FLUID-STRUCTURE INTERACTION (F.S.I.) SIMULATION OF THE HUMAN CYSTIC DUCT

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INTRODUCTION

Statistical observations by Deenitchin et al [1] suggested that complex cystic duct geometry is frequent among cholelithiasis patients. Reduction in gallbladder (GB) motility leads to its inefficient emptying And Jazrawi et al [2] showed that gallstone patients had lower GB turnover rate (GB evacuation fraction). Nakayama and van der Linden [3] observed stratification of the bile in GB, which is often regarded as a precursor to gallstone formation. These studies suggest that fluid mechanics of the biliary system may be an important factor in GB diseases. Our previous numerical simulations [4] showed the effects of cystic duct geometry on bile flow resistance. The model assumes rigid boundaries, implying that the interactions between the fluid flow and structure deformation of the biliary system is in equilibrium. The current work discusses further the simulation of the biliary system that includes deformable feature of the cystic duct and investigates its role in cystic duct resistance using Fluid-Structure Interaction (FSI) technique.

METHODOLOGY

Initially, cystic duct was idealised by a 2D channel with staggered baffles to capture the important flow features. A series of such models with varying geometrical and flow parameters was used to study their contribution towards the cystic duct resistance. In our previous work [4], models with rigid boundaries were simulated to study the salient flow features, using the finite volume based CFD software, Fluent5. This has now been extended to consider the effects of interactions between the compliant cystic duct and bile flow...

The present simulations are performed using the FSI features in the finite element based software Fidap8.6 (Fluent Inc.), which solves the fluid flow and structure deformations via Computational Fluid Dynamics (CFD) and Computational Structure Dynamics (CSD) techniques, respectively. The mesh of the deformed flow domain is then remeshed by employing the Computational Mesh Dynamic (CMD) method [5].

The biliary duct wall is assumed to be a linear elastic material with the values of its Young's Modulus (E) in the range reported in References [6] and [7]. Boundary conditions are obtained from physiological flow measurements. Laminar, steady state flow of Newtonian bile was assumed. The cystic duct Resistance, R_n is defined as:

$$R_n = \Delta P/Q \qquad (1)$$

where ΔP = pressure drop across duct, Q = flow rate,
and the relative resistance R_d is:

$$R_d = R_{n=i}/R_{n=0} \qquad (2)$$

where $R_{n=i}$ is the resistance of duct with i-number of baffles.

RESULTS AND DISCUSSION

In the FSI model, the inlet (in this simulation, assumed to be from the GB) and the outlet (to the common bile duct) of the deformable section (cystic duct) are constraint separately by rigid duct. Therefore it is anticipated that the maximum tube deformation will occur at the middle section when the pressure is constantly decreasing along the duct length (according to the Poiseuille's relation for laminar flow). All the results and figures discussed have a flow Reynolds number, Re_D, of 30. Figure 1 shows the deformation of the duct due to fluid pressure. The dark lines show the original shape of the duct and the gray lines represent the deformed shape.

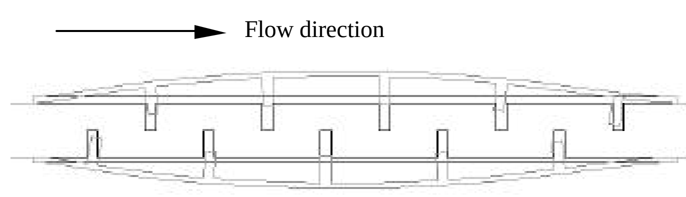

Figure 1. Deformation of the cystic duct model.

The magnitude of the nodal displacement of the duct structure can be seen in Figure 2. The mesh for the flow needs to be remeshed periodically to accommodate changes in the geometry of the flow domain. Figure 3 shows the final mesh with the displacement required by each node when equilibrium state is reached.

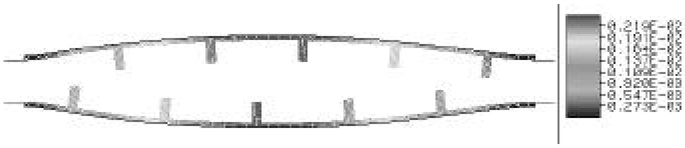

Figure 2. Nodal displacement of the cystic duct structure from CSD simulation (legend unit in m).

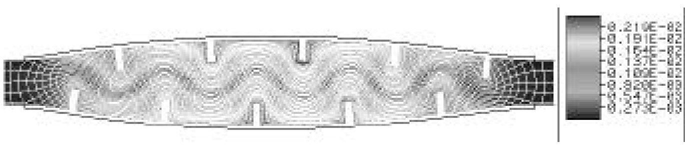

Figure 3. Nodal displacement from CMD remeshing scheme (legend unit in m).

In the rigid duct simulations [4], the bile has to flow through a corrugated path due to the staggered baffles. From the present FSI simulations, the duct experiences maximum expansion at the middle section and hence the main flow may be expected to follow a relatively straight path. Although the two ends of the duct were constraint, the duct is still expected to expand less at the outlet region due to lower fluid pressure there. Smaller local duct dimension there also will lead to higher fluid velocity and this is evident from the results shown in Figure 4. It can be seen from the stream function plot in Figure 5 that little fluid is trapped in the re-circulating regions as most of the bile flows through the gap between the baffle tips ducts. It was found that the resistance, R_n (also the relative resistance, R_d) of the FSI model is about 2.5 times smaller than that of rigid ducts (for Re = 30).

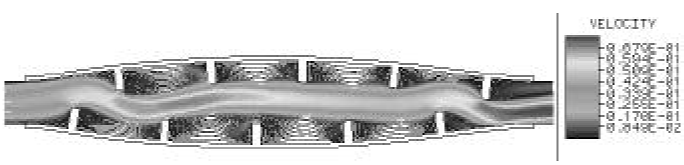

Figure 4. Velocity vector plot from CFD solution (legend unit in ms^{-1}).

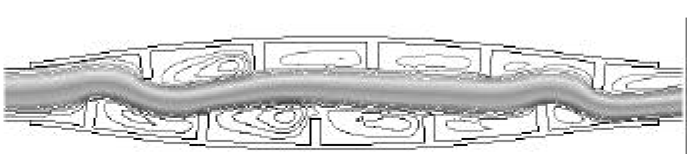

Figure 5. Stream function plot of bile flow.

SUMMARY

Numerical simulation of the human cystic duct shows that the flow resistance increases with complexity of the duct geometry [4]. These models may only approximate the case when the duct muscle in under relatively strong tone (i.e. suffers no further deformation with bile flow). The FSI model with deformable duct shows less resistance for the same geometry and Reynolds number due to the expansion of the duct. Further development of a more representative FSI model will provide promising understanding of the complex dynamical behaviour of the flow in the biliary system. Further work will include *in vivo* and *in vitro* study of the GB motility and the biliary system.

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