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AN EXPLORATIVE CFD STUDY ON STENOSIS-INDUCED FLOW INSTABILITIES IN THE CAROTID ARTERY

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INTRODUCTION

Atherosclerosis is the leading cause of death in the westernized societies and the primary cause of stroke. Atherosclerotic plaques can grow into the arterial lumen sufficiently to obstruct the blood flow. The local narrowing of the lumen, known as stenosis, leads to the occurrence of flow phenomena such as separation, recirculation and instabilities in the downstream region, in addition to larger velocity values as the flow accelerates through the throat of the stenosis. Flow bench studies on stenosed tubes embedded in tissue mimicking gels demonstrate that flow instabilities and pressure fluctuations induce mechanical waves that can be detected by means of accelerometers or laser Doppler vibrometry (LDV). As part of the H2020 project CARDIS, we are exploring the use of LDV as a non-invasive diagnostic tool for carotid stenosis via detection of stenosis induced vibrations at the level of the skin.

In addition to and complementing in-vivo and experimental studies, computational fluid dynamics may provide a better understanding of flow related phenomena leading to the generation of mechanical waves and their propagation through soft tissues. In this study, we present initial computational results obtained in two different settings: (i) flow in a simple tubular model with a 75% area stenosis (mainly for assessment of numerical parameter evaluation), (ii) a patient specific case, with a maximum area stenosis of 82%. The later stages of the study will involve the evaluation of the arterial wall movement generated by flow instabilities and the study of the propagation of the pressure waves from the arterial wall to the skin as compressional and shear waves.

METHODS

The geometry of the first model consists of an axisymmetric 75% area stenosis with length (L) equal to twice the tube diameter (D=6mm). The total length of the model corresponds to 5D and 10D for the upstream and the downstream side, respectively. Previous studies have shown that an upstream length of 2D is sufficient to obtain results independent of the position of the inflow boundary [1]. A Cooper-type meshing was performed in order to obtain a grid of 3251688 hexahedral elements with uniform spacing in the axial direction. Simulations were performed using Fluent (Ansys) with time-dependent 3D Large Eddy Simulations (LES) carried out with the Smagorinsky–Lilly constant C_s equal to zero in order to nullify the viscosity added by the model. Bounded schemes were used for the momentum and for the transient formulation. The time step was set to 1 millisecond. The constant inlet velocity value *U* corresponded to a volumetric flow rate (Q) of 1000 ml/min, leading to a Reynolds number (Re) based on the tube diameter of 1240. A zero pressure condition was set at the outflow boundary. For the patient-specific case, the geometry consists of a carotid bifurcation with a non-axisymmetric 82% area stenosis of the internal carotid artery (ICA). Initial simulations were carried out on a relatively coarse hexahedral grid (439680 elements) with the same settings as in the simplified model except for Q=250 and 500 ml/min, leading to Re=230 and 460, respectively. The outflow boundary was set as flow ratio of 32% for the ICA as defined by Harald et al.[2]. In both cases, simulations were performed for a total duration of 2 seconds with the last 500 milliseconds used for spectral analysis (FFT) to assess the frequency content of the signal. As this is an early stage of the study, in both models the arterial walls are supposed to be rigid.

RESULTS AND DISCUSSION

Although flow in a straight tube would not be transitional (since Re < 2300), in the 75% stenosis model pressure instabilities such as those depicted in Figure 1 are observed: the flow is not able to stay attached and vortices form downstream of the stenosis, as the flow diverges and decelerates. The area-weighted average of velocity at the throat of the stenosis reached a value of 4*U*. The maximum amplitude of the observed pressure oscillations was 0.854 Pa. Frequency analysis of the pressure field showed the highest frequency peaks between 2D and 4D away from the stenosis throat and always in the frequency range of 10-450 Hz, consistent with experimental observations.

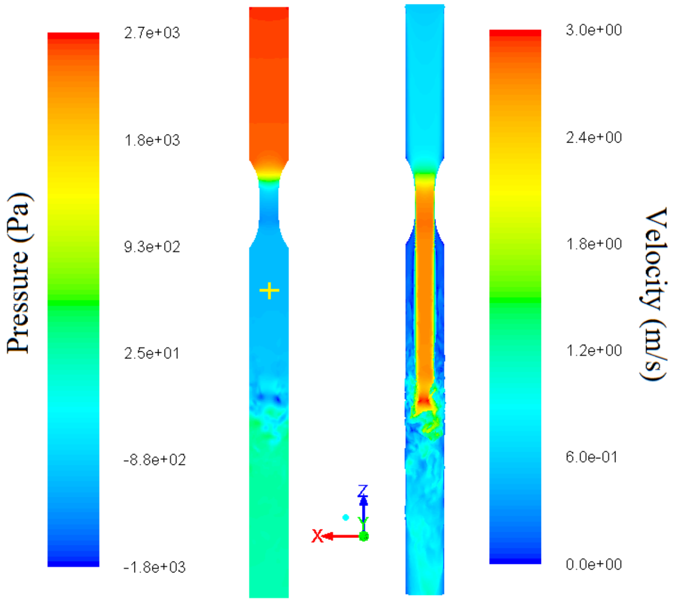

Figure 1: pressure and velocity instabilities at t=0.06s of the 75% simplified model. The yellow crosshair indicates the point where the frequency spectrum was calculated.

For the patient-specific case, only results for Re=460 will be shown. Instabilities are manifested by the swirling motion of the fluid in the post-stenotic region (Figure 2).

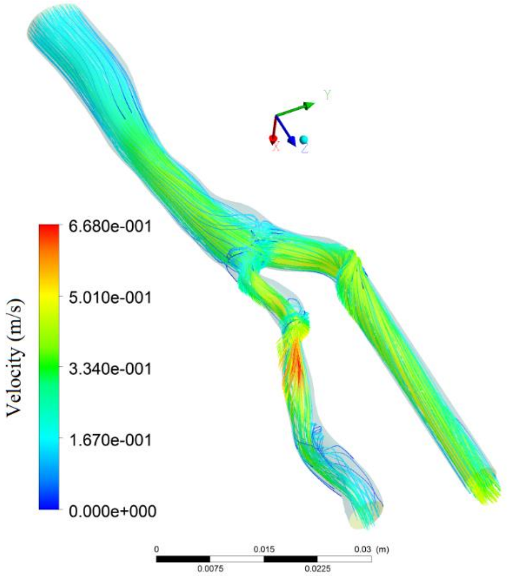

Figure 2: pressure for the patient specific case at t=2s for Re=460

The pressure and its frequency spectrum depicted in Figure 3 were calculated for a point located on the centerline of the ICA at a distance of 2.6 D from the stenosis center. The amplitude of pressure oscillations is in the order of 1.547 Pa. The FFT indicates peaks in the 10-450 Hz frequency band, with an intense low frequency peak. For Re=230 results are entirely different: the pressure does not show any peak at any location in the model. This is likely to be due to the low flow rate, which is insufficient to cause flow instabilities. Further analysis will be performed at different flow rates. The sensitivity of the results to the mesh density and to the time step will be further explored. We believe that the regularity of fluctuations in the patient-specific case, compared to the simple tube model, are likely to be induced by a relatively coarser mesh or low flow. Furthermore, the dependency of the pressure oscillations (and their frequency spectrum) on the shape and degree of stenosis will be assessed.

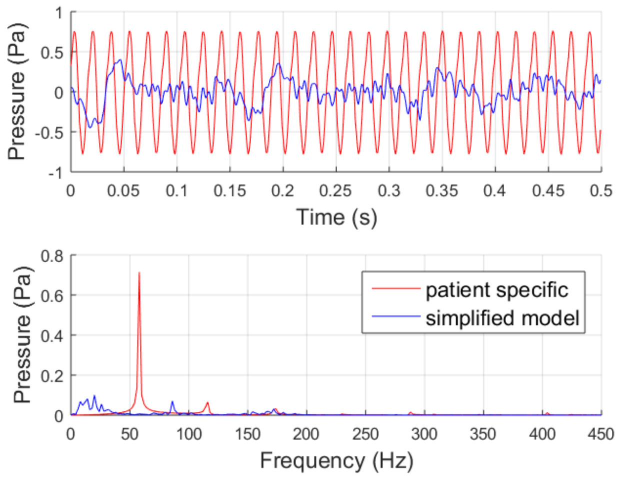

Figure 3: pressure and its frequency spectrum: comparison between the patient-specific model for Re=460 (red) and the simplified model (blue).

CONCLUSIONS

These initial CFD results are in line with previous studies with similar models [3] and our own experimental observations, and indicate that the stenosis-induced flow instabilities for the tested settings give rise to pressure fluctuations in the frequency range of 10-450 Hz.

The 3D printed phantom of the patient-specific model studied in this abstract will be the subject of future experimental studies. The integrated experimental-computational approach will provide further details on fluid dynamics and mechanical phenomena, and give more insights into the sensitivity and specificity of the use of LDV to detect carotid stenosis, providing subsequently guidance for studies on patients.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Mallinger F. et al., *Int Jou Heat and Fluid Flow* 23:657-663 2002.
[2] Harald C.G. et al., *J Biomech*, 43:2332-2338, 2010.
[3] Sherwin A.J. et al., *J Fluid Mech*, 533:297-327, 2005.