Mauroy *et al.* Reply: In the Comment by Butler and Tsuda [1], it is stated that the conclusions obtained from the simulations presented in [2] are not relevant for the flow distribution in the real lung under normal breathing because the boundary conditions (BC) adopted at the outlets of the terminal airways do not represent physiological reality. The last part of this sentence is correct: our BC obviously cannot reproduce the enormous complexity of the lung physiology. In the "normal breathing conditions," the BC are imposed by around 30 000 individual acini, which pump air from the mouth through 16 generations of dichotomic bifurcations. We claim, however, that our results are relevant for the understanding of flow distribution under normal breathing conditions for the following reasons.

First, if one neglects the inertial effects, the physical properties deduced from computations under constant pressure BC are, through a classical transformation resulting from Darcy's law, strictly identical to those computed under imposed flow, or imposed compliance. In this linear approximation of hydrodynamics, the choice of the BC can be made for the simplicity of the numerical implementation. If inertial effects are now taken into account for physiological Reynolds numbers, then the above equivalence remains valid for moderate Reynolds numbers, as shown now.

To justify our approach, we compare the results in [2] with hydrodynamic computations under imposed flow at the outlets. Note that those last BC are closer to physiological reality than imposed pressure or compliance. They require, however, a more complex numerical implementation. Of course, in that case, the asymmetry is not found on the flows that are imposed as equal, but on the pressures at the different outlets. The geometry used for computation and the results are shown in Fig. 1. The close similarity with those obtained in [2] confirms our conclusions. Only for very large angles (i.e., far from the real lung morphology), can significant differences be observed. The very deep reason of the similarity of the results is that the existence of the so-called *M-shape* flow distribution is related to velocity and geometry, *whatever* the BC.

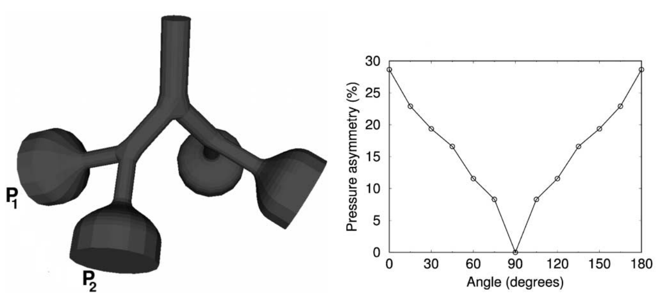

FIG. 1. Pressure asymmetry computed under imposed flow. On the left, the tree geometry used in the simulations. The flow is imposed by the motion of the pistons at each outlet with Reynolds number = 1200 in the upper bronchia. The curve on the right shows the asymmetry of the pressure distribution at the outlets, $|(P_1 - P_2)/(P_1 + P_2)|$, as a function of the rotation angle [2].

In the *in vitro* experiments cited in the Comment, it was found (within explicit experimental uncertainties) that the flow distribution is mainly governed by the distribution of terminal compliances, regardless of the upstream fluid flow conditions and the geometry of the bifurcation. However, their experimental setup corresponds to a *single* bifurcation with only two daughter branches, under forced ventilation. This situation is also very far from normal physiological respiration. Now, the asymmetry effect described in [2] is due to the uneven capture of the flow *M-shape* at the *second* generation of bifurcation, a physical setup that is clearly missing in the experiment quoted in Butler and Tsuda's Comment.

More generally, the essential result in [2] is the fact that flow nonhomogeneity exists even for quasisymmetric systems. The importance for respiration is the fact that *the airway being a tree system, any weak nonhomogeneity will finally build a strongly uneven air distribution* (in fact, multifractal [3], as the necessary consequence of the multiplicative process inherently linked to a tree structure). As the geometrical arrangement of the bronchial tree of mammals is always subjected to some physiological variability, it appears natural to question whether a small modification of the structure disturbs the flow distribution. This type of extreme sensitivity of the system to geometry has also been demonstrated in another context [4]. Such a finding is the type of light that physics can shed on an extremely complex problem as it demonstrates that physiological regulation is needed. This regulation may be achieved through adequate pumping but also by adaptation of airway diameters, a fact known to exist.

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Received 12 March 2004; published 22 July 2004
DOI: 10.1103/PhysRevLett.93.049802
PACS numbers: 87.19.Uv

[1] J. P. Butler and A. Tsuda, preceding Comment, Phys. Rev. Lett. **93**, 049801 (2004).
[2] B. Mauroy, M. Filoche, J. S. Andrade, Jr., and B. Sapoval, Phys. Rev. Lett. **90**, 148101 (2003).
[3] B. Sapoval, *Universalités et fractales* (Flammarion, Paris, 1997).
[4] B. Mauroy, M. Filoche, E. R. Weibel, and B. Sapoval, Nature (London) **427**, 633 (2004).

