Anatomic Models of the Tracheobronchial and Pulmonary Regions of the Rat [1]

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ABSTRACT Models of the lung airways of a rat were developed from complete measurements of the tracheobronchial airways. A silicone rubber cast of the tracheobronchial airways of a rat lung was prepared and all individual airway segments down to and including the terminal bronchioles were measured to obtain the segment diameters, lengths, branching angles and angles of inclination to gravity. Models of the rat tracheobronchial airways were constructed based on the original measurements and the subsequent analysis. Some mathematical assumptions about acinar anatomy distal to terminal bronchioles were made to extend the models to include pulmonary regions. Emphasis was placed on the "Typical Path Lung Model" which used one typical pathway to represent either a whole lung or a lobe of the lung. The models are simple and can be applied in calculation of physiologic variables or particle deposition during inhalation in various lobes of the lung.

It has been shown in inhalation studies using laboratory animals that particle deposition within the lung is not uniform and that the right apical lobe usually has the highest initial relative concentration (Raabe et al., '77). None of the existing deposition models or theories predicts this phenomenon. This lobar difference in deposition pattern may be due to differences in anatomical structure.

The geometry of the tracheobronchial airways is one of the factors influencing particle deposition during inhalation. The airway structural parameters which relate to particle deposition are segment lengths, diameters, branching angles (change in direction of bulk air flow from parent segment) and angles of inclination to gravity, i.e., horizontal angular orientation (Yeh et al., '76). Various lung models have been developed for humans (Davies, '61; Findeisen, '35; Horsfield et al., '71; Landahl, '50; Olson et al., '70; Weibel, '63); rats (Granito, '71; Kliment, '73) and guinea pigs (Kliment et al., '72). Unfortunately, these models supply only part of the needed information, mainly lengths and diameters. Dogs, rats and hamsters are often used in inhalation toxicity studies and the lack of appropriate lung models causes difficulties in predicting particle deposition in each species, comparing data among species and hinders extrapolation of animal data to man. This paper describes the development of two typical-path lung models (whole lung and lobar) for the rat.

MATERIALS AND METHODS

Morphometry data

To provide accurate data on the geometry of rat lung airways, a silicone rubber replica cast of the tracheobronchial airways was prepared and carefully measured from the trachea to the terminal bronchioles. The replica cast used in this study was made from a healthy female rat (Long-Evans black and white hooded rat, *Rattus norvegicus,* Blu: (LE)BR, 330 gm, 12 months old, obtained from Blue Spruce Farms, Inc., Altamont, New York, U.S.A.). Silastic E type silicone rubber (Dow Corning, Midland, Michigan) was used as the casting material because it has excellent replicative ability, negligible shrinkage (less than 0.1%), high tensile strength after curing and produces a strong flexible cast that, when suspended, does not deform under its own weight. Immediately after the animal was sacrificed, the intact lung was flushed with

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CO_2 gas followed by filling with degassed physiological saline at about 10 cm H_2O pressure. The saline dissolves the CO_2 gas within the airways allowing for a bubble-free finished cast. Casting material was then slowly injected through the trachea, using a syringe pump at a rate of 0.1-0.2 ml/min. The saline diffused out of the lung and passed out of the thorax through several small slits in the thoracic wall. The amount of molding compound injected was based on the lung volume value from the literature (Tenney and Remmers, '63; Weibel, '72) in conjunction with the visual observation of being well-filled. About 10 ml of casting material was injected in the present case. After injection was completed the cast was allowed to cure in situ before the lung was removed from the thorax and the tissues digested in sodium hydroxide. Finished cast had an overall shape that corresponded closely to the shape of the thorax. Details of the casting procedure have been reported by Phalen et al. ('73). Casts prepared in this manner were evaluated using a quantitative stereoradiographic technique (Yeh et al., '75). Their results suggested that the airway dimensions in the cast obtained correspond to a lung volume at total lung capacity (TLC).

The completed cast was trimmed to leave only that portion of the tracheobronchial tree down to and including terminal bronchioles for detailed measurements. Airway segment lengths (L), diameters (D), branching angles (θ) and angles of inclination to gravity (Ψ) were measured on the trimmed cast using a seven-power hand-held magnifier-comparator. To provide a basis for morphometric measurements and proper linkage of the airway segments, an idealized branch model, defining the individual airway segment length, diameter and angles, and a unique binary identification scheme were developed (Phalen et al., '78). Measurement errors were estimated, by asking the 5 trained morphometrists to measure the same randomly selected pathway (about 20 airway segments), to be less than 10% for L and D and less than 10° for θ and Ψ.

Development of the models

Tracheobronchial region

Morphometric data [2] (measured to the nearest 0.1 mm for L and D or 5° for θ and Ψ) obtained from the cast were keypunched onto computer cards, fed into a computer and tested for proper segment-to-segment linkage. The following considerations were emphasized when developing the models: (1) the models should be as simple as possible for easy handling and application to various problems, such as flow resistance or particle deposition calculations, (2) regional structural differences should be at least partially preserved and (3) the same modeling technique should be capable of being applied to various mammalian species to allow interspecies comparisons and extrapolations of animal data. With these considerations in mind, a "Typical Path Lung Model" (one using a single unique pathway to represent either the total or a portion of the lung) was developed. Special emphasis was placed on the "Lobar Typical Path Lung Model," since this form of the model has the following advantages: (1) it is semi-symmetric (asymmetric among lobes but symmetric within any particular lobe), (2) structural differences among lung lobes are preserved and (3) it is simple enough for easy handling but also capable for application in lobar deposition calculations, in addition to total or compartmental deposition calculations (Task Group on Lung Dynamics, '66).

A computer program was written to trace all pathways from the trachea to each terminal bronchiole. Figure 1 shows the frequency distribution of the number of generations from the trachea (generation 1) down to and including terminal bronchioles for the whole rat lung. Similar distributions were obtained for each lobe of the lung. If these data are replotted as a cumulative distribution form as shown in figure 2, the median number of generations in that lung portion can be obtained. Table 1 lists the median number of generations obtained for each lobe and for the whole rat lung. It has been observed from the trimmed lung casts that the airway branching of the rat is more monopodial than dichotomous. The broad distributions of the terminal bronchioles in a lobe and of the median number of generations among lobes (table 1) give indirect indications of this monopodial branching structure.

By tracing all pathways terminating at the median number of generations in the portion of the lung involved, mean or median values of the geometrical parameters, such as airway segment lengths, diameters, branching angles and gravity angles can be obtained. To complete the model, the number of segments in

[2] A report detailing all of these raw data has been published as Lovelace Foundation Document Number LF-53 (March 1976), *Tracheobronchial Geometry: Human, Dog, Rat, Hamster.*

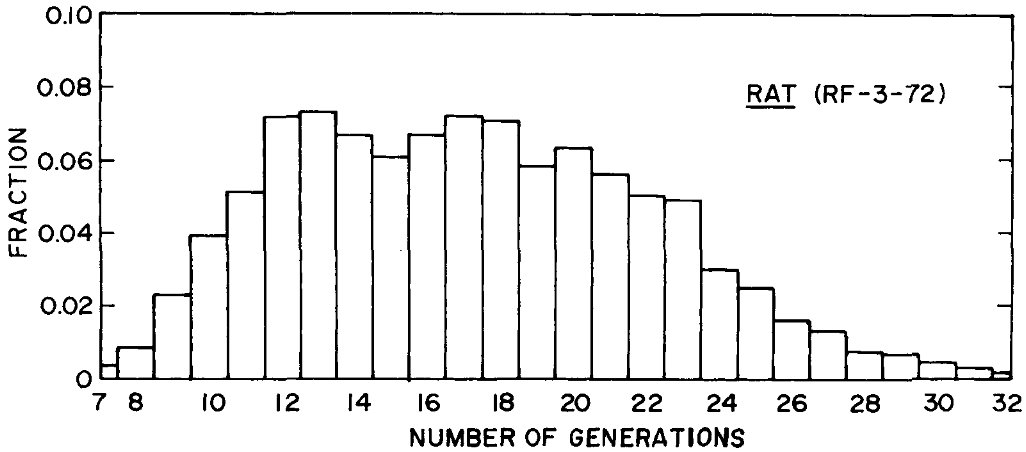

Fig. 1 Frequency distribution of the number of generations for terminal bronchioles (trachea = generation 1).

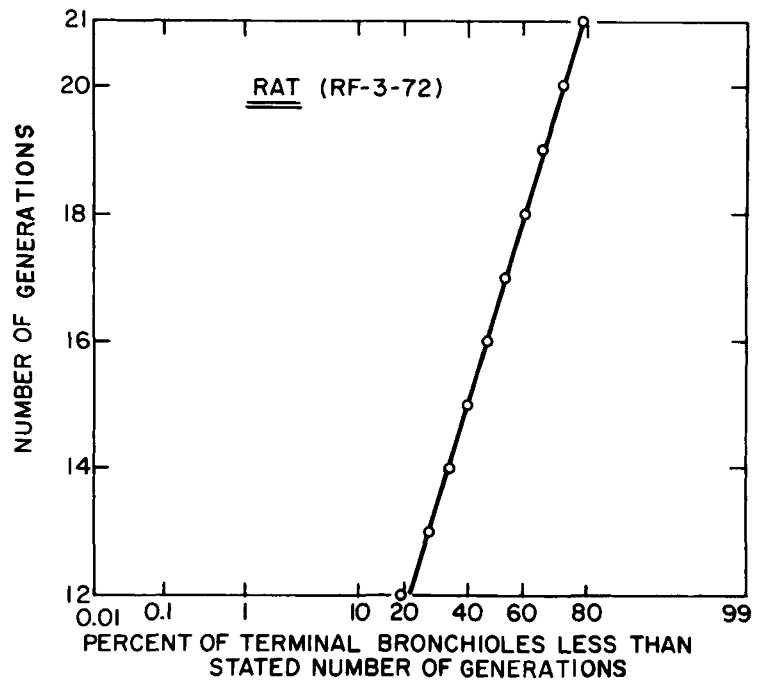

Fig. 2 Cumulative distribution of terminal bronchioles, indicating percent of terminal bronchioles whose generation number is less than the stated number of generations (trachea = generation 1).

each generation in the model has to be given. For regular dichotomous branching, the following equation was given by Weibel ('63) for assigning the number of segments at a given generation,

$$N_n = 2^{n-I} \qquad (1)$$

where n is the generation number and I is the generation number of the main stem. For a whole lung, I = 1 (trachea), while for a given lobe, I is equal to the generation number of the lobar bronchi. Equation (1) cannot be used for the rat because the branching pattern is monopodial. For example, equation (1) will give a value for the number of terminal

TABLE 1

Various parameters used in constructing the rat lung models

Lobe	X value	Terminal bronchioles Median generation number	N	D[1] mm	L[1] mm
R. apical	1.72	13	229	0.19	0.34
R. cardiac	1.68	15	310	0.19	0.31
R. interm.	1.61	17	331	0.21	0.30
R. diaphrag.	1.56	20	790	0.20	0.38
Left lung	1.68	15	827	0.21	0.37
Whole lung	1.68	16	2,487	0.20	0.35

[1] These are the average values of all terminal bronchioles in a given lobe. The extra precision is a statistical estimate for comparative purpose only.

X, branching ratio in the model; N, number of terminal bronchioles; D, diameter; L, length.

bronchioles in the right diaphragmatic lobe that is 32 times greater than that for the right apical lobe in rat ($2^{20\text{-}4} = 32 \times 2^{13\text{-}2}$). If an equal volume is assumed to be associated with each terminal bronchiole (Horsfield and Cummings, '68), this implies that the volume of the right diaphragmatic lobe of rat is 32 times larger than its right apical lobe, which is obviously not true. This problem can be solved by adopting the hypothesis proposed by Yeh ('79). His equation can be written as

$$N_n = X^{n\text{-}I}. \qquad (2)$$

The values of X (branching ratio in the model) in this equation will depend on the branching pattern. For regular dichotomous branching, as in Weibel's model, X = 2. For monopodial branching such as that seen in the rat, it has a value between 1 and 2 and approaches 1 for extreme monopodiality (Yeh, '79). Normally, the number of terminal bronchioles can be obtained or reasonably estimated from morphometric data. Thus, with a given number of terminal bronchioles and the median generation number, the values of X can be calculated. Table 1 lists the values of X for various lobes of the rat, along with the number of terminal bronchioles and their diameters and lengths from morphometric data. One should note that the X value for the whole lung model is not a simple average of X values of all lobes. It is computed from both the number of terminal bronchioles as well as the median generation number by equation (2).

Pulmonary region

Morphometric data for the branching structure beyond the terminal bronchiole are not readily available. For particle deposition calculation, branching structures in the pulmonary region are also needed. To extend the models to include the pulmonary region, the following assumptions were made: (1) about 20 alveoli are associated with each alveolar duct or sac unless otherwise stated, (2) regular dichotomous branching exists beyond the terminal bronchioles, (3) several generations of respiratory bronchioles, if any, and alveolar ducts are followed by a single generation of alveolar sac, thus the total number of alveolar ducts and sacs is approximately equal to twice the number of alveolar sacs since $\sum_{k=1}^{n} 2^k = 2 \times (2^n - 1) \simeq 2 \times 2^n$ for large n, (4) the same number of generations of respiratory bronchioles and alveolar ducts are found in various lobes as well as in the whole lung, (5) the length to diameter ratio of the alveolar sac is similar to that in humans, that is $L_{as} = 1.22\ D_{as}$ where L_{as} and D_{as} are the alveolar sac length and diameter, respectively (Weibel, '63), (6) either the number or the diameter of the alveoli is known and (7) the total volume of the alveoli is approximately equal to 65% of the total lung capacity (TLC) at full inspiration. The first and the last assumptions were made based on Weibel's human data (Weibel, '63) and the rat model of Granito ('71). The second assumption was based on observations that beyond terminal bronchioles, the branching is closer to regular dichotomous than is the case in conducting airways. These observations were made while trimming the cast under a dissecting microscope. The third assumption is the mathematical consequence of assumption 2. Assumptions 4-6 are for conveniences in mathematical modeling. With these assumptions, the dimensions and the generation number of the alveolar sac were determined as follows:

Determination of alveolar number or diameter

The total lung capacity (TLC) was estimated using Weibel's equation of $TLC = 0.032 \times W^{1.05}$, where W is the body weight (Weibel, '72). For a 330 gm rat, this gave TLC = 14.1 ml. From assumption 7, the total alveolar volume becomes $V_{al} = 9.2$ ml. A single alveolar volume can be written as (Taulbee and Yu, '75)

$$v_{al} = 0.478\, D_{al}^3 = V_{al}/N_{al} \qquad (3)$$

where D_{al} is the alveolar diameter and N_{al} is the total number of alveoli. For the present case, N_{al} was taken to be 3×10^7 for a rat (Granito, '71; Tenney and Remmers, '63). Thus, equation (3) gives $D_{al} = 0.0086$ cm. The length of the alveolus then becomes $L_{al} = (5/6)D_{al} = 0.0072$ cm (Weibel, '63). A single alveolar opening area, s_o, and surface area, s_s, can be calculated by the method of Taulbee and Yu ('75).[3]

$$s_o = 0.461\, D_{al}^2 \tag{4}$$

$$s_s = 2.58\, D_{al}^2. \tag{5}$$

The total alveoloar surface area then becomes $S_{al} = s_s N_{al} = 5725\ \text{cm}^2$ at full inspiration.

Determination of the generation number of the alveolar sac, n_{as}

Let N_{as} denote the total number of alveolar sacs. Then from assumptions 1-3,

$$N_{as} = N_{al}/(2 \times 20) = N_t \times 2^{(n_{as} - n_t)} \tag{6}$$

where N_t and n_t are the total number and the median generation number of the terminal bronchiole, respectively. With the values of N_t and n_t as listed in table 1, equation (6) implies that

$$n_{as} = n_t + \ln (N_{al}/40N_t)/\ln 2 = 16 + 8.24 \simeq 24$$

or there are eight generations between terminal bronchioles and alveoli.

Determination of alveolar sac diameter, D_{as}, and length, L_{as}

Let β be the factor converting alveolar opening area, s_o, to the area occupied by an alveolus on the imaginary surface area of an alveolar sac, s_{as}. Assuming this factor, β, is the same for all species. The surface area, s_{as}, can be written as

$$s_{as} = \pi D_{as} L_{as} + \pi D_{as}^2/4 = (1.22 + 0.25)\, \pi D_{as}^2 = 1.47(\pi D_{as}^2). \tag{7}$$

For humans, the following data were obtained by Weibel ('63): $D_{as} = 0.041$ cm, $D_{al} = 0.028$ cm at lung volume = 4,800 ml and each alveolar sac has 17 alveoli. Then with equations (4) and (7) and the definition of β, the following results are obtained

$$\frac{s_{as}}{\beta s_o} = \frac{1.47(\pi D_{as}^2)}{\beta \times 0.461 D_{al}^2} = 17$$

or

$$\beta = 1.26 \tag{8}$$

Now based on assumption 1, the diameter ratio of alveolar sac to alveolus can be obtained from

$$1.47(\pi D_{as}^2) = 20 \times (\beta \times 0.461\, D_{al}^2)$$

or

$$D_{as}/D_{al} = 1.59.$$

With $D_{al} = 0.0086$ cm, this gives $D_{as} = 0.014$ cm and $L_{as} = 1.22 \cdot D_{as} = 0.017$ cm.

Determination of the dimensions between terminal bronchiole and the alveolar sac

The airway dimensions above the terminal bronchiole were obtained as outlined in the previous section and the diameters and the lengths of alveolar sacs were calculated as shown above. In the pulmonary region, random orientation for both branching angles (0-90°, in 2-dimension) and gravity angles (0-90° in 3-dimension) were assumed. Hence, 45° for the branching angle and 60° for the gravity (90° corresponding to a horizontal tube) were obtained. The airway diameters and lengths in this region were obtained as follows. Using the airway dimensions above the terminal bronchiole and the dimensions of the alveolar sacs, a smooth curve was drawn for the diameter (or the length) versus generations. The diameters (or lengths) for the generations between the terminal bronchiole and the alveolar sac was obtained by direct reading from the curve.

RESULTS

In these morphometric measurements, the gravity angle, Ψ, was recorded in a range of from 0° (straight down) to 180° (straight up), based on inhaled air flow direction. The importance of this parameter is a primary concern in determining aerosol deposition due to sedimentation during inhalation. For a system of randomly oriented tubes with gravity angles recorded in the 0-180° range, the average gravity angle would be about 90°, i.e., equivalent to a horizontal tube. Clearly, using $\Psi = 90°$ would overestimate deposition due to sedimentation for the system. Although gravitational deposition of particles between uphill flow ($\Psi > 90°$) and downhill flow ($\Psi < 90°$) through an inclined circular tube differ, the difference is small under realistic inhalation conditions (Heyder and Gebhart, '77). Furthermore, an uphill flow for inhalation will become downhill flow for exhalation and for randomly oriented tubes, one would expect that, either during inhalation or exhalation, about one-half of the tubes will be associated with uphill flow and vice versa. These factors will further reduce the difference in sedimentation deposition between uphill and downhill flow. Therefore, from the above considerations, the range of gravity angle was converted from 0-180° to a range of 0-90°, i.e., neglecting uphill or downhill, before finding

[3] After a misprint in their paper has been corrected.

their mean value at a given generation in the model.

As previously mentioned, development of the pulmonary region in the present models is based on various assumptions. Therefore, airway dimensions for those airways beyond terminal bronchioles are somewhat arbitrary, but it is believed that the assumptions and mathematical treatments made to obtain those dimensions are reasonable. Results of the two models developed are listed in table 2 for the whole lung model and in APPENDIX A (tables A1-A5) for the "Lobar Typical Path Lung Model" with each table representing a different lobe.

The dimensions listed in these tables correspond to a lung volume at total lung capacity (TLC) for a 330 gm rat, because, as previously mentioned, it is believed that the dimensions on the cast were corresponded to TLC. Table 3 shows the comparison of the lobar lung volume and the anatomical dead space between the models and direct data. The second column indicates the dead space volume, starting from lobar bronchi down to and including terminal bronchioles, for each lobe in the model, while the third column indicates the values calculated directly from the raw morphometric data of all airway segments measured from the lung cast. The good agreement between these two columns indicates the adequacy of the modeling technique. The value on the fourth column was obtained by weighing the trimmed cast, on which the morphometric measurements were made, and then divided by the density of the casting material. Comparison of columns 3 and 4 gives some indirect indications of the magnitude of the possible combined measurement errors in lengths and diameters.

DISCUSSION

In this report, the models of the lung airways of the rat were developed from complete measurements of the tracheobronchial airways of a rat lung cast. Although our data are based only on one cast, there is essentially no other data comparable to it in the literature as we know of. The main goal of this study is to develop a model suitable for application in calculation of particle deposition during inhalation or other physiological variables from the best available data. Ideally, it is desirable to use data obtained from a large number of animals for developing such a model. In reality, it is sometimes impossible to accomplish that due to limited time and resources available. The trimming of the cast and subsequent morphometric measurements are tedious and time consuming. It took about one man-year of a trained morphometrist to complete trimming and measurements of a rat lung cast. We had tried to make our cast from lungs as healthy as possible. It is very difficult, if not impossible, for us to answer the question whether or not the rat we used in this study represents normality. But indirect evidence shows that the animal we used, at least, should not be too far away from normality. If one assumes that the lobar weight of a lung is proportional to the number of terminal bronchioles in that lobe, then our data indicate that the relative lobar sizes in the rat we used, in percentage of the total lung weight, are 9.2, 12.5, 13.3, 31.8 and 33.3 for right apical, right cardiac, right intermediate, right diaphragmatic and left lung lobe, respectively. These values compare favorably to the data reported by Raabe et al. ('77), that is 10.4 ± 3.2, 13.9 ± 3.2, 12.1 ± 2.7, 28.8 ± 5.7 and 34.8 ± 6.6, respectively (average of 58 rats).

It is a common belief that except for the major airways, the cross-sectional area per airway generation increases as airway generation increases. In other words, the air flow velocity becomes slower as air penetrates into deeper airways. Contrary to this belief, these rat lung models indicate that the cross-sectional area of the terminal bronchioles is smaller than previous generations. These models for the region between trachea and terminal bronchioles are based on extensive morphometric data rather than interpolation as with other models. From studies of other species (human, dog and hamster) in this laboratory, which are not reported here, the cross-sectional area per airway generation was not always increased as airways get deeper, but rather this has depended upon species. It is true for humans but not for rats. This may be due to the differences in airway branching schemes. Humans are more dichotomous while rats are more monopodial.

Raabe et al. ('77) reported that in their inhalation study using rats and Syrian hamsters, particle deposition within the rat lung was nonuniform with the right apical lobe having the highest initial deposition. This inter-lobar difference was primarily due to the differences in anatomical structures between the lobes. The value of X in table 1 indicates that the right apical lobe has the lowest mono-

TABLE 2

Typical path lung model: rat-whole lung

n	Number of tubes	L (cm)	D (cm)	θ (°)	Ψ (°)	S (cm^2)	V (cm^3)	ΣV (cm^3)
1	1	2.680	0.340	0	86	0.091	0.243	0.243
2	2	0.715	0.290	15	90	0.132	0.095	0.338
3	3	0.400	0.263	43	86	0.163	0.065	0.403
4	5	0.176	0.203	36	71	0.162	0.029	0.431
5	8	0.208	0.163	32	59	0.170	0.035	0.466
6	14	0.117	0.134	22	58	0.197	0.023	0.489
7	23	0.114	0.123	16	61	0.273	0.031	0.520
8	38	0.130	0.112	17	58	0.374	0.049	0.569
9	65	0.099	0.095	20	55	0.461	0.046	0.615
10	109	0.091	0.087	15	58	0.648	0.059	0.674
11	184	0.096	0.078	16	61	0.879	0.084	0.758
12	309	0.073	0.070	17	56	1.189	0.087	0.845
13	521	0.075	0.058	17	58	1.377	0.103	0,948
14	877	0.060	0.049	22	58	1.654	0.099	1.047
15	1,477	0.055	0.036	24	57	1.503	0.083	1.130
16 [1]	2,487	0.035	0.020	44	58	0.781	0.027	1.157
17 [2]	4,974	0.029	0.017	45	60	1.129	0.033	1.190
18	9,948	0.025	0.016	45	60	2.000	0.050	1.240
19	19,896	0.022	0.015	45	60	3.516	0.077	1.317
20	39,792	0.020	0.014	45	60	6.126	0.123	1.440
21	79,584	0.019	0.014	45	60	12.251	0.233	1.672
22	159,168	0.018	0.014	45	60	24.502	0.441	2.113
23	318,336	0.017	0.014	45	60	49.004	0.883	2.946
24	636,672	0.017	0.014	45	60	98.008	1.666	4.612
25 [3]	3×10^7	0.0072	0.0086	45	60	—	9.121	13.733

[1] Terminal bronchioles.
[2] The values for generations distal to the terminal bronchioles were derived from assumptions and formulae and do not represent direct estimates.
[3] Alveoli. n, generation number; L, airway segment length; D, segment diameter; θ, branching angle; Ψ, gravity angle with 90° corresponding to a horizontal tube; S, cross-sectional area; V, volume; ΣV, cumulative volume.

TABLE 3

Comparison of lobar lung volume and anatomical dead space, in cm^3, for the Long Evans rat at total lung capacity

Lobe	Anatomical dead space				Lung volume	
	Lobar model	Morphometric data [1]	Lung cast [2]	Whole lung model	Lobar model	Whole lung model
Right apical	0.058	0.056	—	—	1.211	—
Right cardiac	0.086	0.078	—	—	1.653	—
Right interm.	0.095	0.093	—	—	1.762	—
Right diaphrag.	0.263	0.219	—	—	4.293	—
Left lung	0.308	0.304	—	—	4.491	—
Others (common stems)	0.333	0.333	—	—	0.333	—
Whole lung	1.143	1.083	1.02	1.157	13.743	13.733

[1] Direct calculation from all airway segments measured from the lung cast.
[2] From direct weighing of the trimmed cast divided by the density of the silicone rubber.

podiality among the lung lobes. In addition to being less monopodial, the right apical lobe has the shortest path length between the trachea and terminal bronchioles (APPENDIX A, tables) and the smallest number of generations (table 1) between the trachea and the terminal bronchioles. These structural differences may partially explain the experimental finding by Raabe et al. ('77).

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APPENDIX A

TABLE A1

Typical path lung model: rat—right apical lobe

n	Number of tubes	L (cm)	D (cm)	θ (°)	Ψ (°)	S (cm²)	V (cm³)	ΣV (cm³)
1	1	2.680	0.340	0	86	0.091	0.243	0.243
2	1	0.430	0.300	10	90	0.071	0.030	0.274
3	1	0.380	0.200	90	85	0.031	0.012	0.286
4	2	0.120	0.160	48	78	0.040	0.005	0.291
5	3	0.210	0.108	44	56	0.027	0.006	0.296
6	5	0.110	0.092	27	50	0.033	0.004	0.300
7	9	0.062	0.080	10	58	0.045	0.003	0.303
8	15	0.106	0.074	22	58	0.065	0.007	0.310
9	26	0.041	0.060	15	56	0.074	0.003	0.313
10	45	0.063	0.051	23	65	0.092	0.006	0.318
11	77	0.074	0.040	19	68	0.097	0.007	0.326
12	133	0.046	0.030	29	70	0.094	0.004	0.330
13 [1]	229	0.034	0.019	45	68	0.065	0.002	0.332
14 [2]	458	0.027	0.016	45	60	0.092	0.002	0.334
15	916	0.023	0.015	45	60	0.162	0.004	0.338
16	1,832	0.021	0.014	45	60	0.282	0.006	0.344
17	3,664	0.019	0.014	45	60	0.564	0.011	0.355
18	7,328	0.018	0.014	45	60	1.128	0.020	0.375
19	14,656	0.018	0.014	45	60	2.256	0.041	0.416
20	29,312	0.017	0.014	45	60	4.512	0.077	0.493
21	58,624	0.017	0.014	45	60	9.025	0.153	0.646
22 [3]	2.76×10^6	0.0072	0.0086	45	60	—	0.839	1.485

[1] Terminal bronchioles.

[2] The values for generations distal to the terminal bronchioles were derived from assumptions and formulae and do not represent direct estimates.

[3] Alveoli. n, generation number; L, airway segment length; D, segment diameter; θ, branching angle; Ψ, gravity angle with 90° corresponding to a horizontal tube; S, cross-sectional area; V, volume; ΣV, cumulative volume.

TABLE A2

Typical path lung model: rat—right cardiac lobe

n	Number of tubes	L (cm)	D (cm)	θ (°)	Ψ (°)	S (cm^2)	V (cm^3)	ΣV (cm^3)
1	1	2.680	0.340	0	86	0.091	0.243	0.243
2	1	0.430	0.300	10	90	0.071	0.030	0.274
3	1	0.540	0.350	5	85	0.096	0.052	0.325
4	1	0.480	0.210	65	50	0.035	0.017	0.342
5	2	0.240	0.155	43	63	0.038	0.009	0.351
6	3	0.100	0.123	20	52	0.036	0.004	0.355
7	5	0.105	0.110	19	70	0.048	0.005	0.360
8	8	0.160	0.108	3	53	0.073	0.012	0.372
9	14	0.089	0.084	26	42	0.078	0.007	0.379
10	23	0.066	0.077	12	54	0.107	0.007	0.386
11	39	0.091	0.058	28	58	0.103	0.009	0.395
12	65	0.062	0.044	16	47	0.099	0.006	0.401
13	109	0.044	0.031	20	58	0.082	0.004	0.405
14	184	0.040	0.026	21	64	0.098	0.004	0.409
15 [1]	310	0.031	0.019	44	60	0.088	0.003	0.411
16 [2]	620	0.027	0.017	45	60	0.141	0.004	0.415
17	1,240	0.024	0.016	45	60	0.249	0.006	0.421
18	2,480	0.021	0.015	45	60	0.438	0.009	0.430
19	4,960	0.020	0.014	45	60	0.764	0.015	0.446
20	9,920	0.019	0.014	45	60	1.527	0.029	0.475
21	19,840	0.018	0.014	45	60	3.054	0.055	0.529
22	39,680	0.017	0.014	45	60	6.108	0.104	0.633
23	79,360	0.017	0.014	45	60	12.217	0.208	0.841
24 [3]	3.74×10^6	0.0072	0.0086	45	60	—	1.137	1.978

[1] Terminal bronchioles.
[2] The values for generations distal to the terminal bronchioles were derived from assumptions and formulae and do not represent direct estimates.
[3] Alveoli. n, generation number; L, airway segment length; D, segment diameter; θ, branching angle; Ψ, gravity angle with 90° corresponding to a horizontal tube; S, cross-sectional area; V, volume; ΣV, cumulative volume.

TABLE A3

Typical path lung model: Rat—right intermediate lobe

n	Number of tubes	L (cm)	D (cm)	θ (°)	Ψ (°)	S (cm^2)	V (cm^3)	ΣV (cm^3)
1	1	2.680	0.340	0	86	0.091	0.243	0.243
2	1	0.430	0.300	10	90	0.071	0.030	0.274
3	1	0.540	0.350	5	85	0.096	0.052	0.326
4	1	0.100	0.310	10	85	0.076	0.008	0.333
5	1	0.720	0.230	55	65	0.042	0.030	0.363
6	2	0.110	0.155	43	65	0.038	0.004	0.367
7	3	0.117	0.143	23	67	0.048	0.006	0.373
8	4	0.088	0.108	14	63	0.037	0.003	0.376
9	7	0.128	0.098	13	59	0.053	0.007	0.383
10	11	0.108	0.096	5	66	0.080	0.009	0.392
11	18	0.036	0.081	15	58	0.093	0.003	0.395
12	30	0.069	0.057	17	61	0.077	0.005	0.400
13	48	0.066	0.051	14	52	0.098	0.007	0.407
14	78	0.071	0.043	18	53	0.113	0.008	0.415
15	126	0.050	0.035	27	48	0.121	0.006	0.421
16	204	0.034	0.027	26	51	0.117	0.004	0.425
17 [1]	331	0.030	0.021	43	59	0.115	0.003	0.428
18 [2]	662	0.025	0.018	45	60	0.168	0.004	0.432
19	1,324	0.022	0.016	45	60	0.266	0.006	0.438
20	2,648	0.020	0.015	45	60	0.468	0.009	0.447
21	5,296	0.019	0.015	45	60	0.936	0.018	0.465
22	10,592	0.018	0.014	45	60	1.631	0.029	0.494
23	21,184	0.017	0.014	45	60	3.261	0.055	0.550
24	42,368	0.017	0.014	45	60	6.522	0.111	0.660
25	84,736	0.017	0.014	45	60	13.044	0.222	0.882
26 [3]	3.99×10^6	0.0072	0.0086	45	60	—	1.213	2.095

[1] Terminal bronchioles.
[2] The values for generations distal to the terminal bronchioles were derived from assumptions and formulae and do not represent direct estimates.
[3] Alveoli. n, generation number; L, airway segment length; D, segment diameter; θ, branching angle; Ψ, gravity angle with 90° corresponding to a horizontal tube; S, cross-sectional area; V, volume; ΣV, cumulative volume.

TABLE A4

Typical path lung model: rat—right diaphragmatic lobe

n	Number of tubes	L (cm)	D (cm)	θ (°)	Ψ (°)	S (cm^2)	V (cm^3)	ΣV (cm^3)
1	1	2.680	0.340	0	86	0.091	0.243	0.243
2	1	0.430	0.300	10	90	0.071	0.030	0.274
3	1	0.540	0.350	5	85	0.096	0.052	0.326
4	1	0.100	0.310	10	85	0.076	0.008	0.333
5	1	0.370	0.310	5	85	0.076	0.028	0.361
6	2	0.135	0.195	50	50	0.060	0.008	0.369
7	3	0.147	0.175	35	57	0.072	0.011	0.380
8	4	0.160	0.167	30	63	0.088	0.014	0.394
9	6	0.120	0.138	41	66	0.090	0.011	0.405
10	9	0.115	0.130	16	55	0.120	0.014	0.418
11	14	0.122	0.109	18	57	0.131	0.016	0.434
12	23	0.074	0.097	21	55	0.170	0.013	0.447
13	35	0.132	0.083	22	62	0.189	0.025	0.472
14	55	0.077	0.073	19	61	0.230	0.018	0.490
15	85	0.088	0.067	22	68	0.300	0.026	0.516
16	133	0.084	0.052	24	61	0.283	0.024	0.540
17	208	0.051	0.042	17	65	0.288	0.015	0.554
18	325	0.054	0.036	21	59	0.331	0.018	0.572
19	506	0.049	0.027	30	62	0.290	0.014	0.586
20 [1]	790	0.038	0.020	46	58	0.248	0.009	0.596
21 [2]	1,580	0.031	0.017	45	60	0.359	0.011	0.607
22	3,160	0.027	0.016	45	60	0.635	0.017	0.624
23	6,320	0.024	0.015	45	60	1.117	0.027	0.651
24	12,640	0.022	0.014	45	60	1.946	0.043	0.694
25	25,280	0.020	0.014	45	60	3.892	0.078	0.772
26	50,560	0.019	0.014	45	60	7.783	0.148	0.920
27	101,120	0.018	0.014	45	60	15.566	0.280	1.200
28	202,240	0.017	0.014	45	60	31.132	0.529	1.729
29 [3]	9.53×10^6	0.0072	0.0086	45	60	—	2.898	4.626

[1] Terminal bronchioles.
[2] The values for generations distal to the terminal bronchioles were derived from assumptions and formulae and do not represent direct estimates.
[3] Alveoli. n, generation number; L, airway segment length; D, segment diameter; θ, branching angle; Ψ, gravity angle with 90° corresponding to a horizontal tube; S, cross-sectional area; V, volume; ΣV, cumulative volume.

TABLE A5

Typical path lung model: rat—left lung lobe

n	Number of tubes	L (cm)	D (cm)	θ (°)	Ψ (°)	S (cm^2)	V (cm^3)	ΣV (cm^3)
1	1	2.680	0.340	0	86	0.091	0.243	0.243
2	1	1.000	0.280	20	90	0.062	0.062	0.305
3	2	0.340	0.250	38	88	0.098	0.033	0.338
4	3	0.137	0.193	27	68	0.088	0.012	0.350
5	5	0.150	0.167	15	63	0.110	0.016	0.367
6	8	0.130	0.115	15	60	0.083	0.011	0.378
7	13	0.124	0.089	18	59	0.081	0.010	0.388
8	22	0.124	0.098	18	59	0.166	0.021	0.408
9	37	0.104	0.082	17	55	0.195	0.020	0.429
10	62	0.084	0.071	24	54	0.246	0.021	0.449
11	105	0.079	0.051	15	56	0.215	0.017	0.466
12	175	0.067	0.053	17	55	0.386	0.026	0.492
13	294	0.065	0.040	26	50	0.370	0.024	0.516
14	493	0.059	0.033	20	47	0.422	0.025	0.541
15 [1]	827	0.037	0.021	43	55	0.286	0.011	0.551
16 [2]	1,654	0.028	0.018	45	60	0.421	0.012	0.563
17	3,308	0.024	0.016	45	60	0.665	0.016	0.579
18	6,616	0.022	0.015	45	60	1.169	0.026	0.604
19	13,232	0.020	0.014	45	60	2.037	0.041	0.645
20	26,464	0.019	0.014	45	60	4.074	0.077	0.723
21	52,928	0.018	0.014	45	60	8.148	0.147	0.869
22	105,856	0.017	0.014	45	60	16.295	0.277	1.146
23	211,712	0.017	0.014	45	60	32.591	0.554	1.700
24 [3]	9.98×10^6	0.0072	0.0086	45	60	—	3.034	4.734

[1] Terminal bronchioles.
[2] The values for generations distal to the terminal bronchioles were derived from assumptions and formulae and do not represent direct estimates.
[3] Alveoli. n, generation number; L, airway segment length; D, segment diameter; θ, branching angle; Ψ, gravity angle with 90° corresponding to a horizontal tube; S, cross-sectional area; V, volume; ΣV, cumulative volume.