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Architecture of the Human Lung

Use of quantitative methods establishes fundamental relations between size and number of lung structures.

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With the rapid advances of recent years in quantitative measurements of physiological functions in man, there has developed an increasing need for comparably accurate measurements of structure. While there is now an active interest in this field (1), and while some significant and important preliminary experiments have been carried out—for example, in the study of the kidney (2) and the heart (3)—it is probably not unjust to state that, for the most part, knowledge of quantitative human anatomy lags far behind that of quantitative human physiology.

There is a particularly urgent need for detailed quantitative information about the structures of the human lung. Understanding of the physiology of air flow and air distribution, of blood flow and blood distribution, and of diffusion of gases, in all its phases, in both normal and pathological states, has reached the point where a more exact and detailed knowledge of the anatomical structures involved is needed—knowledge of their numbers, their dimensions, their shapes, their surfaces, and their geometric arrangements and interrelations.

The quantitative study of pulmonary structure in relation to function is, of course, not new. Stephen Hales, in 1731 (4), being interested in the fate of the air in the lungs, made the remarkably accurate estimate of "1/100th part of

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an inch" (0.25 mm) as the diameter of a "middle-sized" alveolus in a calf's lung, and he proceeded from this to calculate the total internal surface of the lung. In recent years there have been various measurements of such single dimensions as alveolar diameter, number of alveoli, and alveolar surface (5), but, so far as we are aware, there has been no comprehensive quantitative survey of the entire lung as an organized and integrated structure.

Over the past two years, in collaboration with our colleagues in physiology in the Cardiopulmonary Laboratory at Bellevue Hospital, we have been engaged in an investigation designed to achieve this objective. The study is being continued, but it has now progressed to the point where the main outlines of the work have been defined and a preliminary communication seems justified.

As in any exploratory endeavor, much of the planning, methodology, and mathematical formulation is new. These will be presented here very briefly; they have been described in full in earlier communications (6, 7).

As a broader objective, we have the hope that the data here presented will be of service to physiologists and biophysicists in the correlation of structure and function. We suggest also that studies constructed according to this general model—quantitative morphology or morphometry—may be useful in describing the anatomy of other structures, such as kidney or liver or other organs of external or internal secretion.

Figure 1 gives in broad outline a description of the "conductive zone" (I and II), of the larger airways and blood vessels, and of the "respiratory zone" (III and IV), with alveolar ducts, alveoli, and capillary network.

For the purposes of morphometry, the small size, large number, and relatively even distribution of the elements of the respiratory zone justify the assumption of their random distribution. This makes it possible to use statistical methods of sampling and quantitation.

The definite orientation of the elements of the conductive zone requires a quite different type of analysis—one which can be carried out successfully, however, once the basic numerical values for the respiratory zone have been found.

We devote the greater part of this article to description of the architecture of the respiratory zone for two reasons: (i) analysis of the respiratory zone is more nearly completed, in our research, than analysis of the conductive zone, and (ii) the respiratory zone is of primary physiological interest in its relation to alveolar ventilation and perfusion and to transcapillary diffusion.

Material and Methods of Preparation

In Table 1 are listed the properties of the five lungs used for microscopical studies. The individuals from which they were taken ranged in age from 8 to 74 years at time of death, and the lung volumes ranged from 2.5 to 7 liters. These lungs were all prepared according to a standardized method of formalin steam fixation, which has been reported elsewhere (6). All the lungs were fixed at a degree of inflation which

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Table 1. Properties of the five lungs studied. $N_{\rm AT}$, number of alveoli; $N_{\rm (D+S)T}$, number of alveolar ducts and sacs combined.

Case No.	Individual		Lung	Deemen	Airway elements	
	Age (yr)	Sex	volume (ml)	inflation (ζ)	N _{AT}	$N_{(D + S)T}$
2471	8	М	2580	0.80	$304 imes10^{6}$	$13.6 imes 10^{6}$
555	16	F	2680	.80	$288 imes 10^6$	$15.8 imes10^6$
9975	34	Μ	5750	.75	$310 imes10^6$	$14.3 imes10^6$
8710	48	М	7100	.74	$286 imes10^6$	$13.5 imes10^6$
3361	74	F	5950	.75	$286 imes10^{6}$	$11.6 imes10^{6}$
	Ave	rages of a	urway elements	296×10	$^{6} \pm 3.9\% *$	$13.8 \times 10^{6} \pm 11\%^{*}$

* Coefficient of variation.

corresponded to approximately threefourths of total lung capacity. This could be estimated by comparing the inflated volume and weight of the fresh lungs. An important antecedent investigation involved the determination of correction factors for artificial tissueshrinkage induced by this standardized procedure. These factors made possible the approximate conversion of all dimensions obtained on either fixed or fully processed material (histological slides) into values for the fresh state. All the data that follow, therefore, refer to a fresh lung at three-fourths of total lung inflation.

The large structures of the conductive zone were quantitated mainly on vinyl casts of bronchial and vascular trees (8).



Fig. 1. Zones of airways and blood vessels of the human lung.

Respiratory Zone

Airways. The airway element of the respiratory zone is the alveolar duct. It consists of a central air channel which is in continuity with other ducts at either end, and which is surrounded by a sleeve of alveoli. Three to four generations of alveolar ducts are connected in series, terminating in an alveolar sac which is of basically identical structure but which is closed at its peripheral end.

Figure 2 shows two alveoli in their relationship to an alveolar duct. A diagrammatic representation of this relationship (Fig. 3, left) reveals that the idealized configuration of the typical alveolus has several features in common with the cells of a honeycomb. It is, however, more complex, in part because the alveoli open on a cylindrical tube rather than on a plane.

For quantitative definition of the airways of the respiratory zone, information is needed on (i) the distribution of the volume of the lung among various components, such as alveoli, alveolar ducts, and tissue; (ii) the number of alveoli and alveolar ducts; and (iii) the geometry and characteristic dimensions of these structural elements.

The volumetric proportions of the various components of the respiratory zone were determined by a linear microscopic integration method (9). This is based on a principle (10) commonly used by geologists: If the fraction of a line traversing a given component on a section can be determined, this linear fraction can be used to estimate the fraction of the volume occupied by the given component. The integrating eyepiece of Leitz (9) makes it possible to carry out the analysis on histological sections. The fractional distribution of the lung volume is represented graphically in Fig. 4. The respiratory zone constitutes about 90 percent of the lung volume; airways and blood vessels of the conductive zone make up the remaining 10 percent. In the lungs of the younger subjects the 90-percent respiratory fraction had the following composition: alveoli, 57 percent; air ducts, 27 percent; tissue and smaller blood vessels, 6 percent. In the two older subjects the alveolar fraction appeared to have been reduced to 52 percent, while the duct fraction had risen to 32 percent.

Although the number of samples is small, the difference between the younger and the older age groups is highly significant (P < .001). Subse-

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quent investigations of a larger number of samples will show whether this difference with age is characteristic of the entire population. It is, however, well known that aging induces changes in the physiological air volumes, a finding which may be related to our observation (11).

In order to count the number of alveoli and alveolar ducts, a new principle had to be devised, since no method of direct counting was available. The method we devised is presented elsewhere in full detail (7). Briefly stated, it is this: If some structures of given shape are randomly distributed within a volume, then the number N of these structures contained in the unit volume can be inferred from counting the number n of transections through these structures on the unit area of a thin histological section by applying the equation

$$N = n^{3/2} / \beta \rho^{1/2}.$$

(1)

In this equation the coefficient β relates the volume of the investigated structures to their average cross-sectional area; it is a function of the shape of these bodies and has been formulated elsewhere (7). In our special case the value of β was found to be 1.55 for alveoli and 1.97 for alveolar ducts. The coefficient ρ represents the fraction of the total volume occupied by the structures under investigation. We have already discussed the volumetric fractions of the respiratory zone occupied by alveoli (ρ_{A}) or alveolar ducts (ρ_{D}) , respectively; they are demonstrated graphically in Fig. 4 for each case. Transections of alveoli and alveolar ducts were counted on histological sections, providing the n of Eq. 1.

From the number of alveoli or (ducts) per unit volume N thus obtained, the total number of alveoli (N_{AT}) and of alveolar ducts and sacs (N_{DT}) could be inferred (Table 1). It was found that all lungs, regardless of their size or of the age of the individual, were con-

Fig. 2 (top right). Photomicrograph of two alveoli opening of an alveolar duct, which is sectioned transversely. Thick section of a human lung.

Fig. 3 (middle right). Three independent methods for determining the alveolar surface area.

Fig. 4 (bottom right). Fractional distribution of the total lung volume and of the respiratory zone among alveoli, air ducts, tissue, and conductive structures.







structed of an essentially equal number of alveoli (about 300 million) and of 14 million alveolar ducts and sacs. The standard deviations from the group means were 4 and 11 percent, respectively.

As we have pointed out, the "typical" alveolus is somewhat similar in geometry to the cell of a honeycomb. A mathematical formulation of this shape, which seems to have a minimal surface, is not attempted here. However, one functionally important geometrical property of the alveolus is the relation σ_A of its surface s_A to its volume v_A , which can be expressed as

$$s_{\rm A} \equiv \sigma_{\rm A} v_{\rm A}^{2/3} \tag{2}$$

where σ_A is a dimensionless coefficient independent of the size but a function of the geometric shape of the body. For example, for a cube of any size, $\sigma = 6$, but for a quadratic prism which is three times as high as it is wide, $\sigma = 7$. Through a rather elaborate procedure, formulated elsewhere, it was possible to determine experimentally the value of σ_A for alveoli. In the five lungs of our study the value was found to be constant, with an average of $\overline{\sigma_A} = 4.87$ (standard deviation, \pm 0.19). By coincidence, this value is close to that for a sphere (4.83)—the smallest possible value of σ for a closed body. We have to consider, however, the fact that the alveolus is open on one side, like an open cubic box, for which $\sigma = 5$.

The alveolar dimensions are best characterized by an "average diameter." Although the alveolus is not spherical, the "diameter" is of the same order of magnitude in all directions (Figs. 2 and 3). This "average alveolar diameter" $\overline{d_A}$ could be obtained by two independent procedures, and these yielded values that were in good agreement. They have been plotted in Fig. 5 against the size of the individual lungs. The crosses indicate values derived from measurements obtained on sections; the horizontal bars, to "average diameters" inferred from the volume-to-surface relationship of the whole lung according to a principle proposed by Hennig (12). The heavy dots represent the mean of the two values; in adults this was found to be of the order of 250 to 290 microns.

The "average alveolar diameter" d_A is a function of the lung volume V_{L} . The relationship is expressed by the equation

$$\overline{d}_{\rm A} \equiv k \ V_{\rm L}^{1/3}$$

(3)

where the coefficient k depends on the total number of alveoli, on their shape, and on the fraction of the lung volume they occupy. These factors were found to be constants for all lungs (except for slight changes in the volume proportions that occur with age). Thus, k is a constant with the approximate value

 1.54×10^{-3} . As Fig. 5 shows, the values of $\overline{d_A}$ obtained for our samples conform well to the theoretical function (3).

It is of interest to consider, on hypothetical grounds, the changes in $\overline{d_{\lambda}}$ at different degrees of lung inflation. If we take the anatomical volume



Fig. 5. "Mean diameter" of the alveolus as a function of constitutional lung volume V_{TLC} and degree of inflation ζ .



Fig. 6. Total alveolar surface as a function of total lung volume and volumetric fraction of alveoli α . "Lung volume" includes gas, tissue, and blood.

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of the lung at a maximal degree of inflation corresponding to the physiological measurement of "total lung capacity" (V_{TLC}) as a standard baseline volume, then every other state of inflation can be expressed as a fraction ζ of V_{TLC} . This has been plotted graphically as a set of isopleths about the abscissa of Fig. 5. Comparison of the inflated volume and weight of, the fresh lungs allowed us to estimate thatthe lungs of our sample were fixed at a degree of inflation $\zeta' \approx 0.75$, so that the curve of $\overline{d_A}$ could be fitted to this set of isopleths (Fig. 5). This combination allows us to make a speculative estimate of the "average alveolar diameter" at any degree of inflation 5 if the constitutional lung volume VTLC is known. The more general form of Eq. 3 is, now,

$$\overline{d_{\mathsf{A}}} = k \, (\zeta \, V_{\mathrm{TLC}})^{1/8} \tag{4}$$

The validity of this equation remains to be established experimentally. As a good approximation it is valid, however, since possible changes in the volume proportions (Fig. 4) occurring with inflation or deflation would affect this relation only by a factor proportional to their cube root.

One of the morphological quantitities of highest functional importance is the extent of the air-tissue interface, since this influences the exchange of gases between the air and the tissue layer of the alveolocapillary membrane (13). The interface is proportional to the total, alveolar surface S_{AT} , which can be estimated from the morphometrical studies by three entirely independent methods (Fig. 3). In the first method the alveoli were considered to be the elements of a geometrical system similar to a honeycomb. The total internal (alveolar) surface S_{AT} of this system is

$$S_{\text{AT}} = N_{\text{AT}} \, \sigma_{\text{A}} \left(\frac{\alpha \, V_{\text{L}}}{N_{\text{AT}}} \right)^{2/3} \tag{5}$$

where N_{AT} is the total number of alveoli (Table 1), α is the alveolar fraction of the lung volume $V_{\rm L}$ (Fig. 4), and $\sigma_{\rm A}$ is the coefficient relating alveolar surface to alveolar volume, as described earlier. All these quantities are known. In the second method no geometrical assumptions had to be made. The value for S_{AT} was calculated by the method of Tomkeieff-Hennig (14) from the "mean linear intercept" of pulmonary parenchyma. Finally, direct measurements of alveolar diam-

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Fig. 7. Interalveolar septum in flat aspect, with alveolar capillary network exposed.



Fig. 8. Model of the capillary network and of cylindrical capillary segments.

eters on histological sections yielded a third value for S_{AT} . As shown in Fig. 6, these three values agreed very well with each other for all samples. The points followed a function expressed by the equation

$$S_{\rm AT} = 3.22 \times 10^3 \, (\alpha V_{\rm L})^{2/3} \tag{6}$$

which is deduced from Eq. 5, since N_{AT} and σ_A were found to be constants. The reduction in the alveolar fraction α observed with age (Fig. 4) led to a relative reduction in the value of S_{AT} ; accordingly, measurements of the alveolar surfaces of the lungs from the two oldest subjects lie on a lower isopleth than measurements for lungs from the younger subjects.

Blood vessels. The alveolar capillaries form a very dense network which is spread in two dimensions within the interalveolar septa (Fig. 7) and is continuous through a large part of the lung. The element of this network is a short cylindrical capillary segment which communicates at either end with two other, identical segments. Geometrical analysis of this network reveals that it can be considered to be built up of hexagonal meshes, as illustrated in Fig. 8, although in the true network we meet with a considerable degree of distortion of this model (Fig. 7). The dimensions of a capillary segment are defined by its axial length $L_{\rm e}$ and its diameter $D_{\rm e}$. In order to define the dimensions of the total capillary network, the average number of capillary segments per unit area of alveolar membrane must be counted, so that the total number of segments on the total area of the alveolar membrane $S_{\rm AM}$ can be estimated. The value for $S_{\rm AM}$ corresponds to about $S_{\rm AT}/2$, since $S_{\rm AT}$ is the estimated area of the surface bounding this double-faced membrane on its two sides.

In Fig. 9 the average length of the capillary segments \overline{L}_e and their average number n_e per square centimeter of alveolar membrane are plotted against S_{AM} . We observe an increase in the length of the segments with an increase in the area of alveolar membrane, whereby

$$\overline{L}_{\rm c} = 2.14 \times 10^{-6} (S_{\rm AM})^{1/2} \tag{7}$$

We find a concurrent decrease in the number of capillary segments on the unit area of the alveolar membrane. As a result, the total number of capillary segments appears again to be fixed for all five lungs, with a group average of 277 billion (standard deviation, ± 8 percent). The average capillary diameter was found to be 8.3 microns. The individual variations in capillary diameter were related not to the size of the lung but, presumably, to the degree of vascular filling.

As stated earlier, the extent of the air-tissue interface determines the degree of gas exchange between the air and the tissue layer of the alveolocapillary membrane. The counterpart of this interface, on the vascular side, is the tissue-blood interface; its extent influences the transition of gases from tissue into the blood and vice versa. The tissue-blood interface is represented by the total alveolar capillary surface $S_{\rm CT}$, which can be calculated from the measurements obtained on the capillary segments. This surface was found to be a function of the extent of the alveolar membrane, and of the degree of capillary filling represented by the average capillary diameter $(2R_{\rm e})$. In Fig. 10 the dots represent the calculated capillary surface for each case; the bars show the position of the corresponding average diameter relative to the isopleths, which indicate how the capillary surface increased with the alveolar surface at a given average capillary diameter. The equation for this family of curves is

$$S_{\rm CT} = N_{\rm CT} [9.48 \times 10^{-6} \,\overline{R_{\rm e}} \times S_{\rm AT}^{1/2} \\ -4.6 \,\overline{R_{\rm e}}]$$
(8)

where $N_{\rm CT}$ (= 2.77 × 10¹¹) is the total number of capillary segments. The numerical coefficients are given by the shape of the segments (Fig. 8). If we accept, pending more precise



Fig. 9 (left). Length $L_{\rm e}$ and number of alveolar capillary segments: $n_{\rm e}$, number of segments per 1 square centimeter of alveolar membrane; $N_{\rm CT}$, total number of segments in the entire lung. Fig. 10 (below). Total capillary surface as a function of total alveolar surface and of degree of capillary filling.



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information, the range of 7 to 9 microns as the normal range of variation of the average capillary diameter, we find that the alveolar capillary surface in adults varies between 60 and 80 square meters. The tissue-blood interface is, therefore, of the same order of magnitude as the air-tissue interface, and both are functions of the size of the lung.

The alveolocapillary membrane. Other morphological quantities that influence the exchange of gases between air and blood are the variations in thickness and composition of the fine tissue layer of the alveolocapillary membrane (13). Conclusive definition of these parameters through morphometrical investigations will eventually make it possible to correlate what the physiologist observes in the exhaled air and in the peripheral arterial blood with the actual events occurring in the lung. It may eventually be possible to demonstrate a quantitative dependence of these functional events on such overall morphological parameters as body size or age of the individual.

As Fig. 1 indicates, the elements of the conductive zone are represented by hollow tubes of basically cylindrical shape. These elements have a distinct polar orientation, and this is one of the important properties of the conductive system of the lung. It serves to distribute the air, or the blood, which enters the lung at a single point among 300 million alveolar units. In order to fulfill this task efficiently the conductive zone is organized according to a rather rigid pattern of branching, which is briefly analyzed in the following paragraphs.

Because of the polar organization of the conductive tubes of the lung, every element is characterized by its dimensions and by its location with respect to its pole-the mouth or the heart, depending on the system. "Location" may have several meanings: it may represent the linear distance from the mouth or the heart, or the order of generations of branching, as discussed in a later section. The dimensions required for definition of the conductive system are the number of elements, their diameter, and their length. These dimensions are significant only if they are related to the location of the element.

Conductive airways. Figure 11 shows a plastic cast (7) of the bronchial tree of an average-sized adult. Part of this tree is shown schematically in Fig. 12. Examination reveals that each bronchus divides into two distal bronchi. This pattern of branching is called dichotomy and is very frequently observed in nature. The dichotomous branching may sometimes be obscured by considerable variation in the length of the elements. Nevertheless, of more than 1000 branchings analyzed in the cast shown in Fig. 11, all of them could be characterized as dichotomous. The irregularity in the dimensions of the elements is related to the shape of the lung. After four generations of airway branching (Fig. 12) the basic shape of the lung appears to be outlined.

In a polar system which is branching dichotomously, the "location" of the element may assume the meaning "the order of the generation of branching z," where the trachea is "generation z = 0." This scheme appears to be particularly useful because the number n(z) of elements in each generation of dichotomous branching is well defined as

$$(z) = 2^z \tag{9}$$

This relationship was applied in determining the order of airway branching at which terminal airways (alveolar ducts and sacs) are found.

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It is known that these airways comprise the four most peripheral airway generations. The total number of about 14 million ducts and sacs (Table 1) must, therefore, correspond to the sum of the values for n(z) for these four generations. It can easily be shown that the summation of 2^{20} , 2^{21} , 2^{22} , and 2^{23} most nearly satisfies this condition. In other words, on the average, the airways terminate in alveolar sacs after about 23 generations of dichotomous branching.

In reality, marked variations in the total number of airway generations



Fig. 11. Cast of the bronchial tree of an adult human lung. [Courtesy A. A. Liebow] 24 AUGUST 1962

Fig. 12. Schematic drawing of the first four generations of airways of the lung of Fig. 11.

are observed in different parts of the lung. This is a result of the irregular pattern of dichotomous branching. Accordingly, the linear dimensions of the elements in each generation do not have a given value but, rather, show a distribution about an average; this is apparent in the measurements obtained on the cast of Fig. 11. We shall, however, at first neglect these irregularities in order to illustrate some of the harmonic features of the system, taking the average value for the linear dimensions of the elements in each generation. This reduction of the true airways to a system of regular branching will prove useful for some over-all

The average diameter of the airway elements is found to be a decreasing function of the order of generation z. When the average diameters of the first ten generations are plotted semilogarithmically against the generation (Fig. 13), they appear to lie approximately on a straight line, which is given by the equation

$$d(z) = d'_{0} \times 2^{-z/3}$$
(10)

where d'_{\circ} is the intercept at the origin (15).

Measurements obtained on histological sections show that the average diam-

Fig. 13. Average diameter of conductive airways, respiratory bronchioles, alveolar ducts, and precapillaries in adult human lung as functions of the order of generation of dichotomous branching (see text).

eter of alveolar ducts and sacs in adults is of the order of 400 to 450 microns. Plotting these dimensions for generations 19 to 23 (Fig. 13), we observe that they do not lie on the straight line. The diameter of an alveolar duct measures about five times the value expected from extrapolation from the graph. The respiratory bronchioles which constitute about three generations just proximal to the alveolar ducts measure about 500 microns in diameter, or more than twice the extrapolated value.

In general terms, analysis of the physical implications of these dimensional relationships indicates that where there is mass movement of air, the principle of minimum resistance and minimum mass seems to hold. Toward the periphery of the lung other physical phenomena-mainly phenomena of molecular diffusion-play a dominant role in the transport of gases. The finding that the actual diameter of the peripheral airways deviate from the values obtained by extrapolation of Eq. 10 toward larger values supports the view that these functional phenomena have a significant role.

Blood vessels. The larger branches of the pulmonary artery follow almost exactly the pattern of the bronchial tree. Their dimensions are nearly the same as those of the accompanying bronchi, and consequently, down to generation 10 they follow approximately the graph of Fig. 13. Preliminary determination of the number of precapillaries leading into the capillary network locates these terminal branches of the pulmonary artery at about the 28th generation. They are found to measure from 15 to 25 microns in diameter-a range which agrees well with the value of 20 microns obtained by extrapolation of values from the graph of Fig. 13 to the 28th generation. This demonstrates once more a wellknown property of the circulation of blood-that its organization appears to agree with the principle of minimum resistance and minimum mass (15).

Summary

An attempt has been made to define quantitatively the architecture of airways and blood vessels of the human lung. For this purpose five normal lungs from individuals aged 8 to 74 years were subjected to a dimensional analysis by several methods of measurement based on statistical principles.

The elements of the "respiratory zone" may be regarded as randomly distributed in the lung. There are essentially the same number of alveoli (300 million), alveolar ducts (14 million), and capillary segments (280 billion) in all lungs. The dimensions of these architectural elements are shown to depend mainly on the size of the lung. The effect on these dimensions of such functional variables as the degree of inflation of the lung or of the filling of capillaries with blood are discussed.

The alveolar and alveolar-capillary surface areas, which are of importance in the analysis of gas exchange between air and blood, are found to increase with the size of the lung. In our material, both varied in the range of 40 to 80 square meters.

The elements of the conductive zone

of the lung show a polar orientation. The airways have, on the average, 23 generations of dichotomous branching; the pulmonary arteries reach the precapillaries after about 28 generations. The average diameters of the airway and blood-vessel elements at each generation appear to follow the laws of "best" dimensions. The functional significance of this finding is discussed.

It is suggested that morphometric studies conducted according to this general model may be useful in the anatomical description of other organs (16).

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Evolution of Intelligence and Vocal Mimicking

Studies of large-brained mammals promise to elucidate some problems of human evolution.

R. J. Andrew

Some 20 years ago McBride and Hebb (1) pointed out that the brain of the bottlenose dolphin (Tursiops truncatus) was comparable to that of man, both in size and in general cortical development, and argued that this species (and presumably other Cetacea) were therefore probably of a very high order of intelligence indeed. This argument has recently been revived and greatly extended by Lilly (2, 3), on the basis of extensive studies on T. truncatus. The advanced nature of the structure of the brain in T. truncatus appears to be fully established. Not only are cells as densely packed in the thalamus (4), for example, as in man, but the cortex shows extensive "silent areas" (2). However, it seems

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unsafe to predict on this anatomical basis alone, as Lilly does (2), that Tursiops will prove to be as intelligent as man, although perhaps with an intelligence specialized along different lines. Direct evidence for very high intelligence (5) in Tursiops seems to be lacking. The most striking difference from other mammals appears to be the degree to which dolphin vocalization can be modified; dolphins can be trained to vocalize for a reward, and there is evidence of some degree of mimicking (2). However, comparison with birds suggests that a difference in the control of vocalization may be involved rather than a difference in intelligence. Anecdotal evidence from animal trainers and from brain-stimulaschen Anatomie (Springer, Leipzig, 1936), vol. 4, pt. 3; G. Hieronymi, Ergeb. Pathol. 41, (1961).

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- 16. We wish to acknowledge our indebtedness to Dr. D. W. Richards and Dr. A. Cournand for their help and stimulating interest in this for their help and stimulating interest in this work. This investigation was supported by a research grant of the New York Heart Asso-ciation, by the National Heart Institute, Bethesda, Md. (grant No. H-2001), and by an Investigatorship (No. I-126) of the Health Research Council of the City of New York.

tion studies suggests intelligence of an order anywhere between that of a dog and that of a chimpanzee. Wide interest has rightly been aroused by current discussions of the brain of Tursiops. In view of this, and of the fact that the acquisition of high intelligence and the ability of vocal mimicking have been crucial in human evolution, it seems appropriate at this time to consider the factors which seem to have affected the evolution of these two characteristics in the mammals in general.

Let us consider the problem of mimicking first. It appears that Tursiops truncatus will answer human laughter, whistles, and Bronx cheers with similar sounds (2, p. 201). This however, is not in itself evidence of true mimicking; it is rather the elicitation of a call by sound which resembles it, since these calls are part of the normal repertoire of the species (3). Such a condition has evolved at least twice, and probably many times, in the Primates. In the Lemuroidea, Lemur fulvus and related species answer any loud, short, deep sound from a social fellow with their contact call, which is loud and deep; Lemur catta gives its contact call (a high wail) in response to high-pitched sounds of similar quality (6). The gelada baboon (Theropithecus gelada) will give the characteristic baboon "segmented grunt" in response to human imitations. Hylo-

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