

Tortuosity of the Residual Cystic Duct is an Independent Risk Factor for Common Bile Duct Stones After Cholecystectomy: A Case-Control and Computational Study

Xiaoyu Zhang^{1, †}, Zhike Xu^{2, †}, Zijie Lin¹, Ziyue Chang¹, Lijin Zhang¹, Wenping Lu^{1, *}

¹Faculty of Hepato-Pancreato-Biliary Surgery, Chinese PLA General Hospital, Beijing, China

²Department of Engineering Mechanics, Tsinghua University, Beijing, China

Email address:

xxy180520@163.com (Xiaoyu Zhang), xzk21@mails.tsinghua.edu.cn (Zhike Xu), calvinkk23@163.com (Zijie Lin), changziyue2024@163.com (Ziyue Chang), lijinzku@163.com (Lijin Zhang), luwenping301@163.com (Wenping Lu)

† Xiaoyu Zhang and Zhike Xu are co-first authors.

*Corresponding author

Abstract

Background & objective: Recurrent common bile duct (CBD) stones after cholecystectomy represent a significant clinical challenge, while the mechanism remains poorly understood. This study aimed to identify geometric characteristics of the bile duct associated with post-cholecystectomy CBD stones, elucidate and validate underlying mechanisms using computational fluid dynamics (CFD) and microfluidic experiments. **Methods:** This retrospective study enrolled 93 patients with post-cholecystectomy CBD stones and 81 without. Geometric parameters of the residual cystic duct (RCD), common hepatic duct (CHD), and CBD were measured on 3D reconstructions. Clinical data and biliary geometry were integrated into univariate and multivariate logistic regression analyses to identify independent risk factors. CFD with discrete phase model (DPM) was employed to observe bile flow and crystal behavior. Microfluidic chips were used to observe crystal aggregation in vitro. **Results:** Multivariate analysis identified RCD tortuosity, maximum RCD diameter, history of ERCP, and CBD angle as independent risk factors for post-cholecystectomy CBD stones. CFD simulations revealed that tortuous RCD geometry induced complex vortex structures and flow stagnation within the blind stump, leading to prolonged particle retention and reduced washout efficiency. Microfluidic experiments demonstrated that crystal aggregation was most pronounced in long and curved channels. **Conclusion:** RCD tortuosity is an independent risk factor for post-cholecystectomy CBD stones. The underlying mechanism involves disturbed bile flow dynamics within the tortuous blind stump, promoting crystal retention and aggregation. These findings provide a rationale for optimizing cholecystectomy procedure about the cystic duct stump, potentially reducing the incidence of postoperative CBD stones.

Keywords

Recurrent Cholangiolithiasis, Magnetic Resonance Cholangiopancreatography, Computed Fluid Dynamic, Discrete Phase Model, Microfluidic