COMPUTER SIMULATION OF THE GEOMETRY OF THE HUMAN BRONCHIAL TREE

KEITH HORSFIELD and ALISON THURLBECK
The Midhurst Medical Research Institute,
Midhurst, West Sussex GU29 0BL, U.K.

Some morphological features of the human bronchial tree were simulated by computer-generated trees. The trees were ordered by the methods of Horsfield and Strahler. Delta, the difference between the Horsfield orders of the two branches at a bifurcation, was determined by pseudorandom numbers generated according to a distribution of probabilities defined on input. By trial and error a distribution was found which resulted in trees being generated with average Strahler order branching ratios of 2.82, similar to a real bronchial tree. Branching angles and length ratio could also be defined on input. By varying these input parameters it was found that the form of the tree was quite sensitive to them, and that by a suitable choice the intrasegmental part of the bronchial tree could be simulated. It is concluded that branching ratio, length ratio, mean branching angles and distribution of delta are controlled within tight limits in the bronchial tree, and this may support the concept of optimal design.

1. Introduction. The similarities of the patterns of branching in rivers, trees, arteries and bronchi is well known and has attracted considerable attention. Observation of these similarities has stimulated the application of methods used in the study of rivers to the study of biological structures (Horsfield and Cumming, 1968, 1976; Holland, 1969; Oohata and Shidei, 1971; Leopold, 1971; Barker et al. 1973; Horsfield, 1978). These methods include calculation of the branching ratio (Strahler, 1953, 1957), diameter ratio and length ratio (Horsfield and Cumming, 1976). Computer simulation of the geometry of botanical trees, based mainly on branching angles, length ratio and differential rates of growth, have produced models which closely parallel the geometry of the living structures (Honda, 1971; Borchert and Slade, 1981; Honda et al., 1981, 1982). These authors calculated the branching ratio in their model trees, but found it variable and of not much more than descriptive value. Some of the factors which might influence diameter, length and branching ratios in the lung have been discussed previously (Horsfield, 1980). The purpose of the present study was to develop a computer programme which would create dichotomously branching trees, to use this to investigate the effect of some morphological parameters on the form of trees and to see whether the human bronchial tree could be modelled. The results might improve our understanding of the factors which determine the form of the bronchial tree in man.
2. Ordering of Trees. Two commonly used methods of ordering the branches of biological tree-like structures are those described by Strahler (1953, 1957) and by Horsfield and Cumming (1968). Briefly, Horsfield orders start at the peripheral branches, which are order 1, and increase by 1 at each junction (Figure 1A). Where branches of dissimilar order meet, the parent branch is one order more than the higher ordered daughter branch. In the Strahler system, where dissimilar orders meet, the parent branch continues with the same order as the higher ordered daughter branch (Figure 1B), order only increasing when two equal branches meet. In the second stage of the Strahler system contiguous branches of the same order constitute just one branch (Figure 1C). Especially with the Strahler system, it is found that in most trees the number of branches in each order increases geometrically with decreasing order, by a factor called the branching ratio ($R_b$). Similarly, mean diameter and mean length increase geometrically with increasing order, by factors called the diameter ratio ($R_d$) and length ratio ($R_l$) respectively. The values of these ratios are determined from the slopes of the regression lines of number, mean diameter and mean length, on order. The symbol ($S$) refers to Strahler orders and ($H$) to Horsfield orders. Thus $R_b(H)$ means branching ratio using Horsfield orders and $R_l(S)$ means length ratio using Strahler orders.

![Figure 1](image-url)

Figure 1. An example of a tree with Horsfield-ordered branches (A) and with Strahler-ordered branches (B) and (C).

Symmetry of branching can be defined in terms of orders, a symmetrical bifurcation being one in which both daughter branches have the same order (Figure 2A). In contrast, the two daughter branches of an asymmetrical bifurcation have different orders (Figure 2B); the greater the difference the more asymmetrical the bifurcation (Figure 2C). The difference between the orders of the daughter branches is called delta ($\delta$), which is thus a measure of the degree of asymmetry (Horsfield et al. 1971).

3. Generation of Trees by Computer. Each branch is recorded in the