Secondary Velocity Fields in the Conducting Airways of the Human Lung

An understanding of flow and dispersion in the human respiratory airways is necessary to assess the toxicological impact of inhaled particulate matter as well as to optimize the design of inhalable pharmaceutical aerosols and their delivery systems. Secondary flows affect dispersion in the lung by mixing solute in the lumen cross section. The goal of this study is to measure and interpret these secondary velocity fields using in vitro lung models. Particle image velocimetry experiments were conducted in a three-generational, anatomically accurate model of the conducting region of the lung. Inspiration and expiration flows were examined under steady and oscillatory flow conditions. Results illustrate secondary flow fields as a function of flow direction, Reynolds number, axial location with respect to the bifurcation junction, generation, branch, phase in the oscillatory cycle, and Womersley number. Critical Dean number for the formation of secondary vortices in the airways, as well as the strength and development length of secondary flow, is characterized. The normalized secondary velocity magnitude was similar on inspiration and expiration and did not vary appreciably with generation or branch. Oscillatory flow fields were not significantly different from corresponding steady flow fields up to a Womersley number of 1 and no instabilities related to shear were detected on flow reversal. These observations were qualitatively interpreted with respect to the simple streaming, augmented dispersion, and steady streaming convective dispersion mechanisms. [DOI: 10.1115/1.2768374]

Keywords: respiratory airway, bifurcation, lung flow, secondary velocity, aerosol transport, dispersion, drug delivery

Introduction

Medical applications such as the administration of anesthesia, alternative modes of ventilation (such as high-frequency ventilation (HFV) [1]), and clinical diagnoses of lung function [2] rely on an understanding of mass transport in the respiratory tract. Aerosol dispersion, and ultimately deposition, is relevant to the delivery of therapeutic drugs by inhalation. Aerosol dispersion, and ultimately deposition, is relevant to the design of inhalable pharmaceutical aerosols and their delivery systems. Secondary flows affect dispersion in the lung by mixing solute in the lumen cross section. The goal of this study is to measure and interpret these secondary velocity fields using in vitro lung models. Particle image velocimetry experiments were conducted in a three-generational, anatomically accurate model of the conducting region of the lung. Inspiration and expiration flows were examined under steady and oscillatory flow conditions. Results illustrate secondary flow fields as a function of flow direction, Reynolds number, axial location with respect to the bifurcation junction, generation, branch, phase in the oscillatory cycle, and Womersley number. Critical Dean number for the formation of secondary vortices in the airways, as well as the strength and development length of secondary flow, is characterized. The normalized secondary velocity magnitude was similar on inspiration and expiration and did not vary appreciably with generation or branch. Oscillatory flow fields were not significantly different from corresponding steady flow fields up to a Womersley number of 1 and no instabilities related to shear were detected on flow reversal. These observations were qualitatively interpreted with respect to the simple streaming, augmented dispersion, and steady streaming convective dispersion mechanisms. [DOI: 10.1115/1.2768374]

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Kamm et al. [18], Tarbell et al. [19], Permutt et al. [20], Paloski et al. [21], Pedley and Kamm [22], Jan et al. [23], and Tanaka et al. [24]. In short, axial dispersion can be maximized in oscillatory flows by strong lateral mixing during periods of low axial velocity and weak lateral mixing during periods of high axial velocity. Secondary flows, therefore, influence convective dispersion, which must be accounted for to determine the transport of gas and aerosols in the lung.

Experiments have been conducted by previous researchers in an attempt to quantify secondary velocity fields in the airways [25–30]. Zhao and Lieber [26,27] constructed a symmetrically bifurcating, single-generation model with constant cross-sectional area. Laser Doppler velocimetry (LDV) captured the flow patterns along two lines in the cross section at various axial locations for steady inspiration and expiration flows at approximately 500 < Re < 2000. On inspiration, they found that flow in the parent tube split at the carina and entered the daughter branches. Centrifugal effects due to the curvature of the bifurcation produced a Dean-type instability [31]. Dean vortices appear when the flow in a tube meets a bend; high momentum fluid at the centerline is forced away from the center of curvature toward the outer wall where it splits symmetrically with each half transiting the circumference to merge at the inner wall, and proceeds again toward the outer wall. Viewed head-on, two symmetric counter-rotating vortices are evident on either side of the plane containing the radius of curvature (here, referred to as the bifurcation plane). Expiratory flows followed a similar pattern. For expiration, however, the two daughter streams now unite in the parent tube to produce two sets of Dean vortices, resulting in a quadruple vortex superposed on the primary axial flow. The quadruple vortex is symmetric about the bifurcation plane, as well as the axial plane normal to the bifurcation (denoted as the normal plane).

Tanaka et al. [28] used LDV to measure one component of the secondary flow in a three-generational, asymmetric model with a sinusoidally oscillating bulk flow. Since the focus was high-frequency oscillation, relatively high Womersley numbers were used (3.8 < $\alpha$ < 7.5). The Womersley number is defined as $\alpha = (d/2) \sqrt{2\pi \nu / \sigma}$, where $\sigma$ is the frequency of oscillation and $\nu$ is the fluid kinematic viscosity. Even so, boundary layer growth was significant enough to produce secondary vortex patterns qualitatively similar to the steady flow results of Zhao and Lieber [26,27]. At these Re (350 < Re < 700), the history of the flow influenced local secondary flow patterns. In particular, a switching of the local curvature by 180 deg (a feature inherent to “opposite” daughter branches in an in-plane, multigenerational model) flips the direction of the secondary vortices (due to a reversal in the direction of the centrifugal force) as the flow traverses successive bifurcations on inspiration and reduces the secondary velocity magnitude.

Comer et al. [32] and Zhang and Kleinstreuer [33] simulated steady (200 < Re < 2000) and oscillatory (0.97 < $\alpha$ < 7.4) flows in planar and nonplanar, symmetric, multigenerational airway geometries. Three features were found to affect the flow in these simulations: upstream flow field (i.e., flow history), local bifurcation curvature, and the carinal ridge shape. Peak unsteady flow patterns closely resembled the equivalent steady flow with only minor differences for off-peak cases. As expected, nonplanar secondary flow patterns did not match the results obtained with an in-plane model geometry.

Independent experimental variables in the current investigation consist of flow direction (inspiration and expiration), Re (6 < Re < 350), axial distance from the junction (0, 1, and 2 diameters from the trisection), generation (1–3), branch at a particular generation (same or opposite), phase in oscillatory cycle, and Womersley number (0 < $\alpha$ < 1). The influence of flow direction is particularly important as the bifurcating structure of the airways produces fundamentally different (and irreversible) flows between inspiration and expiration due to curvature, taper, and flow division characteristics [8–10,34]. It remains unclear how different flows on inspiration and expiration affect the overall dispersion in the lung. Past researchers have primarily focused on relatively higher Re, possibly owing to more interesting convective phenomena, but the overwhelming majority of the conducting region during normal respiration is at lower Re [35]. Persistence of secondary flow structures was evaluated by taking measurements at different axial locations.

Examination of flow evolution at various branches through multiple generations benefits an understanding of the general flow in the lung. What would flow patterns look like if an actual bronchiole in the respiratory tract could be observed? A complete model of the lung, suitable for detailed experimentation, is not feasible. The planar model employed herein at least allows study of the two limiting cases of secondary velocity for inspiration. Secondary flows of a certain direction are set up after traveling through a single bifurcation. When this flow splits at the next bifurcation, one daughter, with the center of curvature on the same side of the bifurcation as the previous generation, features secondary flows in the same direction, while the other is characterized by secondary flows in the opposite direction. The former case, denoted here as S for same, may exhibit more vigorous secondary flows than the latter case, referred to as O for opposite. A schematic of this geometry, along with nomenclature specific to S and O for different generations, is presented in Fig. 1 for both inspiration (right half of tree) and expiration (left half of tree). Note that generation is numbered based on the number of bifurcations the flow has traversed (i.e., numbering scheme reverses for inspiration and expiration).

Since human breathing is cyclic, oscillatory flow experiments have also been conducted here at Womersley numbers representing normal respiration, in contrast to previous measurements and simulations of oscillatory flow patterns, which were conducted at higher Womersley numbers.

The aim of this study is to elucidate fundamental attributes of the secondary flow patterns in the human airways which are relevant to convective mixing by augmented dispersion. Studies are under way to examine the role of secondary flows on longitudinal dispersion in more detail through measuring the transport of a passive tracer.

**Experimental Model and Methods**

The geometry used for the experimental model is representative of the conducting region of the lung. The role of this region is to

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**Fig. 1 Schematic of three-generational model geometry with nomenclature**

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advec fresh air through a series of bifurcating passages to the respiratory zone, where gas exchange takes place in alveoli. The standard, symmetric bifurcation defined by Pedley [35] was used in this study. A symmetric model is routinely employed in experimental and numerical investigations of the respiratory tract and features the benefit of allowing isolation of the effects of interest (namely, flow direction, Reynolds number, axial location with respect to the bifurcation junction, generation, branch, phase in the oscillatory cycle, and Womersley number). Diameter ratio (ratio of daughter-to-parent diameter) is 0.78, for a net increase in cross-sectional area of 20% from parent tube to both daughter branches. Hence, the ratio of daughter-to-parent Re is 0.64. Branch length to diameter is 3.5 and the angle between branches is 70 deg. The radius of curvature of the bifurcation is 7.5 times the parent tube radius. The parent tube changes cross-sectional shape from circular to elliptical, without change of area, as the junction is approached. Both area and shape change as the daughter tubes emerge. Daughter tubules possess a constant cross-sectional area and are initially curved, straightening when the branching angle is achieved. A software was created to accept the physiological values selected above and write the resulting geometry of a single bifurcation unit (as a negative) to a stereolithography file. Figure 2 shows bifurcation geometry, along with dimensions for the largest bifurcation unit.

A multistep molding process [36] was implemented to manufacture the experimental model. The complicated geometry of the lung was reproduced in consolidated cornstarch with a rapid-prototyping machine (Z Corporation). A total of seven bifurcation units representing three generations were fabricated, coated with water-soluble glue to ensure dimensional stability during the subsequent molding process, and assembled in-plane using water-soluble tape (3M). Next, the parts were suspended in a custom-built box into which an elastomer (Dow Sylgard 184) was poured. The box featured facets parallel to desired measurement planes to facilitate distortion-free optical access to regions of interest in the model. The mold was placed in a vacuum chamber to remove air bubbles from the elastomer. The box was separated after the elastomer cured, and the embedded cornstarch pattern was removed by dissolving it in water. The finished product is an optically clear terminal daughter tube openings. The length of these tubes was such that a laminar development length was ensured at the highest Re. Honeycomb sections were inserted at the end of the metal tubes to condition the flow.

The index of refraction of the model and working fluid must be precisely matched to eliminate optical distortions during recording. While the manufacturer-supplied index of refraction for Dow Sylgard 184 of 1.4 is a useful guideline, careful titration was required for accurate refractive index matching. To this end, the model was filled with a glycerol-water mixture and a regular grid was placed beneath the model. A digital camera was placed above this arrangement to record the optical distortion of the grid due to the refractive mismatch between the model and working fluid. Next, the glycerol-water mixture was titrated by adding precise volumes of water. A recirculation pump was used to quickly mix the glycerol and water through the model. In this manner, the mixture was changed in 1% increments until the optical distortion recorded from the camera was completely removed. At this point, the mass of a known volume of the mixture was determined to calculate the mixture density. This density was compared against a table of physical properties of glycerol-water mixtures to determine the mixture ratio. The table gave the index of refraction as 1.41, specific gravity as 1.15, and the kinematic viscosity as $7.837 \times 10^{-6}$ m$^2$/s for a 58% (by weight) glycerol and 42% water mixture at 22°C.

The experimental setup is given in Fig. 3. The three-generational, in-plane model was attached via flexible tubing from the main parent tube to a reservoir containing the working fluid. Flexible tubing connected the distal ends of the model to a battery of syringe pumps, one for each of the eight terminal daughter tubes. A programmable stepper motor and translation stage, mounted with the syringes, drove the steady and oscillatory flow through the model.

Twin Continuum Surelite II Neodymium-doped yttrium aluminum garnet (Nd:YAG) pulsed laser beams (350 mJ/pulse at 532 nm) were passed through sheet-forming and steering optics to illuminate the cross section at selected axial location-branch combinations in the model. A LaVision Imager Intense (10 bits, 1376×1040 pixels) camera oriented perpendicular to the light sheet recorded image pairs for particle image velocimetry (PIV) at different frame rates (depending on the particular experiment). The flow was seeded with fluorescent particles (20–40 μm). A long-wave pass filter was placed in front of the lens to block elastic scattering from the flow boundaries of the test section. An iterative procedure was used to optimize pulse separation, seeding density, and laser-sheet thickness for a given experiment. Image pairs were correlated within a 32×32 pixel interrogation box at 50% overlap. Average secondary velocity magnitude was computed from the resulting velocity fields. These data, in turn, were processed over multiple realizations to determine the average and standard deviation of average secondary velocity magnitude for a particular experiment. The number of realizations was sufficiently large to restrict the uncertainty in the mean to below 10% for all cases.

Results and Discussion

Flow fields in various cross sections of the model, indicated by velocity vectors and computed vorticity, are presented for varying Re, axial location in terms of diameters from the trisection ($X_d$),
and generation/branch for a steady flow. Oscillatory flow measurements yield the flow field throughout a cycle for expiration at various Womersley numbers. These results were used to compare with the steady flow. In all cases, the primary flow is oriented out of the page. The secondary velocity is normalized by the local bulk velocity of the primary flow; reference vector length is given in each caption. Vorticity is nondimensionalized by the inverse of the local time scale \( \frac{L}{u} \), where \( L \) is the length of the tube. Using \( L \) for the length scale allows characterization of mixing by secondary flows throughout the length of the airway. During oscillatory flow experiments, peak bulk velocity is used to obtain vorticity scale. For most figures, the flow direction and location \( X_d \) and generation/branch are indicated in an adjoining schematic of the three-generation tree. Likewise, the points in the oscillatory cycle at which measurements were taken are shown alongside for the unsteady flow fields. Average secondary velocity magnitudes are also presented to further illuminate trends in secondary content over the parameter space.

**Influence of Re.** PIV measurements during an inspiration at G1 and \( X_d=1 \) (location marked with a solid circle in the tree) at various Re (6–128) are shown in Fig. 4. Vorticity is used to effectively characterize the secondary velocity structure and activity; the color bar provides nondimensionalized vorticity magnitude \( (\omega_u) \). Secondary vortices due to local curvature are expected to be counterclockwise in the upper half of the cross section and clockwise in the lower half, with the primary flow out of the page and the carina lying to the right. At Re=6, however, secondary vortices are not evident; the destabilizing centrifugal effects are as yet too weak to overcome the stabilizing effect of viscosity. Clearly, distinct regions of moderate vorticity appear for Re=32. These structures are relatively symmetric about the bifurcation plane and closely resemble the classic Dean vortex [31]. As Re increases to 64 and 128, vorticity strengthens and vortex cores migrate away from the center of curvature.

Figure 5 presents expiration measurements at G1 and \( X_d=1 \) with varying Re. Again, the solid circle on the tree indicates the measurement location, and the color bar signifies vorticity magnitude. As the two daughter flows merge, a quadruple vortex is expected. The rotational sense of the quadruple vortex can be easily visualized by recognizing that the flow from each daughter tube converges to the center of the parent tube along the (horizontal) bifurcation plane, and diverges away from the center along the (vertical) normal plane. A quadruple vortex is very weakly evident at Re=10 by the slight color variations. At Re=50, a quadruple vortex has clearly formed. For Re=100 and 200, vorticity increases and occupies noticeably more of the cross section.

The Dean number \( Dn=Re^{(d/2)/R} \), a measure of the ratio of centrifugal-to-viscous forces, can be estimated for these experiments by multiplying Re by 0.41 on inspiration and by 0.37 on expiration. Here, \( R \) is the local radius of curvature. Figures 4 and 5 illustrate that secondary vortices form on inspiration and expiration at \( X_d=1 \) of a G1 bifurcation around \( Dn=10 \).

**Effect of Axial Location.** The effect of axial location on the secondary flow during inspiration at G1 for Re=64 is given in Fig. 6. Three points on the tree indicate measurements at the tri-

![Fig. 4 Variation of secondary flow with Re during inspiration in G1; vorticity contours are used to depict the strength of the secondary flow](image)

![Fig. 5 Variation of secondary flow with Re during expiration in G1; vorticity contours are used to depict the strength of the secondary flow](image)
section \((X_d=0)\), as well as one \((X_d=1)\) and two \((X_d=2)\) diameters downstream. All experiments were conducted in a plane perpendicular to the axis of the daughter tube. The velocity field at \(X_d=0\) is dominated by the Poiseuille flow of the parent tube with little modification due to the downstream presence of the daughter tubes. Vorticity is high (saturating the scale) although secondary vortex structures are not apparent—the flow field is primarily one directional (left to right in the figure). Essentially, an off-axis slice of Poiseuille flow has been captured because the primary flow from the parent tube has not yet aligned itself with the curving daughter tube axis. Vorticity of the appropriate sign appears primarily due to the vertical gradient of the measured horizontal velocity component of the Poiseuille-like parent flow. Converging of flow toward the bifurcation plane due to the cross-sectional area change from circular to elliptical to slightly dumbbell shaped was negligible. At \(X_d=1\), the secondary vortices materialize although with less vorticity than at \(X_d=0\). Secondary strength decreases further at \(X_d=2\), as shown by the lower vorticity magnitude.

Expiratory flow fields were measured at varying axial locations. Figure 7 presents these data at \(G1\) and \(Re=100\). Analogous to the inspiratory case, the flow field at \(X_d=0\) displays the in-plane velocity components of the Poiseuille flow from each contributing daughter branch resulting in high vorticity despite the absence of secondary vortex structures. Daughter flows combine, mainly directed toward one another. Flow impingement creates a saddle point at the center of the cross section with the flow diverging away from the center along the normal plane. No noticeable component of velocity out of the bifurcation plane due to domain expansion in the normal plane as the flow enters the parent tube was observed. A vigorous quadruple vortex forms at \(X_d=1\) and becomes attenuated by \(X_d=2\). Note the complicated change in geometry, from dumbbell shaped \((X_d=0)\) to elliptical \((X_d=1)\) to circular \((X_d=2)\).

**Impact of Generation/Branch.** Generation, and more specifically the branch at a particular generation for inspiration, was investigated. Recall that secondary flows with a certain sense are set up after progressing through one generation on inspiration. After traversing the next bifurcation of an in-plane model, the local curvature in each daughter tube serves to either maintain the same secondary flow direction \((S)\) or, alternatively, form secondary flows of the opposite \((O)\) sense. This argument can be extended for successive generations of an in-plane arrangement of bifurcations and represents the two extremes (maximum and minimum secondary velocities). The present study measured inspiratory secondary velocity fields at \(G1\), both daughter tubes at \(G2\) \((S\) and \(O)\), and at two \((S-O\) and \(O-O)\) branches of a possible four at \(G3\). For \(G3-S-O\), the nomenclature means that the flow goes through the second bifurcation with the same secondary velocity direction as the first, and then switches direction after the third bifurcation. Similarly, \(G3-O-O\) signifies that secondary vortices change direction after each bifurcation. A schematic of measurement locations for inspiration experiments at \(Re=64\) and \(X_d=1\) is included in Fig. 8. The local secondary vortex direction for flow fields shown in Fig. 8 can be determined with the aid of the tree schematic; recall that the primary flow direction is always out of the page.

Rather than exhaustively discuss each flow field, key findings are summarized. Figure 8 shows that for all cases \((G2-S, G2-O, G3-S-O, \text{and } G3-O-O)\), secondary vortices are determined by local
curvature alone. In contrast with simulations performed by Comer et al. [32] at higher Re, flow history does not significantly impact any inspiration results at Re=64. Thus, characterization of the influence of generation during inspiration does not require a detailed tracking of preceding branches for this Re.

Figure 9 gives the expiratory flow field after one, two, and three generations at Re=100 and $X_d=1$. The pattern at G1 illustrates the quadruple vortex expected when Poiseuille flows in the daughter tubes combine in the parent. Two sets of quadruple vortices would then arrive at G2; however, rather than sustain the pair of incoming quadruple vortices for a total of eight vortices from the daughter tubes, local curvature acts to produce just one quadruple vortex at G2. Again, the influence of upstream bifurcations is not felt at this Re; local effects dominate over flow history. G3 flow patterns further support this finding. Zhang and Kleinstreuer [33], in fact, also found that a quadruple vortex formed during expiration after passing through two and three bifurcations for simulations at Re=200. Vorticity strength and distribution in the cross section are similar between G1, G2, and G3, as seen in Fig. 9.

Unsteady Flow Fields. Oscillatory flow fields were examined for expiration. Oscillatory flows were not measured for inspiration since less complicated secondary flows would be encountered. A sinusoidal wave form drove the bulk flow through the model. This cycle was divided into 12 equal segments for temporal measurements. Phase in the cycle ($\varphi^*$) was nondimensionalized by period; thus, the node separating inspiration from expiration is at $\varphi^*$ =0.5, whereas expiration continues to $\varphi^*$ =1.0.

Figure 10 presents oscillatory expiration flow fields at $X_d=1$ in G1 for Re=100. Experiments were performed at various Womersley numbers to assess the role of unsteadiness for physiologically realistic (at normal respiration) conditions. The steady flow result at Re=100 (top of Fig. 11) may be compared with the oscillatory cycle peak results at the same Re for $\alpha=0.5$ and 1.0 (bottom). Strong similarities in vorticity magnitude and pattern are evident, indicating that even up to $\alpha=1.0$, unsteady effects are small.

Trend Analysis. A large dataset was acquired encompassing several cases; for brevity, it is not possible to present all cases. Instead, a few summary plots are provided to capture the key findings and summarize previous discussions of flow fields. Average secondary velocity magnitude for steady flow experiments ($U_{S,\text{steady}}$) at $X_d=1$, nondimensionalized by average primary flow velocity, is given as a function of Re in Fig. 12. Results are classified by flow direction and generation/branch as given in the legend.

The first observation is that secondary velocity increases with Re. This is evidenced by increased vorticity at higher Re in Figs. 4 and 5. Secondary vortices do not instantaneously appear at some Re. Daskopoulos and Lenhoff [38] showed that secondary velocity increases linearly from Re=0 for steady flow in a curved tube. Results indicate that secondary velocity also increases linearly for
steady flow in a bifurcation up to Re ~ 100. In practice, weak secondary flows at low Re do not perform sufficient rotation over the length of a particular airway to appreciably mix solute. For this reason, a threshold in average secondary velocity magnitude of approximately 5% of the average primary velocity can be used as a metric to identify whether secondary flow magnitudes are of any practical interest to mixing in the lung. These experiments indicate that secondary velocities in the airways cross this threshold in the range 10 < Re < 50. Higher secondary velocities at low Re for G2 and G3 are likely due to imprecision in locating the plane perpendicular to the flow direction; these measurements may contain a small component of primary velocity.

Secondary velocity does not significantly increase with Re for Re > 100. The existence of such a plateau suggests that the secondary vortex state has been fully reached at this axial station. An increase in Re does not increase secondary velocity beyond 10–20% of the average primary velocity, but rather pushes the development of secondary activity farther downstream. Eventually, this may extend into the next bifurcation and materialize as the flow history phenomena uncovered in the simulations of Comer et al. [32]. The development length of steady flow in a curved tube is less than that for a straight tube, and the disparity increases for increasing Dn [39]. Using the expression for laminar development length in a straight tube along with the length-to-diameter ratio (3.5) of the airway model, an upper bound for the flow in the bifurcation to be developed is approximately Re ~ 100. This agrees with the trend in Fig. 12 from linear at Re < 100 to more flat at Re > 100.

The next striking aspect of Fig. 12 is the lack of correlation of secondary velocity with flow direction and generation/branch. Intuitively, the presence of four secondary vortices on expiration as opposed to two on inspiration may be expected to cause differing secondary velocity magnitudes. This is not the case. In fact, our result agrees with arguments based on the well-characterized Dean flow. Secondary vortex strength increases with Dn; since Dn is approximately equal for inspiration and expiration in a given tube at a given Re, so should the secondary velocity strength. The lack of dependence of secondary flow on generation and branch can also be explained using preceding arguments; essentially, for the Re range investigated, the flow in upstream bifurcations has been forgotten and only local curvature plays a role in secondary vortex development.

The variation of secondary velocity with axial location is shown in Fig. 13. Results are given for inspiration (G1, G2-S, and G2-O) at Re = 64 and expiration (G1, G2) at Re = 100. Extremely high secondary velocities measured at the trisection (X_d=0), as previously discussed, are not due to the instantaneous appearance of secondary vortices at the junction. Instead, the relatively high-speed Poiseuille-like flow contributes a substantial in-plane component in an off-axis slice, leading to an inflated value of secondary velocity. Although the elevated vorticity at X_d=0 is not reflective of secondary currents, the vorticity values are certainly accurate and consistent with the mathematical definition of vorticity, and provide physical insight into the flow evolution at the merge. Hence, they have been included for the sake of completeness. Information at X_d=1 reflects the presence of secondary vor-
Fig. 11 Comparison steady versus oscillatory-peak secondary velocity fields during expiration for Re=100 at \( X_d=1 \) in G1. Reference vector lengths are 0.2 of the average primary flow velocity.

Fig. 12 Secondary velocity magnitude as a function of direction, Re, and generation/branch for steady flow at \( X_d=1 \)
tics. The noticeable attenuation in secondary velocity strength from $X_d=1$ to $X_d=2$ results from a lack of significant curvature in the geometry between these stations. While the curves monotonically decrease with $X_d$, some higher $Re$ measurements suggest that the onset of more vigorous secondary activity may be delayed to locations farther downstream, which may result in nonmonotonic behavior.

In Fig. 14, nondimensionalized secondary velocities for the oscillatory flow ($U_{S,\text{oscillatory}}$, divided by $U_{S,\text{steady}}$) illustrate relative magnitude and temporal variation for unsteady expiration. Results are plotted against $\phi^*$ for $Re=100$ and $\alpha=0.5$ and 1.0. In general, secondary flow velocity increases on acceleration, reaches a peak, and then decreases during deceleration. Secondary flow magnitude at the peak unsteady flow is similar to the corresponding steady flow. Although limited, our data suggest that secondary velocity scales with the primary velocity for this parameter range. As previously noted, shear-related instabilities were not encountered during flow reversal.

Conclusions and Implications

In vitro experiments in a representative three-generational in-plane model of the conducting airways of the lung have confirmed that centrifugal forces trigger secondary flows in lung bifurcations. Experiments indicate the critical Dean number for onset of appreciable secondary vortices on inspiration and expiration as
Dn \sim 10, \text{Re as well as Dn decrease steadily with increasing generation number; implementing the symmetric model of Weibel [37], results of this study correspond to approximately generations 5–13 for normal respiration and generations 8–16 under HFV conditions. Depending on local curvature, our results indicate that secondary currents may persist through generation 10 for normal respiration and to generation 13 under HFV conditions.}

Secondary flows throughout the conducting airways may not drastically increase above 20% of the average primary velocity due to two factors. First, these results indicate that for a fully developed flow, secondary velocity scales linearly with Re (reaching a maximum not exceeding 20% of the average primary velocity) as is the case for flow in a curved tube [38]. Second, at higher Re, secondary flows do not have sufficient axial length to fully develop. Subsequent bifurcations constantly interrupt the growth of secondary flows. Secondary velocity does not sharply increase past \text{Re} \sim 100, suggesting delayed development to a downstream location (and possibly the next generation akin to history effects noted at higher Re by Comer et al. [32]). This also agrees with theoretical studies of the development length for flow in curved tubes [39]. The net effect of these two factors may be to limit the efficacy of augmented dispersion.

The secondary velocity strength is largely independent of flow direction. Mixing by secondary flows (augmented dispersion), therefore, may act equally on inspiration and expiration. Generation/branch also does not significantly affect secondary flows for the parameters involved in this study. Local curvature, not previous bifurcation history, dominates flow patterns. Augmented dispersion at these Dn, therefore, will not be due to secondary flow patterns from a higher generation propagating through distal generations. Rather, local secondary flow patterns along with random angular orientations of the bifurcation plane from generation to generation in the lung determine the efficacy of augmented dispersion.

Secondary currents decrease sharply away from the bifurcation. Although vorticity is high right at the trisection due to flow artifacts from the upstream generation, secondary vortices do not appear until at least one diameter downstream. Any mixing by secondary flows (augmented dispersion) then acts over a majority of the tube length.

Oscillatory flow experiments reveal that the flow transitions smoothly during flow reversal; no shear instability was detected at flow reversal for \alpha \leq 1. Oscillatory secondary velocity activity (and therefore augmented dispersion) seems to scale with the primary flow velocity, as hypothesized by Fredberg [16]. Flow patterns at oscillatory peak were similar to steady flow results at the corresponding Re. Unsteady phenomena associated with boundary layer growth were negligible for \alpha \leq 1.

Finally, the efficacy of steady streaming can be considered by superposing secondary velocity fields on inspiration and expiration. This exercise qualitatively shows that a parcel of solute cannot retrace the inspiratory trajectory on expiration.

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Nomenclature

\begin{itemize}
\item \text{Dn} = \text{diffusivity (m}^2\text{s}^{-1})
\item \text{G} = \text{generation}
\item \text{O} = \text{opposite secondary velocity direction}
\item \text{Pe} = \text{Peclet number}
\item \text{Re} = \text{Reynolds number}
\item \text{S} = \text{same secondary velocity direction}
\item \text{X} = \text{axial location (m)}
\item \text{d} = \text{tube diameter (m)}
\end{itemize}

Greek Symbols

\begin{itemize}
\item \text{\(\alpha\)} = \text{Womersley number}
\item \text{\(\varphi\)} = \text{phase in cycle}
\item \text{\(\nu\)} = \text{kinematic viscosity (m}^2\text{s}^{-1})
\item \text{\(\omega\)} = \text{vorticity (s}^{-1})$
\end{itemize}

Subscripts

\begin{itemize}
\item \text{d} = \text{diameter}
\item \text{o} = \text{scaled (for vorticity)}
\item \text{S, steady} = \text{secondary velocity, steady flow}
\item \text{S, oscillatory} = \text{secondary velocity, oscillatory flow}
\item \text{E} = \text{non-dimensionalized}
\end{itemize}

References


