Switching and transport mechanism in the branching tube network due to attached eddies

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Abstract. An experimental study was performed on the quasi-two-dimensional symmetric branching tube under oscillatory flow. The velocity field and transport of materials in the Reynolds number \( Re = 1500 \sim 3000 \) and the Womersley number \( \alpha = 17 \sim 23 \) were visualized by means of a dye or small spheres as well as measured by using Particle Image Velocimetry. The repeated growth and disappearance of the attached eddies near the junction of the branched channel are recognized, which play a role of the throttle valves to control the transport of newly taken gasses or suspended particles into, and older ones out of, the human lung in spite of zero net volume flux.

1. Introduction
The major function of the respiratory system of human is the gas exchange between the external environment and an organism’s circulatory system. This exchange facilitates oxygenation of the blood as well as removal of carbon dioxide and other gaseous metabolic wastes from the circulation \[1\]-[6]. A no less important application of the respiratory system is to use it as an inhaler, in which nano-particles or liquid droplets that contain medicine are taken into through the lung’s air sac, and are transported to the diseased part by means of the blood flow (e.g., [7]). These exchanges occur at the alveoli, which are the tiny sacs to provide very large exchange surface, whereas larger volume of flow is better achieved through larger tubes because it is operated by the pressure difference, which necessitates the branching tube network that becomes narrower, shorter, and more numerous as it penetrates deeper into the lung. According to the anatomical data, the human airway tree consists of the conducting part that starts from the trachea (zeroth generation) to the terminal bronchioles of 14th generation via repeated bifurcation of channels, and the acinar part which consists of the respiratory bronchioles, alveolar ducts and alveolar sacs until the 23rd generation. The length and width \( L_i \) and \( d_i \) of the \( i \)-th generation of the conducting airways follow the geometric ratios: \( L_i/d_i \approx 3.5, d_{i+1}/d_i \approx 0.8 \), whereas the angle of bifurcation of the branched channel \( \phi_i \) is almost constant (\( \approx 70^\circ \)) [1]. In normal situation, one breathing is not sufficient to deliver the fresh air to the terminal parts of the lung, which necessitates the transport mechanism that is operated by the repeated application of pressure in spite of the zero net flux of air. Taking into account the fact that oscillatory flow in a straight channel cannot transport fluid or materials after one cycle of oscillation (in the absence of diffusion), and that the tapered or curved tubes do not drastically improve the latter [3], the role of branching conducting airways seems crucial. In general, oscillatory channel flows
depend on the Reynolds number \( Re \equiv ud/\nu \) and the Womersley number \( \alpha \equiv (d/2)\sqrt{2\pi f/\nu} \), where \( d \) is the width of the channel (of the zeroth generation), \( u \) is the typical velocity there averaged over half period of oscillation, \( f \) is the frequency of oscillation, and \( \nu \) is the kinematic viscosity of the fluid. For the normal respiration \( Re \approx 1000 \) and \( \alpha \approx 3 \). In a medical treatment, the “high-frequency respiration” with \( Re \approx 2000 \) and \( \alpha \approx 20 \) is conventionally adopted to avoid damaging the diseased part of the lung. However, it is not clear whether or not these conditions are optimum. In order to clarify the latter, we should know the mechanism of the transport of fluid and materials under given conditions. In this paper we shall provide both flow visualization and velocity field measurement in wider range of \( Re \) and \( \alpha \), and elucidate the switching and transport mechanism in the branching tubes, which will give deeper insight into more general application of the oscillatory viscous flow to the material transport or ventilation.

2. Experiment

2.1. Experimental apparatus

Figure 1(a) is the block diagram of our experimental apparatus. A branched channel with a branching angle 70° was created up to the second generation between two parallel plates with separation distance 5 mm. The geometric ratios of the lengths and widths between the neighboring ones were adjusted to those in the anatomical data, but the cross section of our channel was chosen rectangular with its aspect ratio about 1/6. This nearly two-dimensional (2-D) setup was used in order to measure the velocity field accurately, with the anticipation that the main contribution comes from the bifurcating plane of the branching tubes of circular cross section (3-D), and that the essential control mechanism will be common to both 2-D and 3-D branching tubes. We used water as a working fluid throughout our experiment. A piston, placed in the zeroth generation channel (first branch), was connected to the motor through a cam, which pushed the fluid sinusoidally, i.e., \( s_p = A\sin(2\pi ft) \), where \( A \) is the amplitude of oscillation, and \( s_p \) is the position of the piston along the channel. The whole system was placed horizontally and was submerged to the water with the outlets of the second generation channels open. Thus the present experimental apparatus is mainly intended to elucidate the structural change of the flow field and the mass transport relation at the first junction, which is expected to be applicable to conducting airways up to another few generations. Typical cases reported in this paper are (I) \( Re = 1500 \) and \( \alpha = 17 \), (II) \( Re = 2100 \) and \( \alpha = 20 \), and (III) \( Re = 3000 \) and \( \alpha = 24 \). We have chosen these combinations of \( Re \) and \( \alpha \) in order to compare the flow fields with the previous works [8][9] as well as to satisfy the fluid mechanical similarity conditions. The material transport was observed by using sodium fluorescein or fine glass beads of diameter 0.1 mm. We also measured the velocity field by means of the particle image velocimeter (PIV). For the latter purpose, nylon beads of a diameter 0.16 mm with a specific density 1.03 were used.

2.2. Material transport from the first branch

We show an example of a sequence of material transport for the case (II) \( Re = 2100 \) and \( \alpha = 20 \) in Fig.1(b). These pictures were taken at the same phase of oscillation (i.e., intake phase), \( t = 0.5T, 1.5T, 2.5T, ... \) and so on, where \( T \equiv 1/f \) is the period of oscillation. Apparently the material (sodium fluorescein) looks transported downward on the average, although the boundary of the dye-containing fluid is of complicated shape. Note that the molecular diffusion of the sodium fluorescein was found to be negligible, which was ascertained by the preliminary experiment of oscillatory flow using a straight channel. We also note that the fluid and materials moved only forward and backward oscillatory within the first branch for flows with \( Re \) lower than a certain critical value \( Re_c \approx 1000 \), so that the average downward transport of the materials was not recognized.

In order to quantify the long-range material transport, we consider a path along the centerlines that connects the centers of the junctions. We divide the channel into rectangular
Figure 1. (a) Block diagram of the experimental apparatus. (b) Examples of the visualization of transported material \((Re = 2100, \alpha = 20)\). (c) Time sequence of the image density profile of the transported material along the channel, where \(L_1\) is the length of the first branch \((Re = 2100)\), and the position of the second branch is \(s/L_1 = 1.78\). (d) Positions of the “front” plotted at the maximum intake phase, showing long-term transport of materials: (I) \(Re = 1500, \alpha = 17\) (triangles), (II) \(Re = 2100, \alpha = 20\) (circles), and (III) \(Re = 3000, \alpha = 24\) (squares).

sections, each of which covers each branch, and measure the image density of the sodium fluorescein along these strips. Figure 1(c) is an example of the above analysis for the case (II), where the abscissa is the position \(s\) along the centerline of the channel with its origin at the inlet position, i.e., the ranges \(0 \leq s \leq 130(\equiv L_1)\) mm, \(130 \leq s \leq 230\) mm, and \(s \geq 230\) mm cover the first, second, and third branches. The ordinate is the sum of the image density of the sodium fluorescein over the cross section at \(s\), which is normalized by the maximum value in each branch. The downward transport of the materials is recognized in spite of considerable variation associated with the structural change of the convecting flow near the channel bifurcation. We further consider the “front” \(s_f\) of the transported materials defined by the weighted mean of the density near the tip of the fluid that contains sodium fluorescein. Figure 1(d) shows the long-term movement of the front, which is monitored at the maximum intake phase. Material transport is larger for flows with larger \(Re\) and \(\alpha\) in the tested three cases.
2.3. Velocity field

We show an example of the velocity field \((Re = 2100, \alpha = 20)\) measured by PIV in Fig.2(a). Figure 2(b) shows the time variation of the velocity component parallel to the wall near the outlet of the first branch (depicted by the line c-d). During the time \(t/T \approx 0.5 \sim 0.6\), the flow in the middle part of the channel is still in the intake phase because of the inertia, whereas the opposite flow grows in the regions near the outer-side of the wall, so that the effective width of the downward flow is reduced. After this phase, the upward flow becomes dominant, but its magnitude decreases toward the end of the period of oscillation of the breathing. Figure 2(c) shows the time variation of the velocity components along the wall measured across the section a-b as is illustrated in the inset. The abscissa of Fig.2(c) is the distance \(y\) from the outer-side wall of the second branch (note that the \(y\) axis is taken in the negative direction to match the illustration). Here the measured cross section is chosen so as to pass through or nearby the center of the attached eddy, because the latter remains almost at the same position during the intake phase. Further observation reveals the time variation of the attached eddies as follows (see also Fig.3): At first, slow but almost unidirectional flow along the channel is recognized, which develops into faster downstream flow in both sides of the second branch, and the separated flow regions starting from the first corners are recognized. Then the separated flow regions grow and the attached eddies are recognized near the outer-side wall of the second branch (Fig.2(a)), although the net flow is still in the downstream direction. The net flow reverses after that so that the attached eddies become obscure. Finally faster upward stream is recognized in the central region of the first branch as well as in the regions near the outer-side wall of the second branch. The Reynolds number dependence of the position of the center of the eddy \(y_c\) from the outer-side wall was also checked, which reveals that the eddy grows faster and larger for larger Reynolds number flows tested in the present experiment.

2.4. Particle path

Figures 2(d)-(f) show the typical particle paths starting from the positions described by the black solid circles. Dotted lines are those in the first cycle \(t = 0 \sim T\), whereas solid lines with solid markers are those in the second cycle \(t = T \sim 2T\). Generally speaking, particles are pushed downward in the inspiration phase, and are carried back in the expiration phase. Particles that are near the outer-side boundary of the second branch are trapped in the "eddy region", which move further downward in the next breathing.

3. Conclusion

The velocity field and the transport mechanism in the oscillatory flow in the branching tube are summarized as follows (see Fig.3): In the intake phase (Fig.3(a)), the fresh materials flow downward almost uni-directionally in the channel. Separated flow regions start from the outer-side corners of the junction and extend along the outer-side walls of the second branch, which prevents the mixing of the newly coming materials with the older ones that remained in the second branch. The separated flow regions grow in thickness, and the eddies attached to the corner of the first junction are formed (Fig.3(b), Fig.2(a)). Fresh materials are firstly carried by either side of the faster stream between the attached eddy and the inner-side wall of the second branch, and are dispersed laterally throughout the second branch after passing around the eddy region. Immediately before the end of intake phase, the materials are further dispersed by convective diffusion in decelerated flows, whereas the attached eddies are weakened and are wiped upward with their upstream ends pinned at the corners (Fig.3(c)). Then they become thicker and spread into the central part of the second branch, so that they prevent the backward flow of the fresh materials. With the start of expiration phase, the attached eddies are further weakened and the separated flow regions are carried upward (Fig.3(d)). The fluid volumes near the outer-side of the branched channel, which mainly contain older materials, are pushed out
Figure 2. (a) The velocity field at $t/T = 1/2$. (b) Time variation of the velocity profile near the outlet of the first branch at the start of the expiration phase, and (c) the growth of the attached eddy near the second branch in the intake phase. (d)(e)(f) Typical particle trajectories in the first cycle $t = 0 \sim T$ (dotted lines), and those in the second cycle $t = T \sim 2T$ (solid lines with solid markers). Black solid circles describe the initial positions.

along with the fast upward stream in the central region of the first branch (Fig.3(e)). Here, the part of the materials that have been carried far downward remains in the second branch. At the end of one period of oscillatory flow (Fig.3(f)), the older materials are still in the outward motion in the central region of the first branch because of the inertia, but the fresh materials in the next cycle are supplied near the outer-side walls of the first branch because of the conservation of mass. In short, the formation and destruction of the attached eddies play the role of throttle valves, in which newly taken materials are transported far downstream via inner side of the second branch around the eddy regions (Fig.3(b')), whereas the older ones that have been trapped in the separated regions are carried backward to the first junction via outer side of the second branch (Fig.3(e')). These processes eventually transport the newly taken materials downward and the older ones upward, so that the circulation of the materials is achieved in spite of zero net volume of fluid during one period of breathing.

4. Discussion
A lot of studies on the transport of fresh air or suspended particles into the human lung have been made in more realistic geometries (including Pendelluft associated with the asymmetry of the branch) as well as by applying more realistic pressure variation in time, which may better describe the realistic situation. These complexities, however, can mask the essential control
mechanism. Recently proposed “trap-and-release” mechanism [10], where the formation-and-
destruction of the separated regions at the junction leads to bidirectional axial gas-exchange in
conductive airways, seems quite promising. Most of their studies, however, are based on flow
visualization, and the quantitative understanding of this mechanism is not necessarily clear. On
the other hand, we have focused our attention to the simplest possible geometry, and elucidated
the role of repeated growth and disappearance of the attached eddies near the junction of the
branched channel. The above-mentioned control mechanism is quite simple and fundamental to
the transport of materials, and will provide wider application of the oscillatory viscous flow to
the material transport or ventilation without using solid valves.

References
[1] Weibel E R 1963 Morphometry of the Human Lung (New York: Academic Press)
[2] Pedley T J 1977 Pulmonary fluid dynamics Annu. Rev. Fluid Mech. 9 229
[3] Grotberg J B 1994 Pulmonary flow and transport phenomena Annu. Rev. Fluid Mech. 26 529
[4] Sera T and Tanishita K 2002 Anatomical aspects of airway flow and gas transport in the pulmonary system
Med. Imag. Tech. 20 (No.6), 654 [in Japanese]
[5] Kleinstreuer C and Zhang Z 2010 Airflow and particle transport in the human respiratory system Annu. Rev.
Fluid Mech. 42 301
[6] Choi J, Xia G, Tawhai M H, Hoffman E A and Lin C-L 2010 Numerical study of high-frequency oscillatory
air flow and convective mixing in a CT-based human airway model Ann. Bioned. Eng. 38 3550
[7] Danier D I and Zhu J 2008 Dry powder platform for pulmonary drug delivery Particuology 6 225
[8] Haselton F R and Scherer P W 1982 Flow visualization of steady streaming in oscillatory flow through a
bifurcating tube J. Fluid Mech. 123 315
[9] Jan D L, Shapiro A H and Kamm R D 1989 Some features of oscillatory flow in model bifurcations J. Appl.
Physiol. 67 147
[10] Mochizuki S, Murata A and Togashi Y 2002 Axial mass transport by reciprocating flow in branching tube
network (Gas exchange mechanism in conducting airways of human lung) Jpn. Soc. Mech. Eng. B68 831 [in
Japanese]; Mochizuki S 2003 Convective mass transport during ventilation in a model of branched airways
Proc. PSFVIP-4 (3-5 June 2003, Chamonix, France).