

# Experimental Assessment of Compliance Effects on Transitional Flow in Intracranial Aneurysm Models Using Particle Tracking Velocimetry

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## ABSTRACT

The progression of intracranial aneurysms (IA) is influenced by hemodynamic factors such as wall shear stress and pressure. The underlying flow regime, i.e., laminar versus transitional or turbulent, can substantially alter these quantities. Although aneurysmal flows have traditionally been assumed to be laminar due to their relatively low Reynolds numbers (typically 100–500), studies have increasingly reported the presence of transitional or disturbed flow behavior. However, the presence of non-laminar flow in IAs is debated as no universal metric currently exists to characterize the extent of transitional flow in the aneurysms. A consequence of this is that factors such as wall compliance, which are believed to affect IA flow and transitional flow characteristics, cannot be presently studied. In this work, we address these gaps by introducing a metric to quantify the extent of non-laminar flow in an IA and using it to investigate the effect of wall compliance on flow transition in IAs. Time-resolved particle tracking velocimetry experiments were performed using manufactured compliant patient-specific aneurysm models. Two levels of compliance and three flow rates were tested for comparison. Our new flow-regime metric—based on a two-line fitting approach applied to the energy spectrum—was employed to identify the degree of transition. We observed that the high-compliance model exhibited more complex rotational flow structures with two distinct rotational directions, whereas the low-compliance model resulted in a centrally symmetric rotational flow structure. Furthermore, all configurations exhibited energy spectral characteristics associated with transitional and turbulence-like behavior. The high-compliance model demonstrated an earlier transition than the less compliant model. Overall, these results suggest that increased wall compliance promotes transition and turbulence-like behavior in IAs in general. The findings highlight the important role of wall deformation in modulating flow instability and indicate that rigid-wall assumptions may underestimate the transitional nature and complexity of aneurysmal hemodynamics.

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## 1. Introduction

Intracranial aneurysms (IAs)—localized dilations of cerebral arteries—are present in approximately 2–3% of the general population (Vlak et al., 2011). Aneurysm rupture is a major cause of hemorrhagic stroke and is associated with an 80% risk of long-term disability or death. In contrast, treatment of IAs carries a 7–10% risk of complications, while most aneurysms remain unruptured and clinically stable over a lifetime (Le Roux et al., 2004; Nieuwkamp et al., 2009).

These competing risks underscore the need to better understand the biomechanical hemodynamic mechanisms that drive IA growth and rupture.

Hemodynamic factors have been widely implicated in aneurysm progression. In particular, regions of low wall shear stress (WSS) have been associated with localized wall degeneration and IA growth. However, the flow regime within IAs—which can substantially alter the temporal and spatial distributions of WSS—remains a topic of active debate. Reynolds numbers in cerebral arteries (typically between 100-500) are often within a nominally laminar range. Yet, studies have shown that aneurysmal flows may exhibit transitional or disturbed behavior as well as high-frequency velocity and pressure fluctuations arising from complex geometric features such as wall expansion, curvature, and impingement-driven shear layers (Ferguson, 1970; Luciano et al., 2024; Yagi et al., 2013). No consensus or universal metric currently exists to characterize this behavior. Consequently, the extent to which transitional flow exists within IAs and its role in IA progression remains unresolved.

From a biomechanics perspective, aneurysmal walls are structurally heterogeneous and spatially nonuniform in thickness and composition (Haggerty & Nirmalan, 2022), implying that local compliance may vary substantially within and across IA geometries. The interaction between wall deformability and potentially transitional flow may produce complex fluid structure interactions (FSI) in the IA. Given the sensitivity of transitional flow to perturbations and shear-layer instabilities, wall compliance may could significantly influence the onset and evolution of non-laminar flow behavior. Yet, most computational fluid dynamics (CFD) studies and *in vitro* experiments continue to assume rigid walls and laminar flow conditions (Cebal et al., 2011; Rahma & Abdelhamid, 2023). Hence, there exists important open questions regarding compliant-wall effects in transitional regimes in IA geometries.

In this study, we employ particle tracking velocimetry (PTV) to investigate how wall compliance modulates transitional flow behavior in IA models. We manufactured compliant aneurysm phantoms with controlled mechanical properties and captured time-resolved measurements of their pulsatile velocity fields. An energy-spectra-based transition quantification metric was then applied to evaluate the relative intensity of transitional flow.

## 2. Methods

### 2.1. Geometry and flow loop

The patient-specific IA geometry was obtained from a local neurosurgeon (Fig. 1a). The rigid IA geometry and the corresponding hemodynamic analysis have been previously studied by the

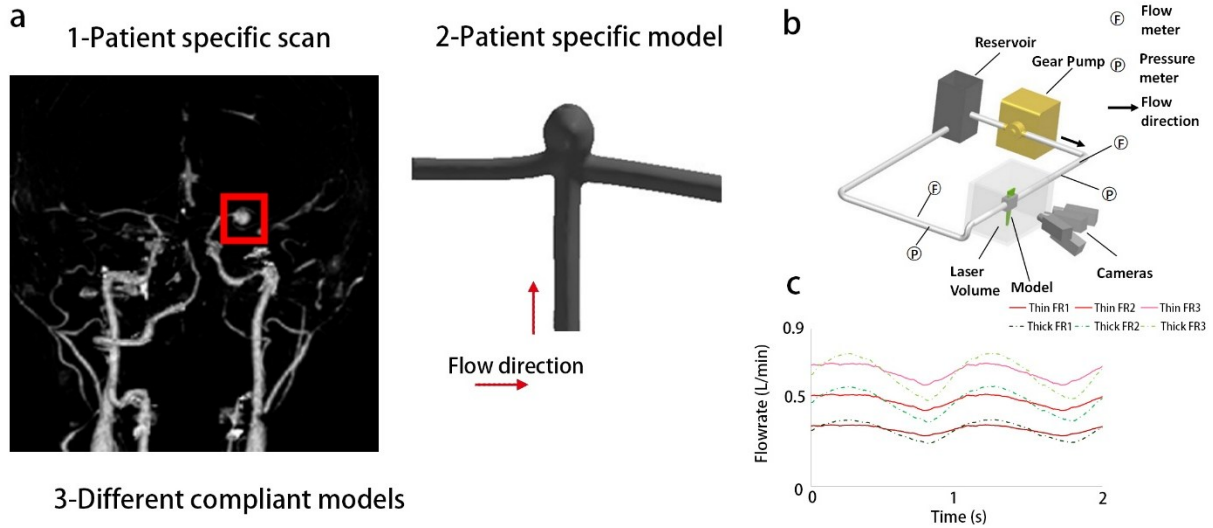


Figure 1. The patient-specific geometry (a) & flow loop diagram (b) & used waveform (c)

same lab and reported in the literature (Korte et al., 2025). In the present work, two compliant IA models were fabricated using polydimethylsiloxane (PDMS; Sylgard 184) with wall thicknesses of 0.3 mm and 0.6 mm. The geometry was produced via 3D printing (LulzBot TAZ 5) using polyvinyl alcohol (PVA) and carefully polished to ensure smooth surfaces. Dip-coat method was used to create different wall thickness PDMS models. Each model was cured at room temperature (25 °C) for 36 h.

An *in vitro* flow loop was assembled to study aneurysmal flow dynamics (Fig. 1b). The inflow waveform was derived from patient-specific measurements obtained using an ultrasonic flow transducer (Fig. 1 c). 3 average flow rate were used, 0.30, 0.50, and 0.70 L/min with 60 beats per minute. The working fluid consisted of a blood-analog mixture of water, glycerol, and urea, yielding a dynamic viscosity of 4.67 cP and a density of 1143 kg/m<sup>3</sup> (Brindise et al., 2018).

## 2.2. Particle tracking velocimetry measurement techniques

Volumetric PTV measurements were performed using an Nd:YLF laser ( $\lambda = 527$  nm) and four high-speed cameras (Phantom VEO 440, 4 MP). The laser sheet thickness was approximately 10 mm, sufficient to illuminate the entire aneurysm model. One camera was positioned normal to the model, while three additional cameras were arranged at  $\pm 25^\circ$  relative to the normal direction, with two cameras in the same horizontal plane and one positioned below the central camera. Camera calibration was conducted using a dual-plane calibration target, resulting in a root-mean-square (RMS) reprojection error below 0.6 pixels. Subsequent volume self-calibration reduced the RMS error to below 0.1 pixels. Time-resolved images with a resolution of 1280 × 960 pixels were

acquired at 2500 Hz, corresponding to a maximum inter-frame particle displacement of approximately 10 pixels. The working fluid was seeded with 19.1  $\mu\text{m}$  fluorescent particles (Spherotech Inc.). To minimize optical distortion, the refractive index of the working fluid was matched to that of the PDMS model ( $n = 1.41$ ). The model was fully submerged in the same fluid used in the flow loop to further reduce refraction-induced imaging artifacts. PTV image processing was performed using DaVis 10.2 (LaVision Inc.) with the Shake-the-Box (STB) algorithm (Schanz et al., 2016). Particle images were pre-processed to remove background noise. The STB procedure employed 12 iterations for both particle addition and position refinement. The maximum allowable triangulation error was set to 10 voxels, and the shaking tolerance was set to 0.5 voxels.

### 2.3. Post-processing

Raw STB particle trajectories were interpolated onto a uniform grid using inverse-distance weighted averaging to obtain time-resolved velocity fields. The gridded velocity data were filtered using proper orthogonal decomposition (POD) combined with entropy-based thresholding and universal outlier detection to suppress spurious vectors while preserving coherent flow structures. This post-processing framework follows previously validated methodologies developed by our group and applied in prior experimental hemodynamic studies.

Based on the reconstructed velocity fields, subsequent analysis focuses on characterizing compliance-dependent vortex structure and quantifying transitional flow behavior using a velocity-field-based transition metric. The detailed implementation and validation of the post-processing framework have been reported by the same group previously (Peng & Brindise, 2024).

### 2.4. Energy spectral analysis

To characterize transitional behavior, an energy-spectrum-based analysis was performed using the reconstructed gridded velocity fields. Specifically, the turbulent kinetic energy (TKE) spectrum along the three spatial directions was computed as

$$E_{ij}(\mathbf{k}, t) = \frac{U_i(\mathbf{k}, t) U_j^*(\mathbf{k}, t)}{N} \quad (1)$$

$$E_d(k_d) = \sum_{i=1}^n \langle \overline{E_{ii}}(\mathbf{k}) \rangle_{\mathbf{k} \perp d} \quad (2)$$

where  $E_{ij}(\mathbf{k}, t)$  denotes the spectral energy tensor at wavenumber vector  $\mathbf{k}$  and time  $t$ ,  $U_i(\mathbf{k}, t)$  represents the Fourier-transformed velocity component in the  $i^{\text{th}}$  direction,  $(\cdot)^*$  denotes the complex conjugate, and  $N$  is the normalization factor. Further,  $E_d(k_d)$  represents the one-dimensional TKE spectrum along the spatial direction  $d$  and  $n$  is the number of spatial directions. Here,  $\overline{E_{ii}}(\mathbf{k})$  denotes the time-averaged spectral energy tensor component, and  $\langle \cdot \rangle_{\mathbf{k} \perp d}$  indicates averaging over the wavenumber components perpendicular to the  $d^{\text{th}}$  direction. The resulting

diagonal components of the temporally averaged energy spectral density tensor were subsequently summed over all spatial directions, as indicated by the summation term in Eq.2, to obtain the TKE spectrum. The resulting temporally averaged TKE spectra were subsequently used for transition analysis.

To distinguish the energy spectra corresponding to laminar and non-laminar regimes, a flow-regime metric was computed from the energy spectrum along each spatial direction. Specifically, a two-line fitting approach described by Brindise and Vlachos (Brindise & Vlachos, 2017) was employed to partition the energy spectrum into two regions. For each candidate point in the spectrum, two linear fits were obtained using the data before and after the point, respectively. The corresponding total absolute fitting error and coefficient of determination ( $R^2$ ) for the two-line fit were then evaluated. The point corresponding to the maximum ratio of the  $R^2$  to the fitting error was selected as the change point. Subsequently, the slopes of the final two fitted lines were obtained, and the ratio of the high-wavenumber slope to the low-wavenumber slope was defined as the flow-regime metric. To account for directional dependence, the metrics corresponding to each spatial direction were combined using a weighted average based on the mean unit flow vector. Specifically, the flow-regime metric is given by

$$M = \sum_{d=1}^n \frac{1 - e_d^2}{\sum_{i=1}^n (1 - e_i^2)} \left| \frac{\alpha_2}{\alpha_1} \right| \quad (3)$$

where  $d$  denotes the spatial direction,  $\alpha_1$  and  $\alpha_2$  represent the slopes of the linear fits in the low- and high-wavenumber regions, respectively, and  $e_d$  is the component of the mean unit flow vector along the  $d^{\text{th}}$  spatial direction.

### 3. Results

Fig. 2 presents the velocity streamlines of two compliant IA models at four representative time points over a cardiac cycle obtained using FR1. In both models, the flow enters the aneurysm sac through a single inlet, impinges on the aneurysm wall, and forms a swirling flow before exiting through the two outlets. This motion generates a strong, coherent intra-saccular vortex structure located near the center of the aneurysm sac. Despite these similarities, a pronounced difference is observed in the rotational behavior between the two compliance conditions. In the thick-walled model, the rotational motion is strongly concentrated near the center of the sac and exhibits a relatively symmetric structure with respect to the inlet. Although the vortex strength varies throughout the cardiac cycle, a single dominant rotation direction is consistently maintained. In contrast, the thin-walled model exhibits a more complex rotational pattern characterized by the coexistence of two distinct rotation directions between the inner and outer regions of the aneurysm

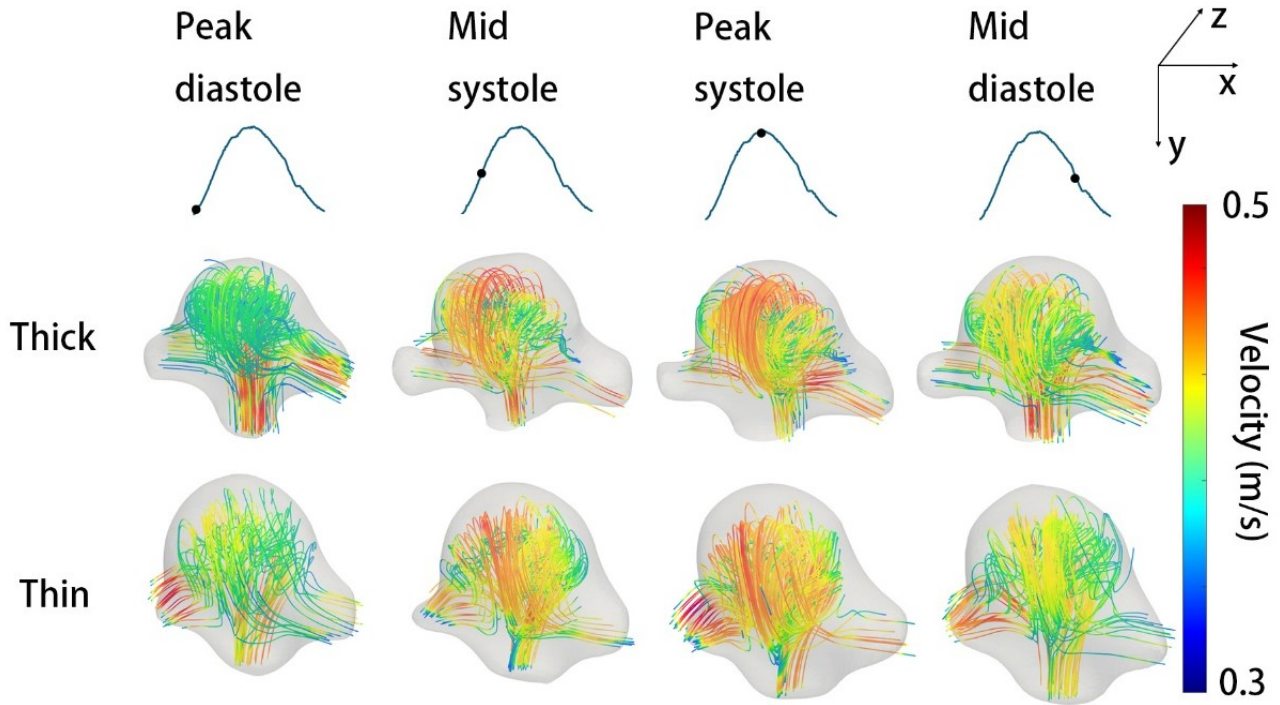


Figure 2. The STB tracks for the two complaint IAs. Four time points in one cycle are listed.

sac. At peak systole, the inner and outer rotational layers form an oblique configuration, resulting in a markedly asymmetric vortex structure. Furthermore, during mid- and peak-diastolic phases, the vortex in the thick-walled model largely preserves its primary structure, whereas in the thin-walled model the reduced inflow is insufficient to sustain the organized rotation, leading to dissipation of the original vortex pattern.

Fig. 3 presents the energy spectra along each spatial direction together with the corresponding metric variation for both compliant geometries across all flow rates. In general, the magnitude of the energy spectrum was observed to increase with increasing flow rate, accompanied by an increase in the mean TKE. The mean TKE values for the thick-walled model were  $1.73 \times 10^{-4}$ ,  $6.65 \times 10^{-4}$ , and  $2.02 \times 10^{-3} \text{ m}^2 \text{ s}^{-2}$  while those for the thin-walled model were  $2.50 \times 10^{-4}$ ,  $8.53 \times 10^{-4}$ , and  $2.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-2}$  for the 0.3, 0.5, and 0.7 L/min average flowrates, respectively. Hence, the mean TKE was on average 24% higher for the thin model than the thick model. Furthermore, the energy spectrum at lower flow rates was predominantly characterized by plateau and shoulder-like features across all spatial directions, with a relatively weak sloped-decay region. As the flow rate increased, the spectra progressively transitioned toward a more pronounced sloped-decay behavior, as illustrated in Fig. 3a. Correspondingly, the flow-regime metric (Fig. 3b) decreased with increasing flow rate for both compliant models, reducing from 4.23 to 3.41 (19%) for the thick-walled model and from 3.77 to 2.93 (22%) for the thin-walled model as the flow rate increased from 0.3 to 0.7 L/min. Thus, the thin-walled model demonstrated an earlier

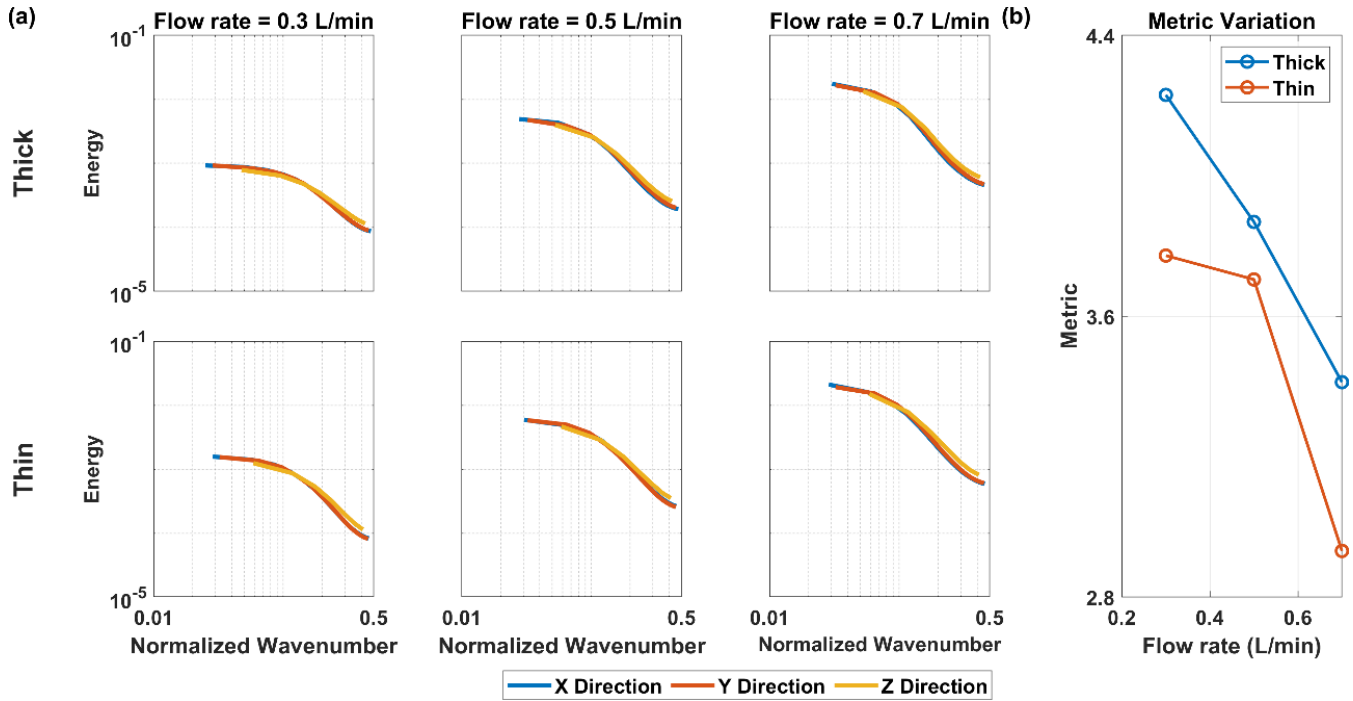


Figure 3. (a) Spatial turbulent kinetic energy spectra for the thin-walled and thick-walled compliant models. (b) Variation of the flow-regime metric for all flow configurations.

transition from plateau-dominated behavior to sloped-decay behavior compared to the thick-walled model, which was quantitatively characterized by the flow-regime metric shown in Fig. 3b. Consistent with this behavior, the thin-walled model consistently exhibited lower metric values than the thick-walled model across all flow rates, with average metric values of 3.84 and 3.47, respectively, corresponding to an average percentage reduction of 10%.

#### 4. Discussion

In this study, the influence of wall compliance on transitional IA hemodynamics was experimentally investigated using time-resolved PTV and energy spectral analysis. The results demonstrated that increased aneurysm compliance substantially alters intra-saccular flow organization, promotes asymmetric and unstable rotational structures, and enhances transitional flow behavior throughout the cardiac cycle. In particular, the thin-walled IA exhibited earlier transition from plateau-dominated to sloped-decay spectral behavior together with consistently lower flow-regime metric values, indicating stronger turbulence-like dynamics relative to the thick-walled model. These findings suggest that wall deformation actively contributes to flow instability, and that rigid-wall assumptions may underestimate the complexity and transitional nature of aneurysmal flow.

In aneurysms located at T-shaped junctions, the canonical flow pattern consists of the inflow entering the sac, impinging on the apex, forming a coherent rotational structure, and exiting

through the daughter branches. Under rigid or weakly deformable conditions, this intra-saccular vortex is typically characterized by a single dominant rotational direction and a relatively symmetric spatial organization. However, the present results demonstrate that wall compliance substantially alters this classical flow structure. In particular, increased wall motion modifies both the stability and organization of the intra-aneurysmal vortex throughout the cardiac cycle. This effect is most pronounced in the thin-walled model during peak systole, where two distinct rotational regions emerge simultaneously within the aneurysm sac. Rather than maintaining a single coherent vortex core, the flow separates into inner and outer rotational layers with different rotational behavior. The resulting oblique vortex organization produces a markedly asymmetric flow structure compared with the thick-walled configuration. Furthermore, during diastole, the vortex structure in the thin-walled model dissipates more rapidly, suggesting reduced persistence and stability of the organized rotational motion. As the aneurysm wall expands and contracts under pulsatile loading, the moving boundary continuously modifies the local shear layers and vortex organization, introducing additional flow perturbations and enhancing spatiotemporal flow instability. Consequently, the compliance-induced breakdown of vortex structures may provide a physical mechanism promoting the onset of transitional behavior within IAs.

The energy spectral analysis provided a physics-based and geometry-independent framework for characterizing flow regimes and identifying transitional behavior in compliant

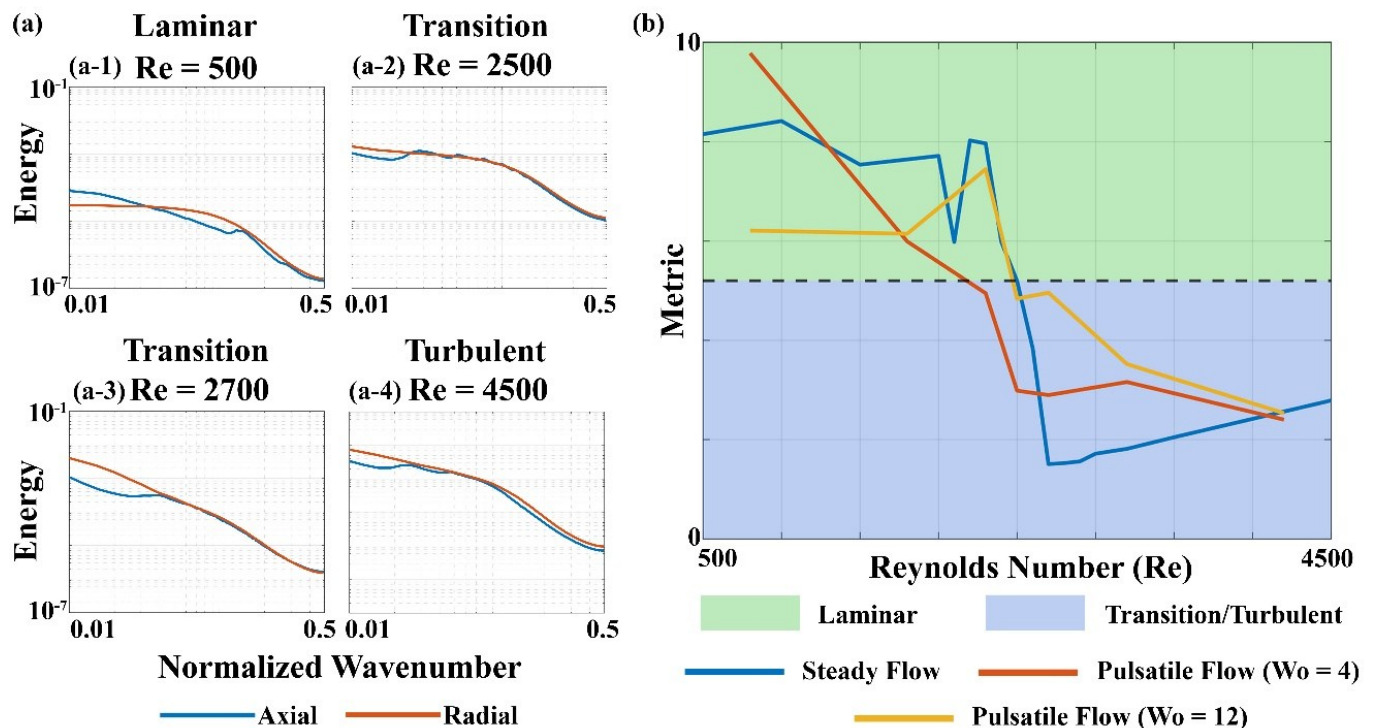


Figure 4. (a) Spatial energy spectra corresponding to laminar ( $Re=500$ ), transitional ( $Re=2500$  and  $2700$ ), and turbulent ( $Re=4500$ ) regimes in steady pipe flow. (b) Variation of the flow-regime metric for steady and pulsatile flows.

aneurysmal flows. Fig. 4 illustrates the spectral characteristics associated with different flow regimes together with the corresponding variation of the flow-regime metric using data from steady pipe flow (Shirdade et al., 2024) and pulsatile pipe flow studies with two Womersley numbers ( $Wo$ ) (El-Khader & Brindise, 2024). The spectral analysis demonstrates that plateau and shoulder-like features are associated with laminar flow behavior, whereas sloped-decay behavior is associated with transitional and turbulent regimes. The plateau and shoulder followed by a sharp decay reflect limited intermediate-scale generation, weak inter-scale energy transfer, and strong viscous damping characteristic of ordered laminar flow, whereas the emergence of a sloped-decay region indicates enhanced nonlinear interactions and increased redistribution of energy to intermediate scales associated with transitional and turbulent flow behavior. The flow-regime metric captures the variation of the energy spectrum from plateau- and shoulder-dominated behavior to sloped-decay behavior, thereby enabling quantitative characterization of flow transition in compliant aneurysmal configurations. Based on the flow-regime metric analysis conducted for steady and pulsatile pipe flows, a flow-regime metric threshold of 5.2 was identified to distinguish laminar flow from transitional/turbulent behavior, where metric values above the threshold correspond to laminar flow and values below the threshold indicate transitional and turbulent behavior. The flow-regime metric values associated with all compliant geometries remained below the identified threshold, indicating the presence of transitional behavior within the investigated aneurysmal flows. Furthermore, the reduction in the flow-regime metric with increasing flow rate indicates enhanced transitional and turbulence-like behavior at higher velocities, as expected. The earlier transition from plateau-dominated behavior to sloped-decay behavior observed in the energy spectrum for the thin-walled model compared to the thick-walled model suggests an earlier onset of transitional behavior in the more compliant configuration. This behavior is further supported by the increased TKE observed in the thin-walled model across all investigated flow rates. This behavior can be attributed to the additional flow disturbances introduced by wall compliance. Specifically, increased compliance introduces additional perturbations and amplification of existing flow fluctuations due to wall motion and the time-varying geometry. The wall motion can retain and reintroduce energy into the flow rather than dissipating it, thereby contributing to higher TKE and accelerated transition. These observations are consistent with previous studies reporting earlier transition in compliant channel flows (Srinivas & Kumaran, 2017) and increased TKE in compliant aneurysmal flows (Tupin et al., 2020). Consequently, the present findings highlight the important role of wall compliance in aneurysmal hemodynamic studies and its influence on flow instability and transition characteristics.

Moreover, this analysis demonstrates our flow regime metric as a universal indicator of the extent of transitional flow behavior in IAs.

Several limitations exist in this study. The aneurysm models were fabricated using 3D printing, which inherently limits the achievable surface smoothness and geometric resolution. In addition, the PDMS wall thickness exhibited an estimated variability of approximately 10% across the model. Such non-uniformity may influence the local wall deformation during the cardiac cycle and, consequently, affect the measured hemodynamic fields. It is important to note, however, that arterial walls *in vivo* are also mechanically heterogeneous and spatially non-uniform, particularly in pathological conditions such as IAs (Guan et al., 2023). In addition to these experimental limitations, the energy spectrum analysis itself is also subject to certain limitations, including the use of a selected threshold to distinguish laminar and non-laminar regimes. Consequently, the identified flow-regime classification depends on the chosen threshold value. Furthermore, the use of temporally averaged energy spectra limits the ability to investigate the temporal variation and intermittency associated with transitional and turbulent behavior over the pulsatile cycle. In addition, the relatively low spatial and temporal resolution of the experimental data limits the resolution and accuracy of the obtained energy spectra. Future studies should aim to address these limitations through improved fabrication methodologies, enhanced thresholding approaches, instantaneous energy spectrum analysis, and higher-resolution measurements.

## 5. Conclusion

In this work, we investigated the influence of wall compliance on transitional flow behavior in IAs using compliant patient-specific aneurysm models, time-resolved PTV experiments, and energy spectrum analysis. In general, the results showed that increased wall compliance led to more complex rotational flow structures within the aneurysm sac. Furthermore, the energy spectrum analysis revealed the presence of transitional behavior in IA flows. Increased compliance was associated with enhanced flow complexity, earlier transition, and stronger turbulence-like characteristics, underscoring the influence of wall deformation on aneurysmal hemodynamics. These results suggest that accounting for compliance is important for accurately characterizing flow dynamics in IAs and that rigid-wall assumptions may not fully capture the underlying flow physics. In addition, the energy-spectrum-based framework and associated flow-regime metric provided a robust means of quantifying transitional behavior, offering a useful tool for future investigations of complex aneurysmal flows.

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