Journal of Engineering Science and Technology
Vol. 1, No. 1 (2006) 1-9

CYSTIC DUCT VISUAL-BASED EVALUATION OF GALLSTONES FORMATION RISK FACTORS

MUSHTAK AL-ATABI[1], S.B. CHIN[2], X.Y. LUO[3]

[1]School of Engineering, Taylor's College
No 1 Jalan SS15/8, 47500 Selangor, Malaysia
Email: mushtak.t@taylors.edu.my

[2] Department of Mechanical Engineering
University of Sheffield, Sheffield S1 3JD, South Yorkshire, UK

[3]Department of Mathematics, University of Glasgow
University Gardens, Glasgow G12 8QW, UK

Abstract

Gallstones are commonly related to the super-saturation of bile with cholesterol in the presence of nucleating agents. Clinical evidence show that gallstones are frequent in healthy persons with complex cystic ducts geometry, an indication that fluid mechanics of the bile flow may play a role in the formation of gallstones. In order to evaluate this role, correlations between idealized cystic duct geometry and the pressure drop across it have been determined both experimentally and numerically simulated with Computational Fluid Dynamics (CFD) technique.

This work presented here forms part of a larger project to understand the functions of the human cystic duct, especially the influence of its various anatomical structures on the resistance to bile flow, to provide insight into the pathogenesis of gallstone formation and the origins of biliary pain. This eventually will lead to the development of a vision based risk factors system to aid the medical consultants to assess the likelihood of a person developing gallstone.

Keywords: Gallstones, Cystic duct, Simulations, CFD, Smart systems.

Nomenclatures

b	Distance between successive baffles [m]
C_P	Pressure coefficient
D	Duct diameter [m]
Re	Reynolds number
V	Average flow velocity in the unobstructed duct [m/s]
Greek Symbols	
ΔP	Pressure drop across the baffle section [N/m^2]
ρ	Density of water[kg/m^3]
μ	Viscosity of water [Pa.s]

1. Introduction

The human biliary system consists of an organ and duct system that creates, transports, stores, and releases bile into the duodenum to aid digestion of fats. The anatomy comprises the liver, gallbladder, and biliary tract (cystic duct, hepatic duct and common bile duct), Fig 1. The most common biliary diseases are cholelithiasis and cholecystitis. Cholecystectomy is the most commonly performed abdominal operation in developed and developing countries. The three essential factors in the pathophysiological genesis of cholelithiasis are believed to be:

1. Super-saturation of bile with cholesterol.
2. Presence of calculi nucleating agents.
3. Reduction in gallbladder motility.

Holzbach et al. [1] showed that supersaturated bile (Factors 1 and 2) frequently exist in healthy people and so research began to focus on the efficiency of the bile transport mechanisms (Factor 3). The gallbladder differs from other hollow organs in only having a single conduit (the cystic duct) for filling and emptying. Recent investigations have pointed out that cholelithiasis is related to abnormal cystic duct configurations. Deenitchin et al. [2] showed that, statistically, subjects with gallstones had longer or narrower cystic ducts than those without. Patients with Cystic Duct Syndrome (non-calculus partial obstruction) have also been found to have a low gallbladder ejection fraction [3]. These studies suggest a link between complex cystic duct anatomy and prolonged retention of bile in gallbladder. It is generally accepted that prolonged stasis of bile in the gallbladder is a significant contributing factor to gallstone formation [1]. This suggests that the fluid mechanics, in particular the relationship between cystic duct geometries and resistance to bile flow, of the biliary system may play an important role in gallstone formation.

Ooi et al [4, 5], employing numerical simulation, and Al-Atabi et al [6] through measurement, showed a direct relationship between the complexity of the cystic duct anatomy and the pressure drop across idealised cystic ducts. Both demonstrated clearly that the greater the complexity of the cystic duct geometry, the greater the pressure drops.

The overall aim of the project is to establish a smart detection system that generates decision-making data to support the specialist in prescribing preventative measures to patients at risk to gallstone. It is envisaged that the smart system will also incorporate Factors 1 and 2 described in the Introduction. The work reported here will only concern the effects of the flow of bile

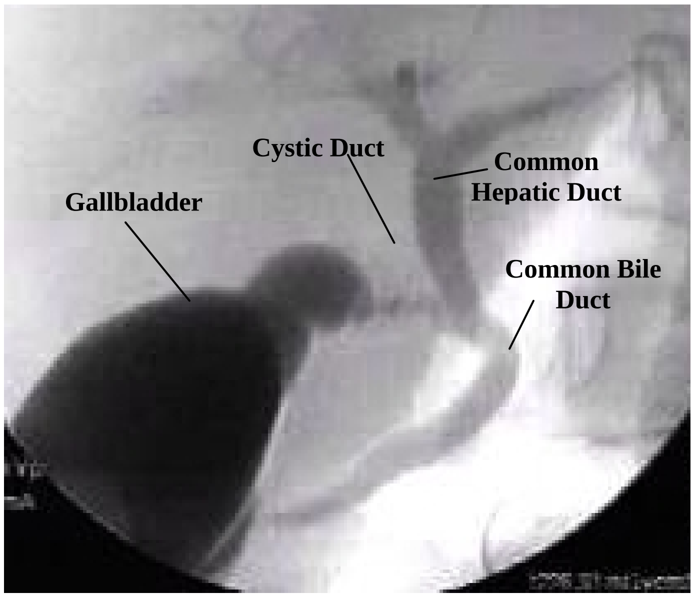


Fig.1. Human biliary system [5]

2. Approach and Methods

An essential component of the smart system is a database comprising the geometry of the cystic duct and its associated pressure drop. The anatomy of the biliary system may be obtained from scanning, e.g. MRI, CT scans. The pressure drop may be calculated from CFD simulations and validated by selected experiment. Hence the images need to be translated into other formats, e.g. ASCI files for CFD simulations, stereolithographic (STL) files for rapid prototyping of model for experiments. The rheological properties of human bile and the mechanical properties of the gallbladder are currently being measured and classified [8].

For idealised cystic ducts, Ooi et al [5] and Al-Atabi et al [6] have identified the clearance ratio (c/D) and baffles spacing (b/D), shown schematically in Fig. 2, as the significant anatomical parameters of the cystic duct geometry contributing to increasing pressure drop, hence resistance to the flow of bile. Patients with a high resistance cystic duct may face a greater risk of forming gallstones, by facilitating stasis of gallbladder bile.

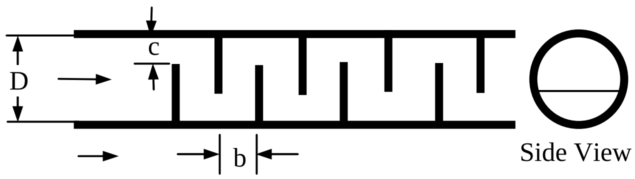


Fig.2. Idealised cystic duct geometry

2.1 Algorithm Structure

Figures 3 and 4 show the block diagrams of the proposed procedure that utilizes the correlations between cystic anatomy and the prognosis of gallstone formation to supply the medical practitioners with useful data that shall assist them in the decision making process.

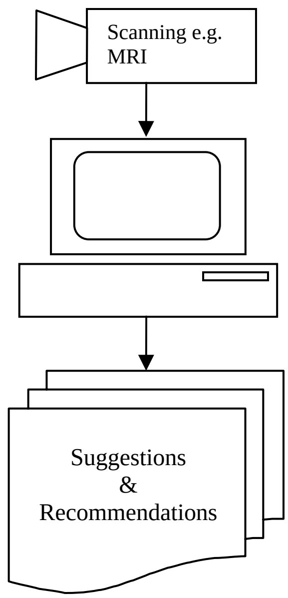


Fig.3. Block diagram of the proposed procedures

The abdominal scanned images are converted into electronic files (e.g. ASCI). These files are then compared with the data compiled over time from the patients' and idealized geometries. In the event that an image is unavailable in the library data, the images is translated into a CFD software readable file in order to estimate the cystic duct resistance. Based on that, suggestions are made by the smart system to enable the doctors to make the right decision. This is shown schematically in Fig. 4.

3. Results and Discussion

To establish the relationship between the cystic duct geometry and the bile flow resistance, a series of experimental and CFD test (using FLUENT^{TM}) were performed using the idealized geometry shown in Fig. 2.

The experimental rig comprises a 40-liter storage tank supplying water to a changeable 21mm diameter transparent plastic tube test section through a bell-mouth. Since measured viscosity of healthy bile is close to that of water [7], reversed osmosis (RO) drinking water was used as the test fluid. The flow of water in the test section was controlled by two needle valves. An inclined manometer was connected to pressure tappings upstream and downstream of the test section to measure the pressure drop. This is shown schematically in Fig. 5.

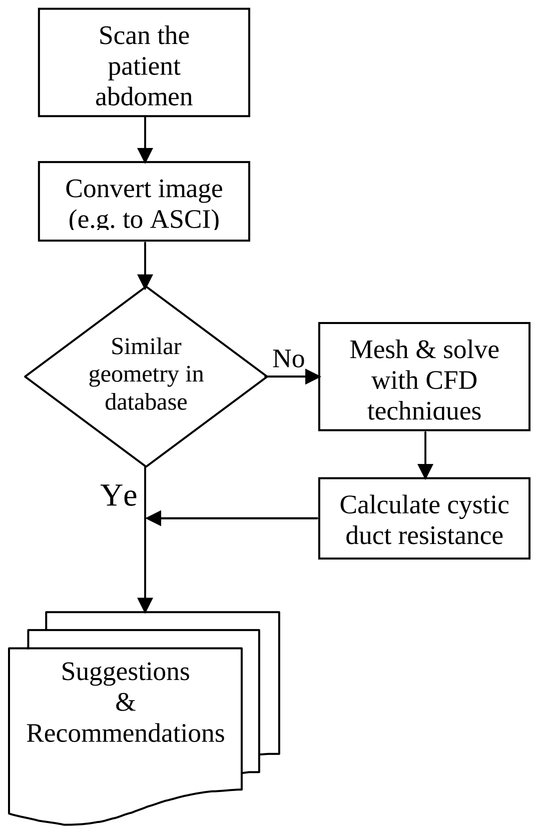
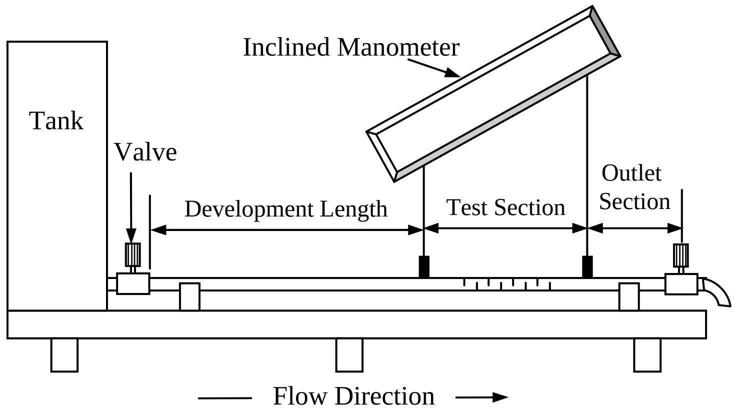


Fig.4. Flow chart of the proposed procedures



Development Length = 0.75 m
Test Section = 0.286 m
Outlet Section = 0.2 m

Fig.5. Schematic diagram of the experimental apparatus

Figure 6 shows the comparison between the measured and the CFD simulated relationship between the Euler number (Cp) and the Reynolds Number (Re) given by Eqs. 1 and 2, respectively. Euler number represents the flow resistance in the cystic duct, whilst Reynolds number describes the flow condition.

It is also noted that a sail with a significant camber at the root is likely to have root separations from the undersurface of very small wing incidences because the angle between the local flow direction and the chord of the sails can be too large and negative. In this case the drag of the sail would be significantly increased. As wing incidence increased the root flow would attach to the undersurface and the drag would decrease. This behavior is clear in Fig. 4 which shows the effect of the number of sails on the drag reduction. It's obvious that after recovery from sails' undersurface separation addition of more sails reduces the drag coefficient.

For a given clearance ratio, c/D, the Euler number decreases with increasing Reynolds number. The Euler number also increases with decreasing clearance ratio. The model with c/D = 0.3 has always higher Cp compared to those for c/D = 0.5 and c/D = 0.7.

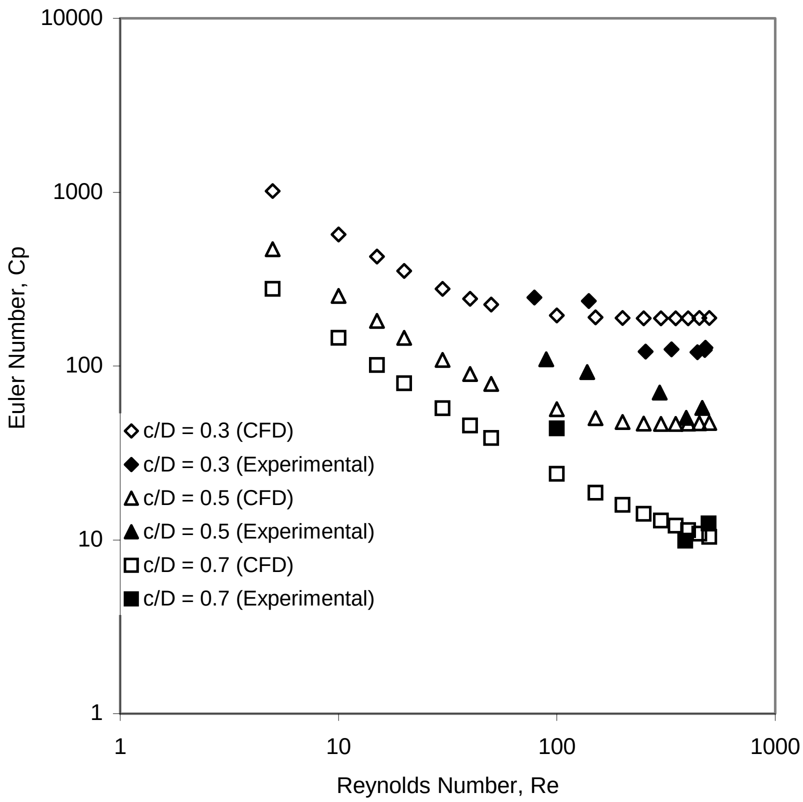


Fig. 6. Relationship between Euler number and Reynolds Number

$$Cp = \frac{\Delta p}{\frac{1}{2}\rho v^2} \tag{1}$$

$$\mathrm{Re} = \frac{\rho V D}{\mu} \tag{2}$$

At larger clearance ratios, the flow passage is relatively unobstructed and the flow negotiates the baffles with minimal resistance, hence the lower Cp. When the clearance ratio is reduced, the flow is forced through a series of sudden expansions and contractions leading to large recirculation downstream of the baffles which is an indication of higher pressure loss.

Good agreement between the experimental and CFD results is apparent in Fig. 6. Similar results were obtained by Ooi et al [5] working on cystic geometries obtained from clinical MRI images. Figure 7 shows a sample MRI image of the biliary system of a patient with gallstones whilst Fig. 8 the typical computational mesh generated for a CFD simulation of the flow. The pressure drop (flow resistance) across the cystic duct of a patient with gallstones is higher than that of the healthy person. Figures 7 and 8 are indicative of the correlation between the complexity of the anatomy of the cystic to tendency to gallstone.

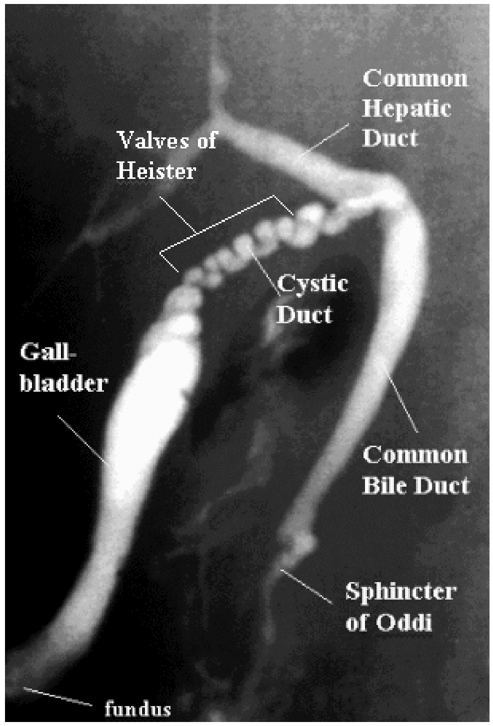


Fig.7. MRI image of biliary system of a patient with gallstones [5]

4. Conclusions

The significant parameters affecting the bile flow resistance in human cystic duct were identified and studied both experimentally and numerically. A procedure is proposed to employ medical imaging techniques and CFD techniques to compile a library of biliary system images with their flow characteristics. The smart system may be used to aid the specialist to diagnose gallstones formation in a patient and prescribe appropriate preventative measures.

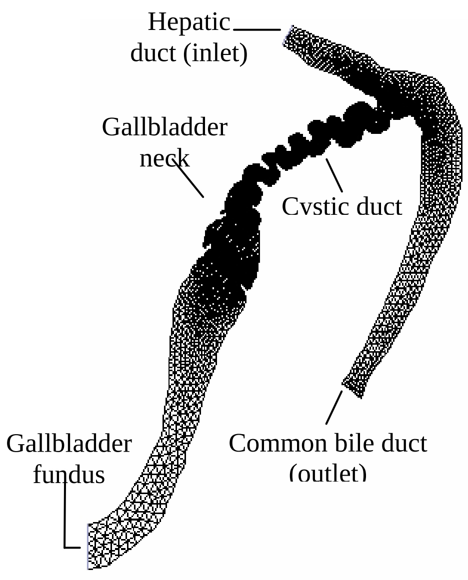


Fig.8. CFD mesh of the biliary system of a patient with gallstones (based on Figure 7) [5]

References

1. Holzbach, R.T., Marsh, M., Olszewski, M. and Holan, K. (1973). Cholesterol Solubility in Bile. Evidence that Supersaturated Bile is Frequent in Healthy Man. *Journal of Clinical Investigation*. 52, 1467-1479.
2. Deenitchin, G.P., Yoshida, J., Chijiiwa, K. and Tanaka, M. (1998). Complex Cystic Duct is Associated with Cholelithiasis. *HPB Surgery*. 11, 33-37.
3. Fink-Bennett, D., DeRidder, P., Kolozsi, W., Gordon, R. and Rapp, J. (1985). Cholecystokinin Cholescintigraphic Findings in the Cystic Duct Syndrome. *J. Nucl. Med*. 26, 1123-1128.
4. Ooi, R.C., Luo, X.Y., Chin, S.B., Johnson, A.G. and Bird, N. (2003). Fluid-Structure Interaction (F.S.I) Simulation of the Human Cystic Duct, In *Proc. of Summer Bioengineering Conference*, Florida, USA.
5. Ooi, R.C., Luo, X.Y., Chin, S.B., Johnson, A.G. and Bird. (2004). The Flow of Bile in Human Cystic Duct. *Journal of Biomechanics*. 37, 1913-1922.
6. Al-Atabi, M., Chin, S. B., and Luo, X. Y. (2004). An Experimental Study of the Flow in an Idealized Human Cystic Duct. In *Proc. First Asian Pacific Conference on Biomechanics*, Osaka, Japan.
7. Matthew, C. (2003). The Rheological Properties of Human Bile. B.Eng. Thesis, Department of Mechanical Engineering , University of Sheffield.
8. Ooi, R.C. (2004). The Flow of Bile in Human Cystic Duct. PhD Thesis, Department of Mechanical Engineering, The University of Sheffield.