml $O_2 \cdot s^{-1} \cdot mbar^{-1}$. The values of K_t and K_p correspond to the lower range of estimates of these permeation coefficients (Weibel, 1970/71). Reliable data for Θ_{O_2} are not available for the various species; therefore we have adopted the value of Θ_{O_2} given by Holland *et al.* (1977) for human blood. The choice of a single value for Θ_{O_2} for all animals seemed reasonable because an estimate of erythrocyte size in the Kenyan animals showed that the variability in the range 5.5–7 µm was not related to body mass.

To expand the comparison we also included the morphometric estimate of DL_{O_2} on 114 animals of 17 additional species which had been investigated in connection with earlier studies (Burri and Weibel, 1971; Geelhaar and Weibel, 1971; Siegwart *et al.* 1971; Weibel, 1972; Forrest and Weibel, 1975; Gehr *et al.*, 1978; Gehr and Erni, 1980; Gehr *et al.*, 1980a,b). They ranged in body mass from 2 g to 700 kg and comprised laboratory animals, European domestic animals, European and African shrews, as well as man. In accordance with the approach used by Taylor *et al.* (1981) this broad interspecies comparison was based on average values for a species rather than on individual animal data; in order to deal with the larger size range of dogs and rats we divided the dogs into four and the rats into two groups on the basis of M_b.

Results

1. FINE STRUCTURE OF THE LUNG OF AFRICAN BOVIDS

The construction and fine structure of the gas exchange parenchyma of these African mammals does not differ from that of other mammals. In essence, the alveolar ducts emanate from respiratory bronchioles (fig. 2a) and are surrounded by densely packed alveoli (fig. 2b). The relative size of alveolar ducts and alveoli showed great variations, but these did not in any obvious way relate to the size of the animals, nor did the alveolar surface density depend on body mass. Figure 3 shows scanning electron micrographs of lung parenchyma of a suni (3.5 kg) and a gnu or wildebeest (100 kg) taken at the same magnification; in spite of a thirty-fold difference in body mass the alveolar surface density is equal in these two lungs. Figure 4 shows a plot of alveolar surface density against body mass: for the wild animals the data vary by about a factor of 2 but show no size dependence; the domesticated animals show a tendency towards lower values.

* Conversion of conventional into SI units.
1 mm Hg = 1.3332 mbar = 133.32 Pa.
Equivalence for:

$$\Theta_{O_2} = 1.5 \text{ ml } O_2 \cdot ml^{-1} \cdot min^{-1} \cdot mm\ Hg^{-1} = 1.87 \cdot 10^{-2} \text{ ml } O_2 \cdot ml^{-1} \cdot sec^{-1} \cdot mbar^{-1}$$

$$DL_{O_2}: \{\text{ml } O_2 \cdot min^{-1} \cdot mm\ Hg^{-1}\} = 1.2501 \cdot 10^{-2} \cdot \{\text{ml} \cdot sec^{-1} \cdot mbar^{-1}\}$$

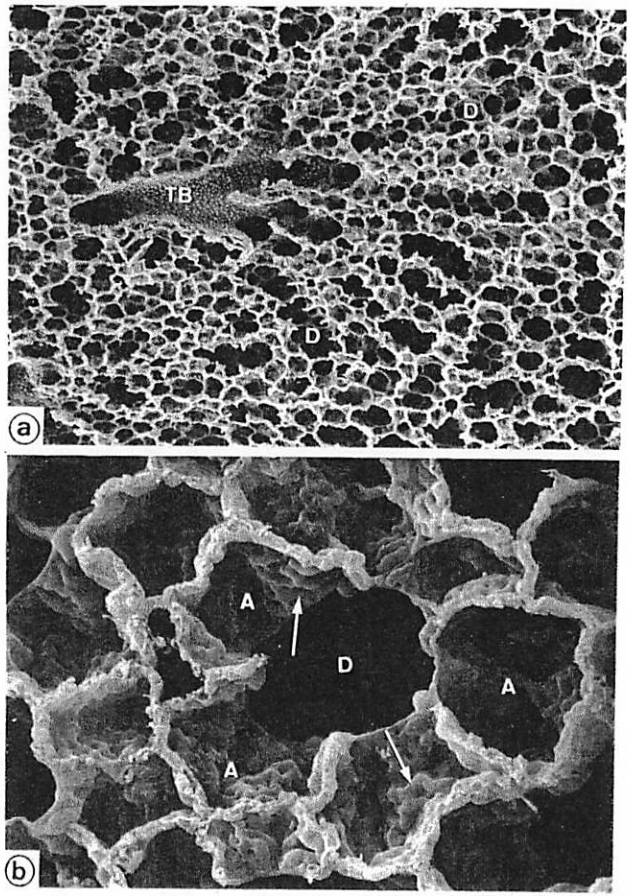

Fig. 2. Scanning electron micrographs of lung parenchyma in Grant's gazelle showing in (a) a terminal bronchiole (TB) branching into several short respiratory bronchioles and then into alveolar ducts, and in (b) a cross-section of an alveolar duct (D) surrounded by alveoli (A). Note the dense loading of the alveolar septa with a network of bulging capillaries (arrows). Magnification: a: 100×; b: 460×.

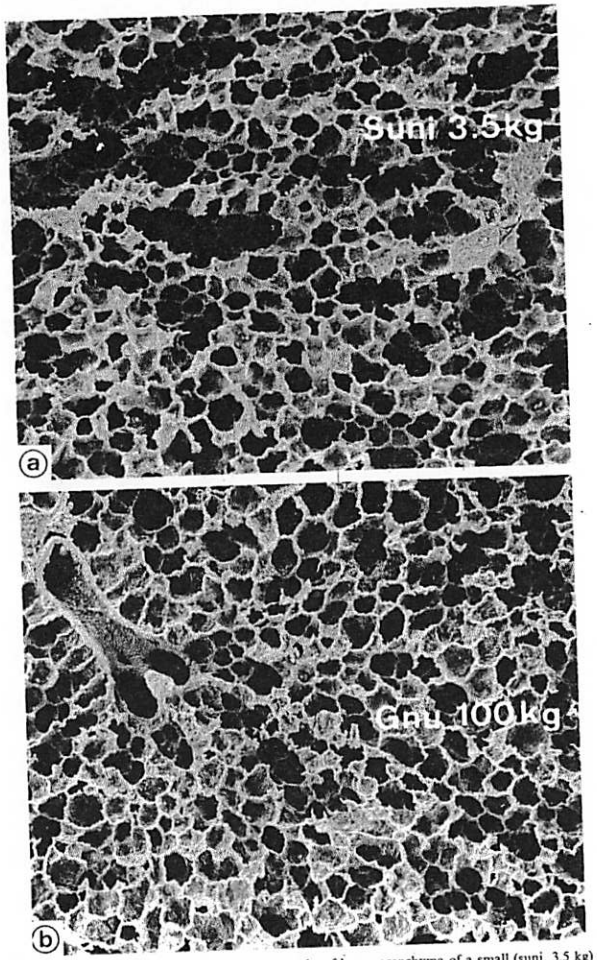

Fig. 3. Comparison of scanning electron micrographs of lung parenchyma of a small (suni, 3.5 kg) and a large animal (gnu, 102 kg) to show similarity of alveolar sizes in spite of a large difference in body mass. Magnification: 110×.

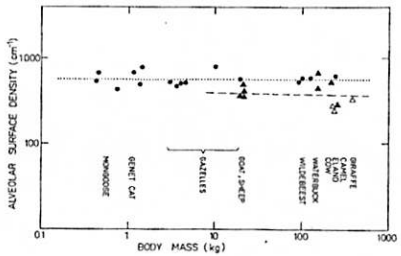

Fig. 4. Plot of alveolar surface density in parenchyma against body mass for African mammals. *Note:* in all graphs full symbols indicate animals for which $\dot{V}_{O_2max}$ estimates are available, circles are wild and triangles domesticated species. Dotted line is regression for wild, broken line for domesticated species.

In the interalveolar septa the largest part of the space is taken up by capillaries which are arranged in a single sheet (fig. 5). Capillary blood flow is thus intercalated between two air chambers, separated from the air on either side by a very thin tissue barrier made of the three layers endothelium, interstitium, and epithelium. The supporting fibers are restricted to one side of the capillaries, whereas on the other side epithelium and endothelium are separated merely by their fused basement membranes. The observed bulging of capillaries is the result of fluid filling of the airways due to instillation fixation which removes the surface lining layer (Gil *et al.*, 1979).

2. MORPHOMETRY OF PULMONARY GAS EXCHANGE APPARATUS IN AFRICAN BOVIDS AND VIVERRIDS

The morphometric data obtained on the 27 African mammals are presented in table 1 and plotted allometrically against body mass in figs. 6–8. Table 2 presents furthermore the parameters of the allometric regression. Total lung volume, V_L, ranged from 23 ml to 21 l and scaled linearly with body mass with a slope of 0.99. The estimates of alveolar surface area, S(A), ranged from 1.3 to 636 m² with an allometric slope of 0.92. The capillary surface, S(c), was on the average some 10% smaller than S(A) and scaled similarly. The capillary volume, V(c), ranged from 1.2 to 965 ml with a scaling factor of 0.97. There was a trend towards a size-dependence of the capillary loading of the alveolar surface, V(c)/S(A), with values ranging from less than 1 ml/m² in small to more than 2 ml/m² in large animals (table 1). However, the allometric regression was not significant; neither

TABLE I

Morphometric lung parameters and diffusing capacity estimated for three groups of African mammals. The estimates are means over 8–16 stratified samples from each lung; the coefficients of variation were between 5 and 10% for all estimates. Body masses given here are those measured at time of sacrifice and may differ from those reported by Taylor *et al.* (1981); $\dot{V}_{O_2max}$ values are taken from table 1 of Taylor *et al.* (1981) and adjusted to final body mass. [Note: for dwarf mongooses and one genet cat $\dot{V}_{O_2max}$ (in parentheses) was measured on different individuals of the same batch and of similar body weight.]

Species	Animal	M_b (kg)	V_L (ml)	$S_{(A)}$ (m^2)	$S_{(c)}$ (m^2)	$V_{(c)}$ (ml)	$\tau h_{(t)}$ (μm)	$\tau h_{(pl)}$ (μm)	$D_{L_{O_2}}$ $\left(\frac{\text{(ml } O_2\text{)}}{\text{sec} \cdot \text{mbar}}\right)$	$\dot{V}_{O_2max}$ $\left(\frac{\text{(ml } O_2\text{)}}{\text{sec}}\right)$
Family Viverridae										
Dwarf mongoose										
(Helogale pervula)	2133	0.418	27.4	1.313	1.003	1.20	0.398	0.158	0.017	(0.89)
	2134	0.441	22.9	1.373	1.281	1.98	0.418	0.155	0.026	(0.92)
	2135	0.724	41.4	2.131	2.118	3.01	0.366	0.189	0.041	–
Banded mongoose										
(Mungos mungo)	2121	1.140	63.3	3.944	2.606	2.53	0.409	0.181	0.038	2.17
Genet cat										
(Genetta tigrina)	2120	1.330	111.2	4.992	4.068	4.40	0.485	0.117	0.064	(2.26)
	2132	1.415	86.8	6.279	4.389	5.66	0.527	0.303	0.073	2.41
Family Bovidae – wild species										
Suni										
(Nesotragus moschatus)	2125	3.0	208.7	10.24	6.85	11.72	0.654	0.203	0.139	4.83
	2124	3.6	210.0	9.14	9.41	13.11	0.469	0.161	0.173	5.76
Dik-dik										
(Madoqua kirkii)	2123	4.1	314.6	14.67	13.65	19.35	0.446	0.187	0.257	3.69
	2131	4.3	312.2	14.52	12.34	25.91	0.412	0.140	0.321	3.93
Grant's gazelle										
(Gazella granti)	2122	10.1	562.0	39.90	30.27	37.00	0.537	0.115	0.519	9.03
Thomson's gazelle										
(Gazella thomsoni)	2114	19.5	1670.0	95.00	78.76	119.0	0.370	0.220	1.597	–
Wildebeest										
(Connochaetes taurinus)	2137	102.0	7678.0	390.8	281.3	472.5	0.373	0.219	6.232	75.7
Waterbuck										
(Kobus defassa)	2127	93.5	6288.0	287.7	291.7	486.0	0.492	0.143	6.075	70.6
	2128	126.1	9383.0	478.1	383.9	682.3	0.420	0.196	8.662	102.6
Eland										
(Taurotragus oryx)	2138	240.0	10668.0	557.0	460.8	833.2	0.496	0.142	10.40	143.3
Giraffe										
(Giraffa camelopardalis)	2102	383.0	21000.0	636.1	551.6	964.8	0.596	0.220	11.08	–
Family Bovidae – domestic species										
African goat										
(Capra hircus)	2111	19.9	1384.0	43.77	42.67	93.33	0.512	0.243	0.993	16.9
	2110	21.9	1355.0	46.10	45.02	109.08	0.567	0.399	0.988	19.2
African sheep										
(Ovis aries)	2109	21.6	1749.0	74.21	78.39	180.52	0.481	0.337	1.792	18.4
	2108	22.0	1662.0	59.95	50.53	110.66	0.580	0.310	1.118	15.3
Zebu cattle										
(Bos indicus)	2113	151.0	8036.0	313.4	308.3	504.3	0.416	0.237	6.306	68.0
	2112	154.0	6081.0	354.1	353.6	482.8	0.430	0.231	6.348	72.3
	2119	251.0	14987.0	364.8	365.1	827.6	0.566	0.191	8.628	115.7
	2118	214.0	11475.0	507.6	491.1	986.8	0.577	0.201	10.759	111.8
Camel										
(Camelus dromedarus)	2104	229.0	17300.0	488.9	301.7	478.2	0.589	0.157	6.170	–
	2101	234.5	14500.0	372.1	243.3	277.5	0.601	0.128	3.918	–

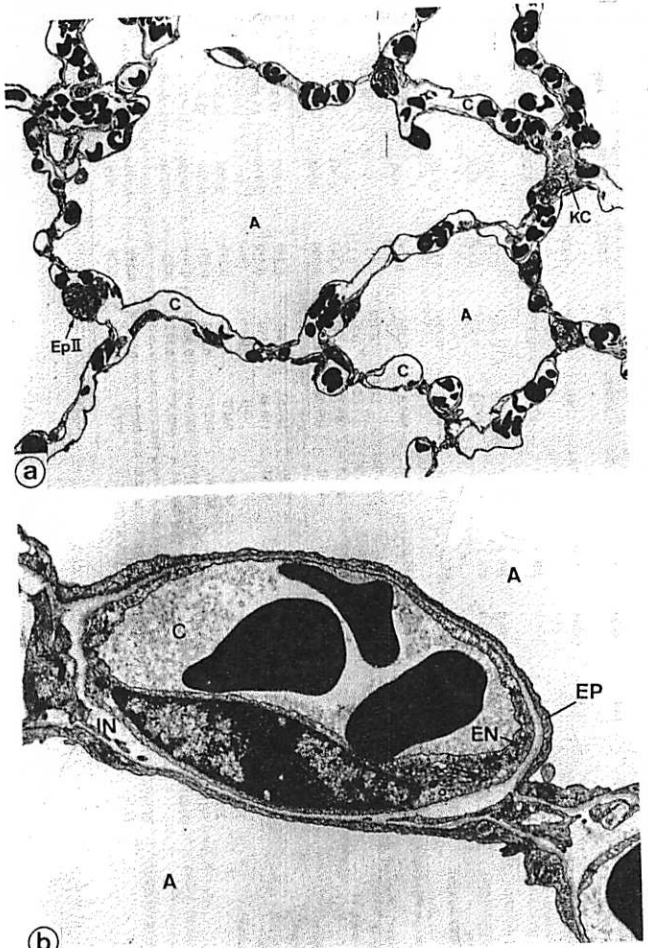

Fig. 5. (a) Low power electron micrograph of wildebeest lung showing dense packing of capillaries (C) into alveolar septa between alveoli (A). Note that barrier is very thin for the most part but contains cell bodies, such as type II epithelial cells (Ep II). Magnification: 950×. (b) Capillary of dik-dik lung at higher power to reveal the barrier made of endothelium (EN), epithelium (EP) and interstitial space (IN) with fibroblast processes. Magnification: 9000 ×. .

TABLE 2

Allometric regressions for morphometric respiratory variables for restricted population of African mammals, based on individual animal data (table 1). Part (A) considers all 27 animals, (B) and (C) only those 21 where $\dot{V}_{O_2max}$ measurements are available. Allometric equation $y = a \cdot M_b^b$ (M_b in kg) for (A) and (B) and $y = a \cdot \dot{V}_{O_2}^b$ for (C). 95% confidence intervals for **a** and **b**, as well as correlation coefficient **r**, are reported

Parameter	Units	Coefficient a		Exponent b		r
		Mean	*95% confidence interval*	Mean	*95% confidence interval*	
(A)						
VL	ml	66.13	*58.27 , 75.04*	0.986	*0.951 , 1.020*	0.996
S(A)	m^2	3.577	*3.007 , 4.255*	0.918	*0.871 , 0.966*	0.992
S(c)	m^2	2.988	*2.488 , 3.588*	0.924	*0.874 , 0.974*	0.991
V(c)	ml	4.190	*3.231 , 5.432*	0.971	*0.900 , 1.042*	0.985
$\tau h(t)$	µm	0.444	*0.400 , 0.494*	0.028	*−0.001 , 0.057*	0.364
D_{LO_2}	ml O_2/sec · mbar	0.055	*0.044 , 0.069*	0.950	*0.889 , 1.012*	0.988
V(c)/(SA)	ml/m^2	1.171	*0.936 , 1.465*	0.053	*−0.009 , 0.114*	0.333
(B)						
$S(A)/M_b$	m^2/kg	3.474	*2.880 , 4.189*	−0.066	*−0.120 , −0.013*	−0.510
D_{LO_2}/M_b	ml O_2/sec · kg · mbar	0.051	*0.043 , 0.063*	−0.003	*−0.057 , 0.052*	−0.022
$\dot{V}_{O_2max}/M_b$	ml O_2/sec · kg	1.71	*1.48 , 1.976*	−0.221	*−0.262 , −0.179*	−0.932
(C)						
S(A)	m^2	1.879	*1.455 , 2.428*	1.188	*1.107 , 1.268*	0.990
D_{LO_2}	ml O_2/sec · mbar	0.027	*0.020 , 0.037*	1.265	*1.168 , 1.363*	0.987

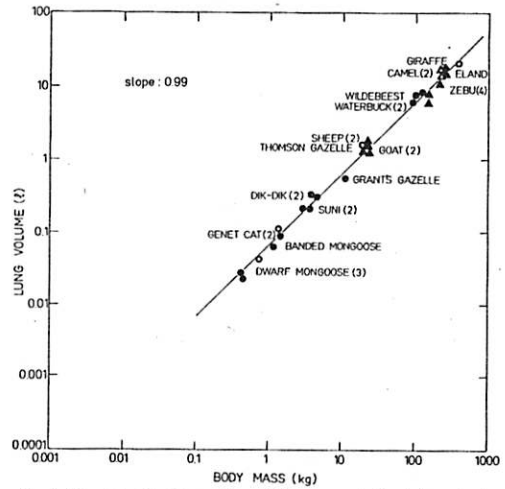

Fig. 6. Allometric plot of lung volume. African mammals. Symbols see fig. 4.

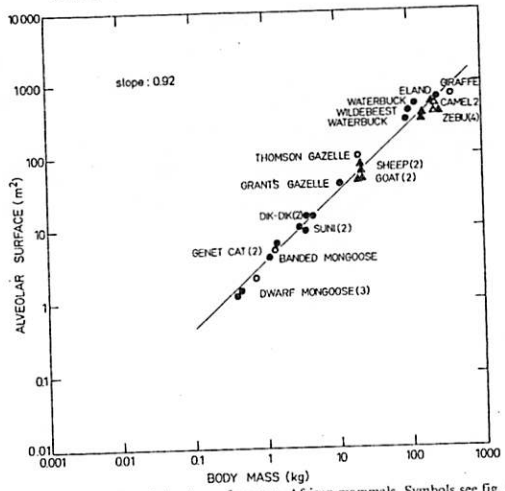

Fig. 7. Allometric plot of alveolar surface area. African mammals. Symbols see fig. 4.

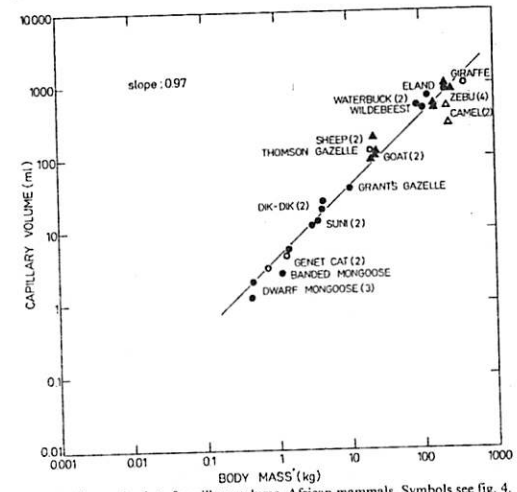

Fig. 8. Allometric plot of capillary volume. African mammals. Symbols see fig. 4.

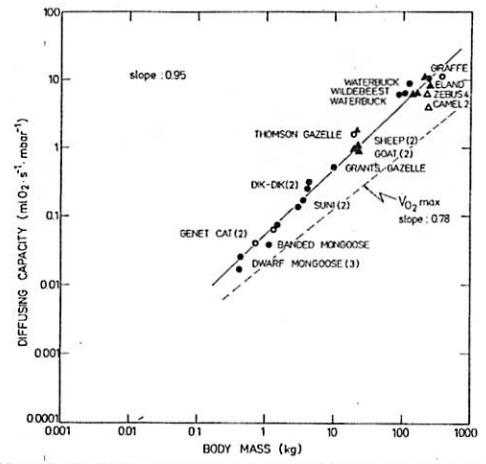

Fig. 9. Allometric plot of pulmonary diffusing capacity. African mammals. Symbols see fig. 4.

was that found for the harmonic mean thickness of the tissue barrier (τ_H) whose mean was of the order of 0.5 µm with a range from 0.37 to 0.65 µm (table 2).

From these data the morphometric pulmonary diffusing capacity for oxygen, $D_{L_{O_2}}$, was calculated and found to vary between 0.017 and 11.1 ml $O_2 \cdot s^{-1} \cdot mbar^{-1}$; it scaled linearly with M_b ($b = 0.95$), as shown in fig. 9. It is noteworthy that the slopes for diffusing capacity, alveolar and capillary surface areas, and capillary volume were close to 1, and that they were all significantly different from the slope of 0.78 obtained on the same animals by Taylor *et al.* (1981) for $\dot{V}_{O_2max}$ (table 2b). Figure 10 finally plots diffusing capacity against maximal oxygen consumption for the 21 animals on which both measurements had been obtained; $D_{L_{O_2}}$ increases with the power 1.27 of maximal oxygen consumption (table 2c). Thus, as shown in fig. 11, the flow of oxygen across the unit alveolar surface area or the unit diffusing capacity is smaller in large than in small animals.

Finally, comparing the wild and domestic bovids comprised in this study for which both $\dot{V}_{O_2max}$ and $D_{L_{O_2}}$ estimates were available (fig. 12) it is clear that the large domestic animals had consistently a lower mass-specific $\dot{V}_{O_2max}$ and also a lower mass-specific $D_{L_{O_2}}$. It was surprising that goats and sheep did not show a reduced $\dot{V}_{O_2max}/M_b$ and $D_{L_{O_2}}/M_b$ compared to gazelles.

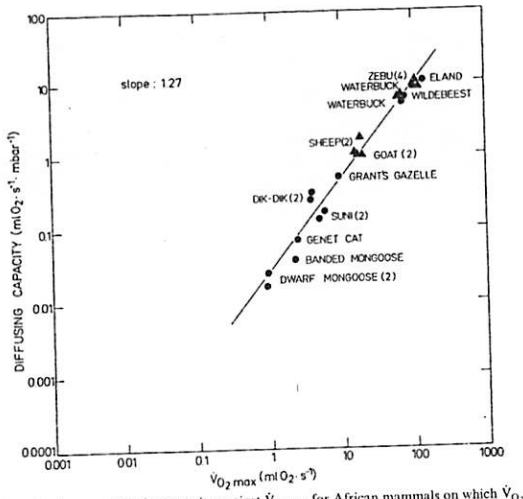

Fig. 10. Plot of pulmonary diffusing capacity against $\dot{V}_{O_2max}$ for African mammals on which $\dot{V}_{O_2max}$ was measured individually (Taylor *et al.*, 1981).

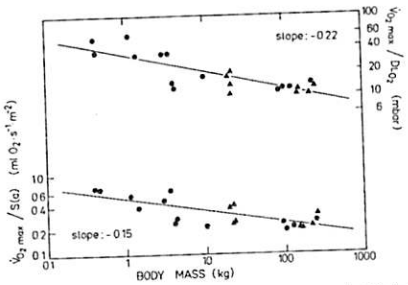

Fig. 11. Plot of maximal O_2 flow per unit alveolar surface and per unit diffusing capacity against body mass for African mammals on which $\dot{V}_{O_2max}$ was measured individually (Taylor *et al.*, 1981).

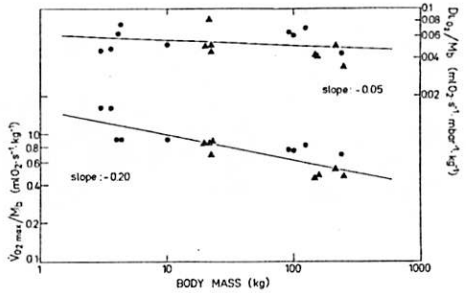

Fig. 12. Comparison of specific $\dot{V}_{O_2max}$ and specific $D_{L_{O_2}}$ in wild and domesticated bovids.

3. COMPARATIVE MORPHOMETRY OF MAMMALIAN LUNGS

An important question to answer is whether the group of Kenyan mammals considered in this study is representative of a broader population of mammalian lungs. For this purpose we have compared the present data with those obtained on other mammalian species using the same basic method. Rather than presenting individual animal data table 3 and figs. 13–16 report average values for species estimates. The species considered range in body weight from 2 g in the Etruscan shrew to 500 kg in the horse and 700 kg in a Swiss cow. Of the 32 species 15 represent those investigated in the present study. It is clearly seen from figs. 13–16 that the data obtained on the African ruminants and viverrids fit well into the general population, and that the allometric regressions for all parameters are identical for the Kenyan mammals and the overall population (tables 2 and 4). In addition the broader population reveals that the slight increase in thickness of the air–blood barrier with body mass is significant; it should be noted that the allometric regression coefficient for τ_{bl} found in the Kenyan animals is the same as that for the overall population. Also the capillary loading of the alveolar surface area, estimated by the ratio V(c)/S(A), is significantly increasing with body mass.

Discussion

LUNG FINE STRUCTURE AND BODY SIZE

Although the animals investigated span a body size range of almost three orders of magnitude, there were no striking size-dependent differences in the fine structure

TABLE 3

Mean values (±SE in parentheses where sample size permits) of morphometric parameters of pulmonary gas exchange apparatus for mammalian species (extended population). Species for which joint estimates of $\dot{V}_{O_2max}$ and $D_{L_{O_2}}$ were obtained are marked by asterisk (cf. Taylor *et al.*, 1981). Because of the large differences in M_b among rats and dogs they were divided into 2 and 4 groups, respectively, on the basis of M_b. The two groups for the rats were: mean 0.140 kg, range 0.114–0.178; and mean 0.457 kg, range 0.440–0.480. The four groups for the dogs were: mean 5.4 kg, range 2.6–8.2; mean 11.6 kg, range 10.0–14.5; mean 22.3, range 16.0–29.3; and mean 46.1, range 36.0–57.0)

Species	N	M_b (kg)	V_L (ml)	S(A) (m^2)	S(c) (m^2)	V(c) (ml)	th(t) (μm)	$D_{L_{O_2}}$ $\left(\frac{ml\,O_2}{sec \cdot mbar}\right)$
Family Soricidae								
Shrew								
(Sorex minutus)	1	0.0029	0.11	0.024	0.017	0.011	0.26	0.00019
(Neomys fodiens)	1	0.017	0.61	0.104	0.077	0.060	0.29	0.00096
(Suncus etruscus)	4	0.0026	0.10	0.017	0.013	0.0116	0.27	0.00018
				(0.0018)	*(0.004)*	*(0.004)*	*(0.04)*	
(Crocidura juvenata)	1	0.007	0.22	0.031	0.023	0.018	0.37	0.00028
(Crocidura russula)	2	0.0122	0.39	0.062	0.042	0.034	0.36	0.00053
(Crocidura poensis)	2	0.017	0.49	0.067	0.050	0.043	0.42	0.00065
(Crocidura flavescens)	2	0.035	1.13	0.156	0.123	0.135	0.38	0.00197
(Crocidura giffardi)	2	0.096	2.7	0.25	0.202	0.245	0.35	0.00354
Family Muridae								
White mouse								
(Mus musculus)	9	0.042	1.45	0.125	0.113	0.147	0.29	0.00213
				(0.006)	*(0.006)*	*(0.007)*	*(0.012)*	
Waltzing mouse								
(Mus wagneri)	5	0.013	0.571	0.063	0.054	0.065	0.26	0.00097
				(0.008)	*(0.006)*	*(0.017)*	*(0.005)*	
White rat								
(Rattus rattus)	8	0.140	6.34	0.388	0.407	0.480	0.37	0.00679
				(0.054)	*(0.056)*	*(0.063)*	*(0.039)*	
	3	0.457	13.4	0.786	0.816	1.48	0.40	0.0183
				(0.066)	*(0.059)*	*(0.043)*	*(0.021)*	
Family Caviidae								
Guinea pig								
(Cavia porcellus	15	0.429	13.04	0.91	0.74	1.46	0.42	0.0179
				(0.11)	*(0.09)*	*(0.32)*	*(0.03)*	
Family Leporidae								
Rabbit								
(Oryctolagus cuniculus)	6	3.56	79.2	5.86	4.70	7.15	0.50	0.0917
				(1.24)	*(0.88)*	*(1.88)*	*(0.04)*	
Family Viverridae								
Dwarf mongoose								
(Helogale parvula)	3*	0.53	30.6	1.61	1.46	2.06	0.39	0.028
Banded mongoose								
(Mungos mungo)	1*	1.14	63.3	3.94	2.60	2.53	0.41	0.038
Genet cat								
(Genetta tigrina)	2*	1.37	99.0	5.63	4.23	5.04	0.51	0.069
Family Canidae								
Dog								
(Canis familiaris)	3	5.4	284.2	18.2	14.1	26.0	0.43	0.325
				(13.5)	*(11.1)*	*(24.9)*	*(0.02)*	
	9	11.6	764.4	43.2	35.5	55.8	0.47	0.716
				(8.9)	*(8.8)*	*(21.1)*	*(0.03)*	
	11	22.3	1406	82.7	65.5	110.0	0.50	1.369
				(20.2)	*(15.2)*	*(35.0)*	*(0.03)*	
	5	46.1	2888	176.9	131.9	233.7	0.53	2.841
				(45.6)	*(37.5)*	*(68.7)*	*(0.08)*	
Family Camelidae								
Camel								
(Camelus dromedarius)	2	231.7	15900	430.5	272.6	377.9	0.60	4.937
Family Giraffidae								
Giraffe								
(Giraffa camelopardalis)	1	383.0	21000	636.1	551.6	964.8	0.60	11.172
Family Bovidae – wild species								
Suni								
(Nesotragus moschatus)	2*	3.3	209.4	9.69	8.13	12.45	0.56	0.154

TABLE 3 *(continued)*

Species	N	M_b (kg)	VL (ml)	S(A) (m^2)	S(c) (m^2)	V(c) (ml)	th(t) (μm)	D_{L-O_2} $\left(\frac{ml\ O_2}{sec \cdot mbar}\right)$
Dik-dik	2*	4.2	313.4	14.6	13.0	22.6	0.43	0.284
(Madoqua kirkii)								
Grant's gazelle	1*	10.1	562.0	39.9	30.3	37.0	0.54	0.501
(Gazella granti)								
Thomson's gazelle	1	19.5	1670.0	95.0	78.8	119.0	0.37	1.613
(Gazella thomsoni)								
Wildebeest	1*	102.0	7678.0	390.8	281.3	472.5	0.37	6.305
(Connochaetes taurinus)								
Waterbuck	2*	109.8	7835.5	382.9	337.8	584.2	0.46	7.241
(Kobus defassa)								
Eland	1*	240.0	10668.0	557.0	460.8	833.2	0.50	10.058
(Taurotragus oryx)								
Family Bovidae - domesticated species								
African goat	2*	20.9	1369.5	44.9	43.9	101.2	0.54	1.062
(Capra hircus)								
African sheep	2*	21.8	1705.5	67.1	64.5	145.6	0.53	1.554
(Ovis aries)								
Zebu cattle	4*	192.5	10145.0	385.0	379.5	700.4	0.50	8.010
(Bos indicus)								
Swiss cow	1	700.0	22450.0	1283.0	1138.0	2770.0	0.51	29.346
(Bos taurus)								
Family Equidae								
Horse	2	510.0	37650.0	2456.0	1663.0	2800.0	0.60	34.080
(Equus caballus)								
Family Cercopithecidae								0.205
Monkey	6	3.71	184.2	13.3	11.6	15.5	0.50	
(Macaca irus)				*(1.27)*	*(1.54)*	*(2.69)*	*(0.03)*	
Family Hominidae								2.470
Man	8	74.0	4341.0	143.1	125.9	213.1	0.62	
(Homo sapiens)				*(34.1)*	*(34.7)*	*(86.6)*	*(0.11)*	

Fig. 13. Allometric plot of mean lung volume against body mass for all species. Full dots: African species of this study, open circles: other species.

Fig. 14. Allometric plot of alveolar surface area and harmonic mean barrier thickness for all species. See fig. 13.

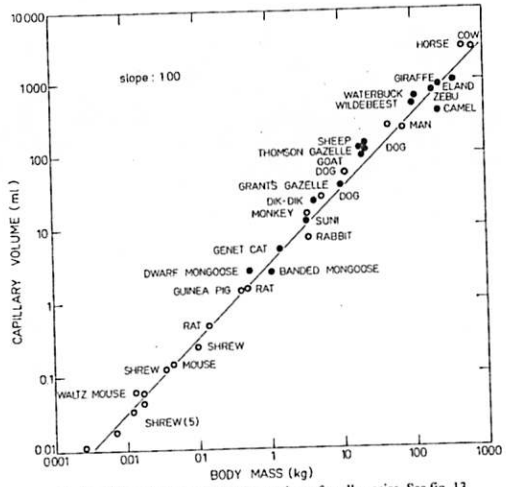

Fig. 15. Allometric plot of capillary volume for all species. See fig. 13.

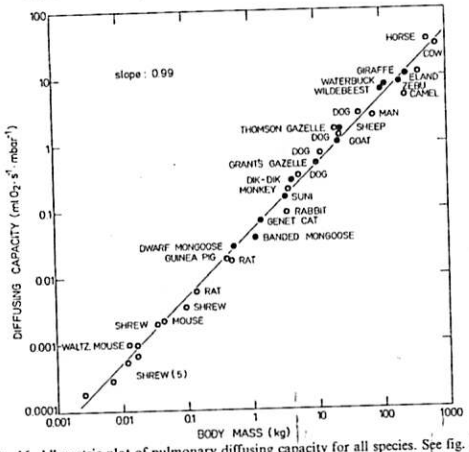

Fig. 16. Allometric plot of pulmonary diffusing capacity for all species. See fig. 13.

TABLE 4

Allometric regression for morphometric respiratory variables for extended population based on species data (table 3). Reported as in table 2

Parameter	Units	Coefficient a		Exponent b		r
		Mean	*(95% confidence interval)*	Mean	*(95% confidence interval)*	
VL	ml	45.994	*41.42 , 51.08*	1.059	*1.031 , 1.087*	0.997
S(A)	m^2	3.342	*2.971 , 3.759*	0.949	*0.917 , 0.980*	0.996
S(c)	m^2	2.727	*2.456 , 3.027*	0.952	*0.924 , 0.980*	0.996
V(c)	ml	3.198	*2.305 , 4.437*	1.000	*0.912 , 1.087*	0.970
τh(t)	µm	0.416	*0.396 , 0.437*	0.050	*0.037 , 0.064*	0.796
$D_{L_{O_2}}$	ml O_2/sec · mbar	0.049	*0.044 , 0.055*	0.991	*0.962 , 1.021*	0.996

of the lung parenchyma. The main difference lies perhaps in the number of alveolar pores which are sparse in bovids but very dense and conspicuous in the viverrid lungs; the latter resemble shrew or dog lungs with their notoriously large number of pores, occupying nearly every capillary loop (Gehr *et al.*, 1980a,b). There were also considerable differences in the dimensions of terminal airways and of alveoli, but these did not show any obvious relation with body size.

This was confirmed by the morphometric analysis which revealed a great variation in the volume density of tissue and capillaries, as well as in the alveolar surface density, the largest and smallest values differing by 2–3 times. But with the sole exception of the capillary volume density which was slightly larger in bigger animals, these morphometric variables were not correlated with body size. It is interesting to note, however, that some of these variables are significantly different between domesticated and wild animals, so that they may be related to differences in the level of O_2 consumption.

SCALING OF MORPHOMETRIC VARIABLES

The present study was undertaken to compare the scaling of maximal metabolic rate with that of the major morphometric determinants of pulmonary diffusing capacity. The study was done on a group of mammals ranging in body mass from 400 g to 250 kg. The first question to answer is whether the morphometric data thus obtained are representative of the data obtained on a more extended population ranging from 2 g to 700 kg and derived from 34 different species (Weibel, 1972, 1973, 1979).

The morphometric method used in this present study was slightly modified as compared to that used in previous studies, particularly with respect to the sampling protocol. In a companion paper (Weibel *et al.*, 1981a) we have shown that the

new and the old method yield comparable results. The two data sets can therefore be considered jointly.

Tables 2 and 4 present the allometric correlations derived for the restricted and extended populations respectively; none of the correlations differ significantly between restricted and extended population. We can therefore conclude that the range of African mammals considered in the present study is representative of the extended population. On the other hand, due to the limited weight range the confidence intervals for the regression coefficients for the Kenyan animals are wider than those for the extended population; this had however no effect on the statistical significance of the correlations, with the exception of the scaling of the harmonic mean barrier thickness, τ_{bi}, which is significant only for the extended population.

The lung volume, V_L, corresponding to submaximal inflation, was found to scale linearly with body mass with a narrow confidence limit. This is in line with most evidence which also shows that lung weight and total lung capacity are linearly related to M_b (Brody, 1945; Tenney and Remmers, 1963; Stahl, 1965, 1967; Weibel, 1972; Bartlett and Areson, 1977; Gehr *et al.*, 1980b).

The alveolar and capillary surface areas both scaled with a factor of 0.92 which differed significantly from 1.0. In contrast the capillary blood volume scaled with a factor which was not significantly different from 1.0, and as a consequence the capillary loading of the alveolar surface, estimated by the quotient V(c)/S(A), shows a tendency to increase slightly with body weight. The morphometric pulmonary diffusing capacity, $D_{L_{O_2}}$, scaled linearly with M_b, the exponent 0.95 not being statistically different from 1.

The present study has thus, in essence, confirmed the previously established finding that the main morphometric parameters of the pulmonary gas exchange apparatus, namely alveolar surface area, capillary volume, and the compound parameter $D_{L_{O_2}}$, all scale about linearly with M_b.

RELATION OF MORPHOMETRIC VARIABLES TO $\dot{V}_{O_2max}$

The main purpose of the present study was to see how the morphometric variables defining the lung as a gas exchanger related to maximal oxygen consumption. As set out in the introduction two approaches are possible: (1) one can compare animals of comparable size but different oxygen requirements; (2) one can compare the scaling of $\dot{V}_{O_2max}$ with that of morphometric variables over an extended range of size classes. In our previous studies these two approaches had yielded conflicting results (Weibel, 1973, 1979).

When comparing species of comparable size such as cow and horse (Gehr and Erni, 1980), or normal and waltzing mice (Geelhaar and Weibel, 1971; Hugonnaud *et al.*, 1977) we had found that the morphometric variables defining pulmonary diffusing capacity were closely related to the animals' oxygen requirements. In the present study this finding was confirmed by comparing wild and domesticated African bovids (fig. 12): the large domesticated bovids had a tendency to lower oxygen needs and smaller pulmonary diffusing capacity.

This study has however also confirmed the finding, that $\dot{V}_{O_2max}$ and the morphometric variables determining $D_{L_{O_2}}$ scale differently to body mass. Restricting this analysis to the 12 species (21 animals) for which both estimates of $\dot{V}_{O_2max}$ and lung morphometry were available we find that $\dot{V}_{O_2max}$ scales with the power $b = 0.78$ of body mass, with a 95% confidence interval for this slope of 0.72–0.83. In contrast, alveolar surface area scales with $b = 0.92$ (confidence interval 0.87–0.97) and $D_{L_{O_2}}$ with $b = 0.95$ (confidence interval 0.89–1.01). It is evident from this that the slopes for S(A) and $D_{L_{O_2}}$ are significantly different from the slope of $\dot{V}_{O_2max}$.

If we relate $D_{L_{O_2}}$ directly to $\dot{V}_{O_2max}$ we find $D_{L_{O_2}} = 0.027 \cdot \dot{V}_{O_2max}^{1.27}$.

It should be noted that the same general relationship also holds if we compare the scaling of morphometric variables in the extended population with the scaling of $\dot{V}_{O_2max}$ for an extended population as presented by Taylor *et al.* (1981). These two extended studies cover roughly the same size range, but were for the major part done on different animals.

From these results we conclude, that bigger animals require a larger pulmonary diffusing capacity than smaller animals in order to admit the flow of oxygen required by the organism during heavy work. For example, a wildebeest weighing about 100 kg requires a diffusing capacity five times larger than a mongoose of 1 kg body weight to transfer the same amount of oxygen from air to blood (see fig. 11).

COMPARISON WITH OTHER DATA

When comparing the results of the present study with those of other authors we first observe that physiological estimates of $D_{L_{CO}}$ and $D_{L_{O_2}}$ have repeatedly been found to scale about linearly with M_b; Stahl (1967) obtained slopes of about 1.1 whereas O'Neil and Leith (1980) recently found a linear relation between $D_{L_{CO}}$ and M_b.

Our findings are in apparent conflict with those of Tenney and Remmers (1963) who had found the alveolar surface area to be linearly related to $\dot{V}_{O_2}$ in a range of mammals spanning six orders of magnitude from the bat to the whale, whereas we find S(A) to be related to $\dot{V}_{O_2}^{1.2}$. We have said before (Weibel, 1973) that this apparent conflict cannot result from differences in the morphometric estimates: comparing those species that are contained in both studies one finds good agreement between the data; the fact that Tenney and Remmers (1963) obtained their measurements on air-dried lungs by light microscopy whereas we use electron microscopy should have no effect on a comparative study of this kind. The difference seems to lie essentially in the selection of animals. Tenney and Remmers (1963) included in their study terrestrial and marine mammals whereas our own

studies only considered terrestrial mammals. A problem, possibly leading to bias, may arise in the study of Tenney and Remmers (1963) because all their large animals, with the exception of one cow, were marine mammals. These animals not only have a notoriously low $\dot{V}_{O_2}$ they also use their lungs differently, prolonged breath-holding being one functional characteristic. Furthermore, it is known that their lungs are structurally quite different from terrestrial mammals on various accounts: among other differences they have unusually large alveoli, and the alveolar septa are provided with two layers of capillaries (Fanning and Harrison, 1974) in contrast to the simple capillary sheet of terrestrial mammals; although the alveolar surface area of marine mammals is relatively small its loading with capillary blood is much greater than in terrestrial mammals. Because of such fundamental differences in pulmonary morphology and physiology it is questionable to indiscriminately include these marine species in an allometric study on the respiratory system, particularly if their size range does not coincide with the range of terrestrial mammals; the danger of bias cannot be excluded. Such a bias is clearly evident in the graphs of Tenney and Remmers (1963), where the values of S(A) for the marine mammals can be shown to lie on a lower regression line than those of the terrestrial mammals, and the two partial regressions are statistically significantly different. Considering only the terrestrial mammals in the data of Tenney and Remmers we find that S(A) is proportional to $\dot{V}_{O_2}^{1.3}$ which is in excellent agreement with our results; it is noteworthy that the correlation coefficient improves considerably when the marine mammals are eliminated. We hence conclude that there is no real conflict between our results and those of Tenney and Remmers (1963), except on the question whether large marine mammals should be included in an allometric study of this kind.

We should finally mention the interesting findings of Bartlett and Areson (1977) who studied the relation of alveolar surface to $\dot{V}_{O_2}$ in newborn mammals from mouse to cow and found $S(A) \propto \dot{V}_{O_2}^{1.23}$; they also found alveolar surface density to be invariant with size in the neonatal lung, all in agreement with our results on the adult, and in fact with those of Tenney and Remmers (1963) if the same group of terrestrial species is considered. It is rather interesting and intriguing that a neonatal lung should have proportionally the same complement of gas exchange surface as the adult, suggesting a genetic determination of the size of the gas exchange apparatus. However, these findings must be considered with caution because they do not consider the loading of the alveolar surface with capillaries which may be much higher in the neonate than in the adult, at least in some species (Burri *et al.*, 1974).

THE PARADOX UNSOLVED

This study was designed to help us solve the paradox that morphometric diffusing capacity was related to $\dot{V}_{O_2}$ when animals of the same size range were compared, but closer to M_b than to $\dot{V}_{O_2}$ when mammals of varying size were considered. Rather than solving it, this study has confirmed the paradox. This means that a large animal has a relatively larger diffusing capacity with respect to $\dot{V}_{O_2max}$ than a small animal (fig. 12). As a consequence, it follows from the equation of Bohr (1909):

$$\dot{V}_{O_2} = DL_{O_2} \cdot \Delta P_{O_2}$$

that ΔP_{O_2}, the driving force for O_2 transfer from air to capillary blood, must decrease with increasing body size, scaling with a factor of −0.22 of body mass (fig. 11). This would mean that an animal weighing 100 g might have a driving force for O_2 flow from alveolar air to capillary blood about four times as large as an animal of 100 kg. Such a change in partial pressure gradient can be due either to a change in alveolar and/or in capillary P_{O_2}. There is evidence that DL_{O_2} can respond to alterations in alveolar P_{O_2} from the studies on adaptation to high altitude (Bartlett and Remmers, 1971; Burri and Weibel, 1971). The question arises whether there are size dependent factors that could modify alveolar P_{O_2}. As one possibility, preliminary structural findings suggest the diffusion pathway for O_2 in the air phase from the front of inspired air to the gas exchange surface to be longer in large animals; it is conceivable that this could cause the head pressure of the driving force to be smaller in large animals. Other possibilities that may influence the magnitude of ΔP_{O_2} as a function of size will be discussed by Weibel *et al.* (1981b).

References

Bartlett, D., Jr., and J.E. Remmers (1971). Effects of high altitude exposure on the lungs of young rats. *Respir. Physiol.* 13: 116–125.

Bartlett, D., Jr., and J.G. Areson (1977). Quantitative lung morphology in newborn mammals. *Respir. Physiol.* 29: 193–200.

Bohr, C. (1909). Ueber die spezifische Tätigkeit der Lungen bei der respiratorischen Gasaufnahme. *Scand. Arch. Physiol.* 22: 221–280.

Brody, S. (1945). Bioenergetics and Growth. New York, Reinhold Publishing Company, 1023 p.

Burri, P.H. and E.R. Weibel (1971). Morphometric estimation of pulmonary diffusion capacity. II. Effect of P_{O_2} on the growing rat lung to hypoxia and hyperoxia. *Respir. Physiol.* 11: 247–264.

Burri, P.H., J. Dbaly and E.R. Weibel (1974). The postnatal growth of the rat lung. I. Morphometry. *Anat. Rec.* 178: 711–730.

Fanning, J.C. and R.J. Harrison (1974). The structure of the trachea and lungs in the South Australian bottle-nosed dolphin. In: Functional Anatomy of Marine Mammals. Vol. 2, edited by R.J. Harrison. London, Academic Press, pp. 231–252.

Forrest, J.B. and E.R. Weibel (1975). Morphometric estimation of pulmonary diffusion capacity. VII. The normal guinea pig lung. *Respir. Physiol.* 24: 191–202.

Geelhaar, A. and E.R. Weibel (1971). Morphometric estimation of pulmonary diffusion capacity. III. The effect of increased oxygen consumption in Japanese waltzing mice. *Respir. Physiol.* 11: 354–366.

Gehr, P., M. Bachofen and E.R. Weibel (1978). The normal human lung: Ultrastructure and morphometric estimation of diffusion capacity. *Respir. Physiol.* 32: 112–140.

Gehr, P. and H. Erni (1980). Morphometric estimation of pulmonary diffusion capacity in two horse lungs. *Respir. Physiol.* 41: 199–210.

Gehr, P., S. Sehovic, P. H. Burri, H. Claassen and E. R. Weibel (1980a). The shrew lung: Morphometric estimation of diffusion capacity. *Respir. Physiol.* 40: 33–47.

Gehr, P., B. Siegwart and E. R. Weibel (1980b). Allometric analysis of the morphometric pulmonary diffusion capacity in dogs. *J. Morphol.* (In press).

Gil, J., H. Bachofen, P. Gehr and E. R. Weibel (1979). Alveolar volume–surface area relation in air- and saline-filled lungs fixed by vascular perfusion. *J. Appl. Physiol.* 47: 990–1001.

Holland, R. A. B., W. Van Hezewijk and J. Zubzanda (1977). Velocity of oxygen uptake by partly saturated adult and fetal human red cells. *Respir. Physiol.* 29: 303–314.

Hugonnaud, C., P. Gehr, E. R. Weibel and P. H. Burri (1977). Adaptation of the growing lung to increased $\dot{V}_{O_2}$. II. Morphometric analysis. *Respir. Physiol.* 29: 1–10.

Kleiber, M. (1932). Body size and metabolism. *Hildgardia* 6: 315–353.

Kleiber, M. (1961). The Fire of Life. New York, Wiley, 454 p.

O'Neil, J. and D. E. Leith (1980). Lung diffusing capacity scaled in mammals from 25 g to 500 kg. *Fed. Proc.* (Abstract).

Seeherman, H. J., C. R. Taylor, G. M. O. Maloiy and R. B. Armstrong (1981). Design of the mammalian respiratory system. II. Measuring maximum aerobic capacity. *Respir. Physiol.* 44: 11–23.

Siegwart, B., P. Gehr, J. Gil and E. R. Weibel (1971). Morphometric estimation of pulmonary diffusion capacity. IV. The normal dog lung. *Respir. Physiol.* 13: 141–159.

Stahl, W. R. (1965). Organ weights in primates and mammals. *Science* 150: 1039–1042.

Stahl, W. R. (1967). Scaling of respiratory variables in mammals. *J. Appl. Physiol.* 22: 453–460.

Taylor, C. R., G. M. O. Maloiy, E. R. Weibel, V. A. Langman, J. M. Z. Kamau, H. J. Seeherman and N. C. Heglund (1981). Design of the mammalian respiratory system. III. Scaling maximum aerobic capacity to body mass: wild and domestic mammals. *Respir. Physiol.* 44: 25–37.

Tenney, S. M. and J. E. Remmers (1963). Comparative quantitative morphology of mammalian lungs; diffusing areas. *Nature* 197: 54–56.

Weibel, E. R. (1970/71). Morphometric estimation of pulmonary diffusion capacity. I. Model and method. *Respir. Physiol.* 11: 54–75.

Weibel, E. R. (1972). Morphometric estimation of pulmonary diffusion capacity. V. Comparative morphometry of alveolar lungs. *Respir. Physiol.* 14: 26–43.

Weibel, E. R. (1973). Morphological basis of alveolar-capillary gas exchange. *Physiol. Rev.* 53: 419–495.

Weibel, E. R. (1979). Oxygen demand and the size of respiratory structures in mammals. In: Evolution of Respiratory Processes: A Comparative Approach. Vol. 13 of Lung Biology in Health and Disease, edited by C. Lenfant. New York and Basel, Marcel Dekker Inc., pp. 289–346.

Weibel, E. R., P. Gehr, L. M. Cruz-Orive, A. Müller, D. K. Mwangi and V. Haussener (1981a). Design of the mammalian respiratory system. IV. Morphometric estimation of pulmonary diffusing capacity: critical evaluation of a new sampling method. *Respir. Physiol.* 44: 39–59.

Weibel, E. R., C. R. Taylor, P. Gehr, H. Hoppeler, O. Mathieu and G. M. O. Maloiy (1981b). Design of the mammalian respiratory system. IX. Functional and structural limits for oxygen flow. *Respir. Physiol.* 44: 151–164.

Respiration Physiology (1981) 44, 87–111
Elsevier/North-Holland Biomedical Press

DESIGN OF THE MAMMALIAN RESPIRATORY SYSTEM. VI. DISTRIBUTION OF MITOCHONDRIA AND CAPILLARIES IN VARIOUS MUSCLES*

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Abstract. The variability of structures supporting tissue oxygen transport (capillaries) and oxygen consumption (mitochondria) was analyzed in skeletal muscles of wildebeest and dik-dik. Regional differences in mitochondria and capillary densities within individual muscles were found for M. semitendinosus (twofold) but not for M. longissimus dorsi and diaphragm. Comparing 20 different muscles from both animals, the volume density of mitochondria in the muscle fibers [V_V(mt,f)] was significantly higher in diaphragm (10–12%) and varied considerably (1–6%) in the other muscles. The relation between V_V(mt,f) and the number of capillaries per cross-sectional fiber area N_A(c,f) showed great variability. In glycolytic fibers V_V(mt,f) was typically low (1%) whereas in oxidative fibers it ranged from 5–15%. No systematic trend was found for the packing of cristae in subsarcolemmal and interfibrillar mitochondria from both types of fibers in large and small animals.

Capillary number — Mitochondrial volume
Muscle fiber types — Muscle morphometry

Relating structure and function of the respiratory system at the cellular level for skeletal muscle presents a real challenge because of the heterogeneity of this multi-compartmented system. Each muscle represents an anatomical compartment which is tailored to fulfil a number of specific motor tasks. The single compartments are neither quantitatively nor qualitatively equal, they rather exhibit a large

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