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Investigation of the Flow in a Compliant Idealised Human Cystic Duct*

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Abstract

The cystic duct is a very complicated conduit that connects the gallbladder to the common bile duct. The geometry of the cystic duct and its functions, in particular the valves of Heister, in the flow of bile into and out of the gallbladder have always been a subject of speculation. It has been suggested variously that their function is to: impede the flow of bile into the gallbladder, prevent the outflow of bile from the gallbladder, or prevent the collapse of cystic duct.

Presented in this paper are the results of a novel experiment to assess the role of the valves of Heister during both the filling and the emptying phases of the gallbladder. The results suggest that the existence of these valves helps both the filling and the emptying of the gallbladder by providing structural support and preventing the duct from total collapse. A surge of pressure upstream of the cystic duct is observed prior to the opening of the cystic duct which is consistent with previous in-vivo biological observations.

Key words: Cystic Duct, Gallstones, Valves of Heister

1. Introduction

The human biliary system is responsible for creating, transporting, storing and releasing bile into the duodenum to aid digestion of fats. The biliary anatomy comprises the liver, gallbladder, and biliary tract (cystic duct, hepatic duct and common bile duct), Fig. 1. Bile is an aqueous fluid secreted by the liver into the biliary tracts. The gallbladder is unique amongst other hollow human organs in only having a single conduit (cystic duct) for both filling and emptying functions [(1)].

Clinical studies suggest that the formation of gallstones is associated with the complex geometry of the cystic duct [(2)] as it causes prolonged stasis of bile in the gallbladder, which contributes significantly to gallstone formation. Patients with cystic duct syndrome are found to have a low gallbladder ejection fraction [(3)]. Gallstone formation (cholelithiasis) and gallbladder inflammation (cholecystitis) are the most common biliary disorders. Though these conditions are rarely life threatening, they cause considerable deterioration in the quality of life in those so afflicted [(4)], and operations to remove diseased gallbladder (cholecystectomy) are the most commonly performed abdominal operations in developed countries [(5)].

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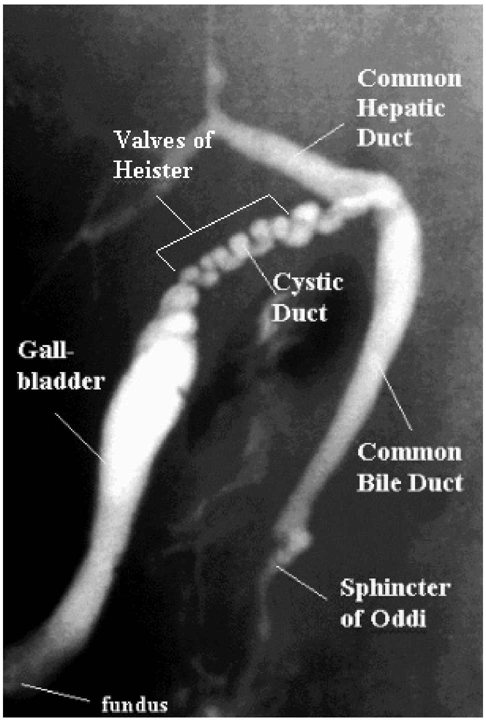

Fig. 1 Operative cholangiograms of a patient with gallstones (Image kindly provided by Department of Radiology, Royal Hallamshire Hospital, Sheffield.)

Our knowledge of the anatomy of the human cystic duct has mostly been derived from dissection of the duct at post-mortem stage or after surgical removal of gallbladder and cystic duct. The geometry of the cystic duct is complex and varies from one individual to another. The cystic duct diameter and length range from 2 to 5 mm and 10 to 60 mm, respectively [(6, 7)]. Heister [(8)] described the presence of folds in the cystic duct, later termed "Valves of Heister". The number of these valves can vary from 2 to 14. Gray and Lewis [(9)] reported that the mucosal folds project into the lumen in the form of oblique ridges or crescentic folds, presenting the appearance of a continuous spiral valve. Mentzer [(10)] had observed what he called "leaflets" in the lumen of the duct after incising it longitudinally. He went on to describe instances where several "leaflets" joined to form spiral "valves," a description also used by Lichtenstein and Ivy [(11)].

Recently, Bird et al [(12)] obtained resin casts of the lumen of 37 samples of cystic duct. In 29 of these, the length of cystic duct cast was sufficient to allow a morphological description and measurements to be made. The tissue samples used for the casting process were collected from patients undergoing cholecystectomy and partial hepatectomy. A sample of their work is shown in Fig. 2. Winding was the term used to describe a sinusoidal course with no apparent rotational component. The "spiral valves" originate in the gallbladder neck and appear to be small indentations on the funneling neck. The casts showed that cystic duct lumen possess spiral, corrugated and kinked structures with a diameter as small as 0.5mm and a number of Heister valves as high as 11. Based on these investigations, the cystic duct can generally be viewed as a winding (or kinked) conduit with internal protruding tissue similar to baffle plates.

The functions of the cystic duct and the role of its complicated geometry, and in particular the valves of Heister, in the flow of bile into and out of the gallbladder have always been a subject of speculation. Mann [(13)] suggested that their function is to impede the inflow of bile into the gallbladder, other researchers have suggested that they impede [(14)] or prevent [15] the outflow of bile from the gallbladder. Keith [16] has suggested that they keep the cystic duct open.

The investigation of the physiological function of the cystic duct continued throughout the twentieth century [17, 18, 19]. Although it was discovered that the resistance of the cystic duct is a significant factor affecting flow within the biliary system, these studies offered no description of flow within the duct and no firm conclusions regarding the true purpose of the valves of Heister [6].

This work aims at understanding the role of the valves of Heister during the bile transportation process. This is done using idealised compliant models of the cystic duct with and without idealised valves of Heister.

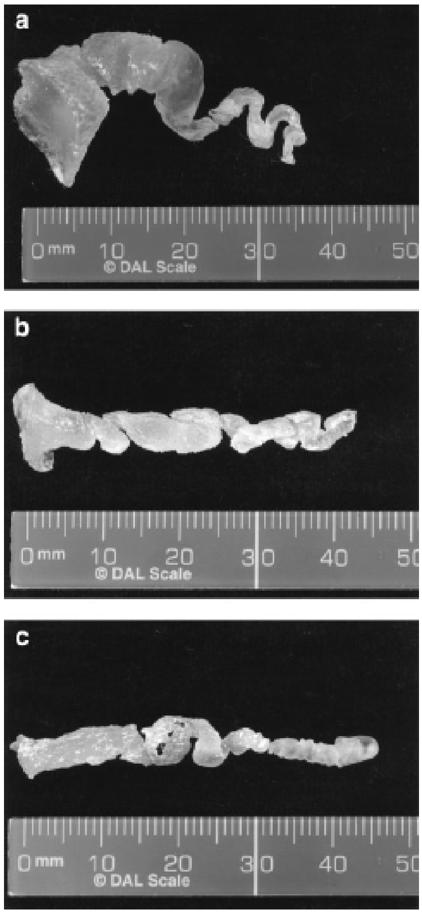

Fig. 2 Examples of acrylic casts (a) Neck and tortuous proximal cystic duct, (b) M-shaped loop followed by spiral course, and (c) Elongated cystic duct containing a small pigment stone [12].

2. Materials and Methods

2.1. Idealised Cystic Duct Model

A representative cystic duct can be depicted as a winding, kinked or spiral flexible tube that contains folds (baffles) at the lumen side "valves of Heister". Although other geometrical features may be present in different cystic ducts, the valves of Heister and the windings are the most prominent features. The existence of the baffles has been confirmed by examining cystic ducts after surgical removal of the gallbladder and the cystic duct, where the kinked/spiral duct can be extended straight, yet the existence of the internal baffle still prevents a thin metal tube from passing through the extended cystic duct.

The compliant idealised cystic ducts used in this study are modelled using flexible latex Penrose tube of 13 mm interior diameter and length of 46 cm (Sherwood Medical, Tullamore, Ireland). To understand the effects of the valves of Heister, two models were built for comparison, one with valves of Heister and one without. The valves of Heister were represented by eight semi-circular baffles made of 2 mm thick rubber sheet located at regular alternating intervals within the tubing. Eight baffles were used as this was the average number of baffles encountered in different cystic ducts while the thickness of the baffle was selected to make it strong enough not to deform without being rigid and thin enough to prevent flow from developing. The winding of the tubes were represented by right angle bends of the tube for easy set up and repetition of the experiment.

The semi-circular baffles were cut out of rubber using a metal punch. The flexible tube is then turned inside out and the baffles are glued to the exposed interior one by one. This tube is shaped into the structure shown in Fig.3 and placed in the hydraulic rig for testing.

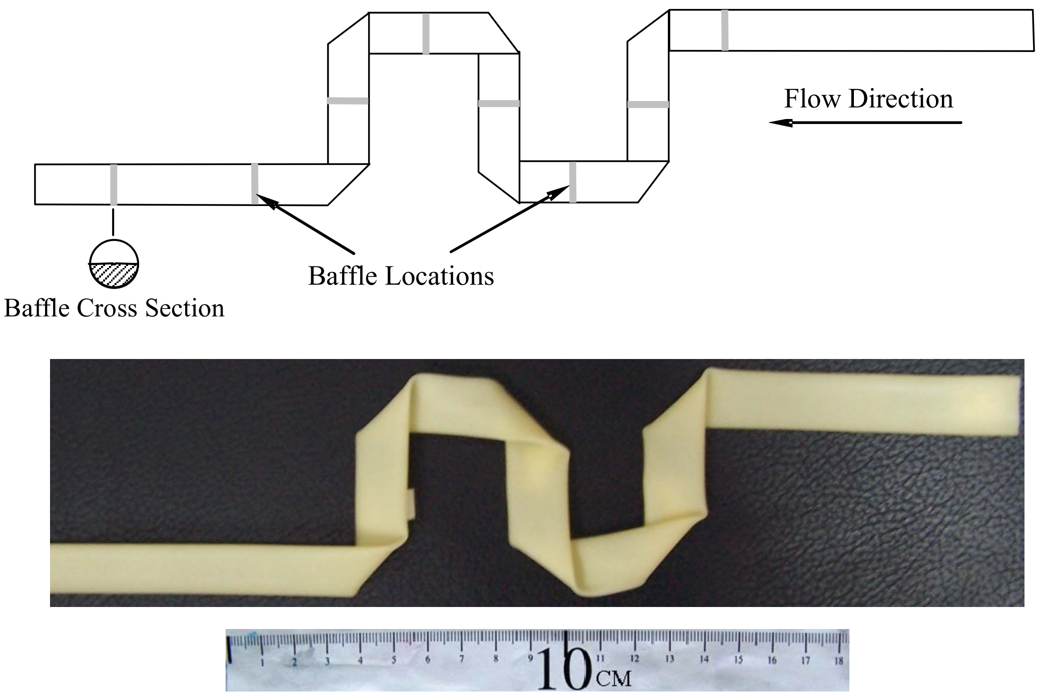

Fig. 3 Collapsed idealised compliant cystic duct model.

2.2. Working Fluid

Although a literature search reveals that there are few convincing rheological data on human bile, preliminary measurements of fresh bile [20] suggest that for a healthy person without gallstones, the gallbladder and hepatic bile is a Newtonian fluid with a constant viscosity of about 1 mPa s and a density of nearly 1000 kg m^{-3}. Since these values are close to those for water, filtered water was used as the test fluid in this study.

2.3. Experimental Rig

The experimental rig used in this study is shown schematically in Fig. 4. It comprises, from the entrance of the water, a filter, followed by a 40-litre elevated reservoir fitted with a float and anti-splashing overflow to maintain a constant head supply. The water discharges, under the effect of gravity, from the reservoir through a bell-mouthed (well-rounded) inlet to a flexible hose that delivers it to a vertical transparent tube. The flow out of the tank is controlled by a needle valve and the flexible hose extends all the way to the bottom of the vertical transparent tube to minimise the pressure fluctuations in the test section. The vertical transparent tube acts both as a variable height water reservoir and a water manometer to measure the gallbladder pressure. The exit of this vertical tube is fitted with a 90^{o} elbow that connects to the inlet of the flexible tubing (cystic duct model) which has its outlet opening to a drain at atmospheric pressure.

2.4. Experimental Procedures

With the cystic duct model in a collapsed state initially, water at a constant flow rate is allowed to flow into the vertical tube (reservoir). If the rate of flow leaving the cystic duct model is less than that entering the vertical reservoir, the level of water in the vertical reservoir keeps on rising until it reaches a level that can no longer be supported by the resistance of the cystic duct, thus forcing the cystic duct to open causing the water level to rapidly drop. This is when the cystic duct is deemed open and the maximum height of water represent the opening pressure. This procedure simulates the emptying phase of the gallbladder, where the pressure build-up upstream of the cystic duct model simulates the gallbladder contraction.

The experimental procedures involve recording the time needed to reach the opening pressure, the opening pressure itself and the constant pressure drop after achieving the cystic duct opening. This is repeated for kinked tubing with and without baffles. If the rate of flow entering the reservoir is too small, it will not force the inflation of the collapsed duct and a steady state is reached when this flow equals the flow leaving the cystic duct mode. The height of water in the reservoir represents the pressure drop due to the duct resistance and this case simulates the filling stage of the gallbladder.

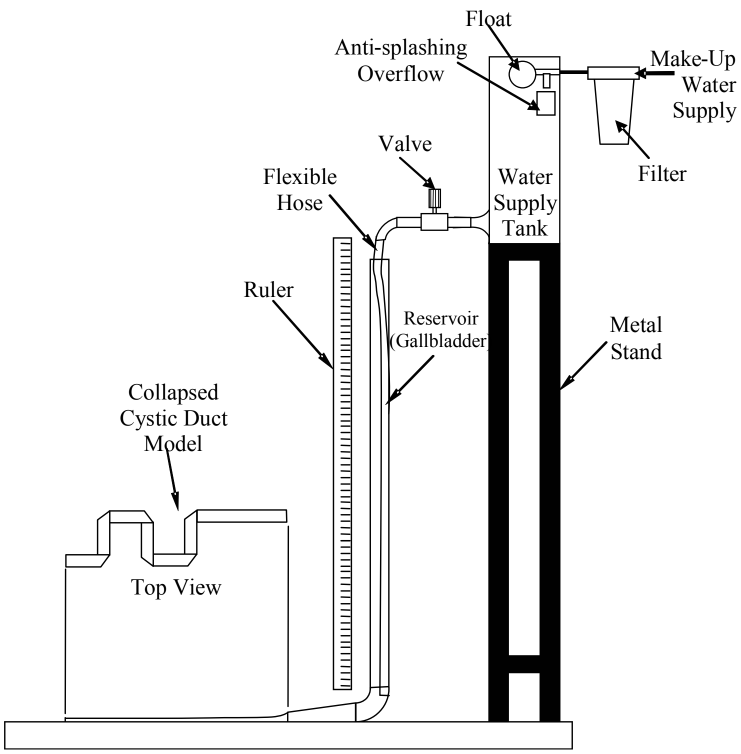

Fig. 4 Experimental set-up to study the compliant cystic duct models.

3. Results and Discussion

To shed some light on the behaviour of the compliant cystic duct under different flow scenarios, two (initially collapsed) compliant tubes are arranged in kinked position to represent the compliant cystic duct models; one of them is fitted with eight alternating baffles (representing the valves of Heister) while the other has no baffles. The term “valve of Heister” is suggestive of its function as a flow controlling device. The compliant cystic duct models described earlier were constructed in an attempt to explore this possibility. These two models are each connected to the vertical reservoir, one at a time and tested as described above. The results from these experiments to show the behaviour of these kinked tubes are summarised in the graph shown in Fig. 5.

The experiments were conducted with two constant flow rates into the vertical reservoir. The first, the smaller flow rate (corresponding to a steady flow at a Reynolds number of 10 based on the inflated tube diameter) was employed to test the behaviour of kinked tubes with and without baffles. Figure 5 shows the pressure at the reservoir as a function of time until water flowed steadily through the (initially collapsed) models. The solid and empty triangles in Fig. 5 represent the model with no baffle and the one with, respectively. The collapsed kinked tube with no baffles appears to resist opening up until the water level in the vertical reservoir reached an average of 17 cm high. The tube with baffles allowed steady flow to be established through it at just 5 cm of water in the vertical reservoir, about one third of that with no baffles.

This scenario is akin to the filling phase of the gallbladder where a small flow rate from the hepatic bile duct, supported by small pressure difference, needs to negotiate the cystic duct resistance. Although in a rigid flow model, the presence of baffles impedes the flow, the baffles in a compliant collapsed model seem to assist the flow and make it possible.

The second part of the experiment involved a bigger flow rate (corresponding to a Reynolds number of 200 based on the inflated tube diameter) to simulate the gallbladder emptying. Figure 5 shows that both the kinked tubes with or without baffles behaved similarly. Water level in the vertical reservoir initially rose until a critical pressure is reached, then the collapsed tubes were forced open and steady flow eventually prevailed through the tubes. The kinked tubes with baffles required a much lower critical pressure for flow to commence through the tubes; this pressure was just over half of that required for the kinked tubes without baffles.

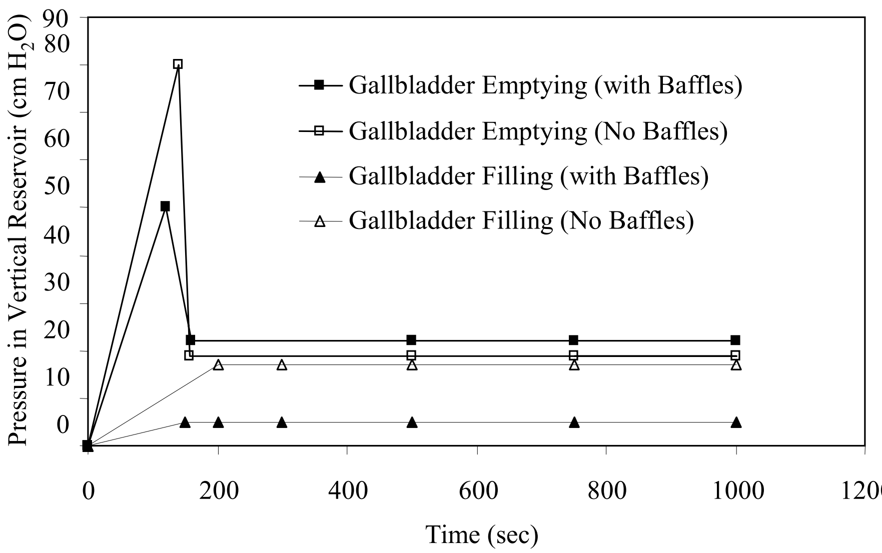

Fig. 5 Vertical reservoir pressure as a function of time.

Despite the simplicity of this experiment and the uncertainty on the material properties of the model compliant tube, the results in Fig. 5 show that the baffles reduces the threshold pressure required to effect flow through the initially collapsed tubing significantly from the tubes without baffles. The results suggest that the valves of Heister may act as a passive flow controlling device and aid the flow of bile to and from the gallbladder. The baffles (or valves of Heister) prevent the total collapse of the tube and hence a smaller threshold pressure is needed for flow to commence. It is interesting to compare the results of this study to those reported by Majeed et al [21], Fig. 6, which is a sample of in vivo pressure reading form a patient's gallbladder in real time before and after the administration of Cholecystokinin (CCK-8) hormone which when released into the blood supplying the biliary system to stimulates gallbladder contraction and relaxes the sphincter of Oddi.

After injecting the CCK-8 hormone the gallbladder pressure rose to about 40 cm H_2O. This is comparable to the average opening pressure of the compliant cystic duct model with baffles of about 50 cm H_2O in Fig. 5. Similarly it can be seen that the gallbladder pressure prior to the injection of CCK is about 20 cm H_2O which is similar to the steady state gallbladder pressure for the emptying stage described in this study. This gives some credence to both the results reported here and to the conclusion that the baffles prevent the total collapse of the cystic duct facilitating the flow of bile both during the gallbladder filling and emptying. However, when comparing the results of Figs. 5 and 6, it should be noted that the pressure indicated on the y-axis of Fig. 5 represents the pressure drop across the cystic duct with one end opened to the atmosphere while the y-axis of Fig. 6 reads only the pressure in the gallbladder with the other end of the cystic duct opens to the common bile duct which may be at a pressure higher than the atmospheric.

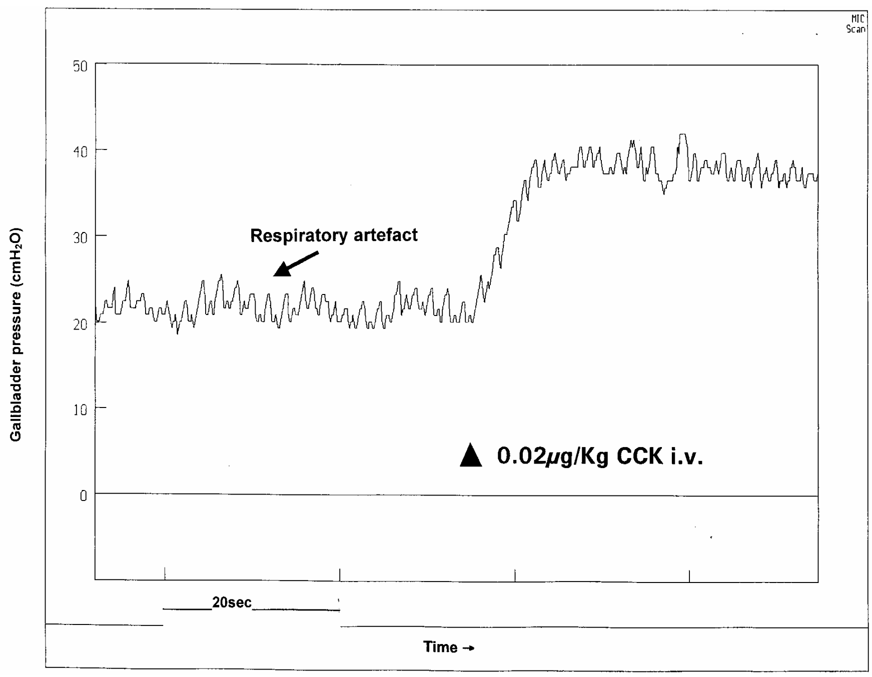

Fig. 6 Sample gallbladder pressure profile before and after 0.02 μg/kg i.v. CCK-8 [21].

4. Conclusions

A novel experiment was conducted to investigate the functions of the valves of Heister in the human cystic duct. This involved testing idealised compliant cystic duct models with and without valves of Heister for comparison. The behaviour of the idealised compliant cystic duct models encountered supports the hypothesis that the valves of Heister provide structural support preventing the total collapse of the cystic duct and providing passive control to the flow. The presence of the valves (represented by the baffles) allows for the emptying of bile from the gallbladder to commence at a lower opening pressure than a duct without baffles. This reduced opening pressure may aid the gallbladder in emptying and prevent the prolonged stasis of bile, which in turn may reduce the likelihood of gallstone formation. During the filling phase, the bile flow rate from the liver to the gallbladder is small; the baffles then also help to prevent the cystic duct from total collapse to enable the filling process to be conducted more easily.

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