Pancreatic Duct Flows for a Novel Non-invasive Diagnosis of Chronic Pancreatitis

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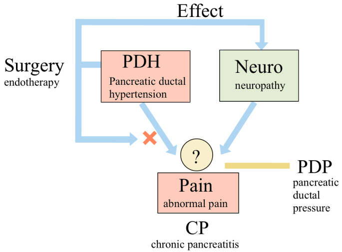
Introduction

Chronic pancreatitis (CP) which results in debilitating abdominal pain can be caused by pancreatic ductal (PD) hypertension (PDH) or from neuropathy.

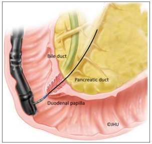


Surgery could relieve PDH, but will effect neuropathic pancreatitis.

Need to measure pancreatic ductal pressure (PDP) to limit endotherapy to patients have PDH

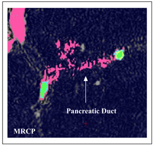
PDP measurements:

Traditional Way: ERCP



- **Invasive procedures**
- Costly
- Significant health risks

New Method: MRCP

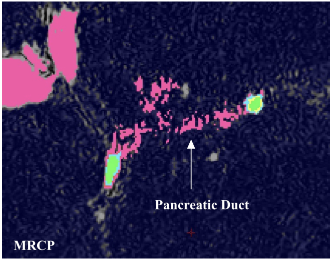


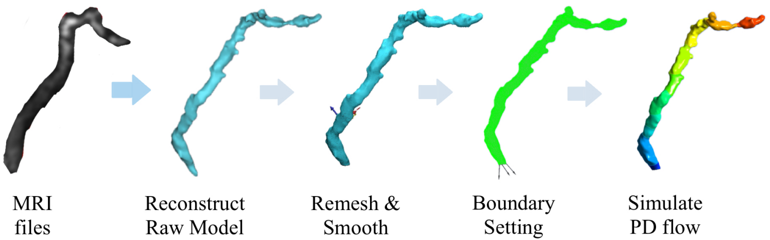
- **Non-invasive approach**
- Improve diagnostic accuracy
- Reduce patient exposure to harmful procedures

Pipeline: From MRI to CFD Simulation

In order to investigate the correlation between PD pressure and abdominal pain, patient-specific image-based CFD analysis of PD flows has been performed.

- 3D model of the PD is reconstructed from: magnetic resonance cholangiopancreatography (MRCP)
- Simulation is performed to determine the flow pattern and measure the pressure drop across the duct.





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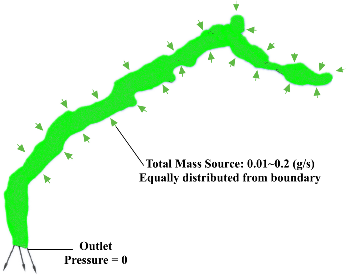
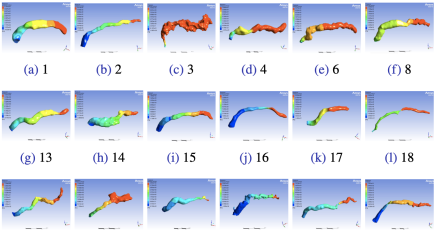
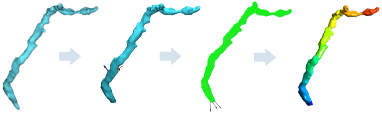




(a) 1 (b) 2 (c) 3 (d) 4 (e) 6 (f) 8

(g) 13 (h) 14 (i) 15 (j) 16 (k) 17 (l) 18

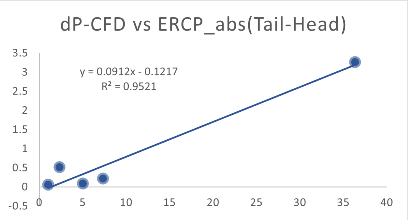
(m) 19 (n) 20 (o) 21 (p) 24 (q) 26 (r) 27



Result: Compare Wirh Clinical Data

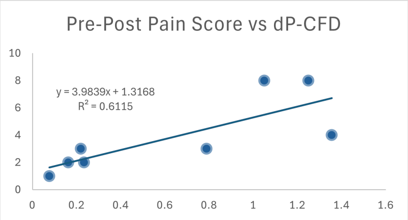
Correlation of ERCP Pressure Drop (clinical data) and CFD Pressure Drop ($R^2 = 0.95$):

Q	Tail-Head	0.1
1	1	0.0488
2	2	0.55
4	4	2.21
6	6	0.317
8	8	0.117



Correlation of Pre-Post Pain Score (clinical data) and CFD Pressure Drop ($R^2 = 0.61$):

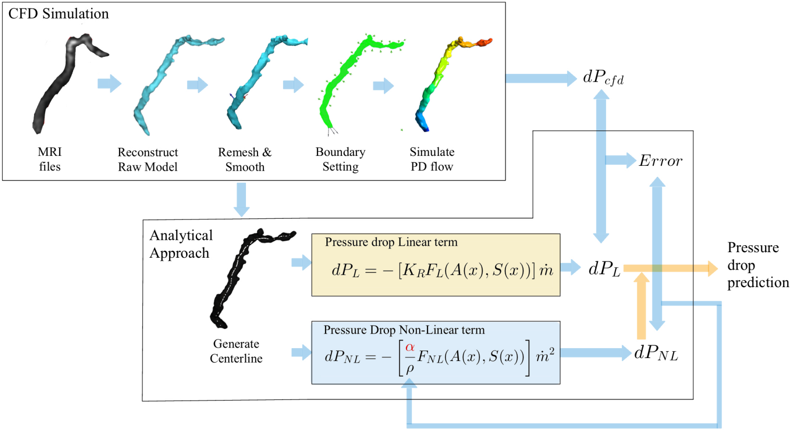
ID	Pain Score	dP_{cfd} ($\dot{M} = 0.1\, g/s$)
2	8	1.05
6	4	1.355
45	2	0.234
50	2	0.163
58	3	0.789
61	8	1.25
69	1	0.077
70	3	0.219



Now we have build up **patient-specific pipeline** for Pressure measurement, compared to ERCP and Pain score in limited cases, we have verified the **effectiveness** of CFD pressure prediction based on MRI.

Analytical Approach: Road Map For Pressure Prediction

However, CFD simulation require high-computational resources,



So we developed analytical approach using CFD and ERCP result for limited cases, and applying machine learning algorithm to performe pressure prediction in clinical environment.

Formula:

$$\begin{cases} \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = V_{gm} \\ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\alpha \frac{Q^2}{A}\right) + \frac{A}{\rho}\frac{\partial P}{\partial x} + K_R \frac{Q}{A} = 0 \end{cases} \Rightarrow \begin{cases} \rho Q = \int_x \Delta \dot{M} dx \\ P = -\int_x [K_R \frac{\rho Q}{A^2} + \frac{\rho}{A}\frac{\partial}{\partial x}(\alpha \frac{Q^2}{A})] dx \end{cases}$$

We could separate calculate the linear and non-linear part:

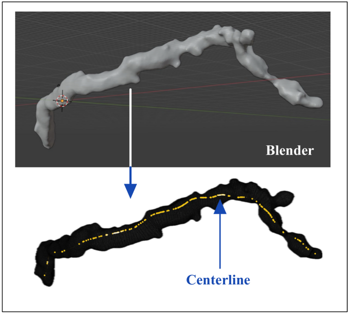
$$P = -k_R \dot{m} \left[\int_{x_0}^{xmax} \frac{1}{A^2}\left(\int_{x_0}^{x} dS\right) dx\right] - \frac{\alpha}{\rho}\dot{m}^2 \left[\int_{x_0}^{xmax} \frac{2}{A^2}\Delta S(x)\left(\int_{x_0}^{x} dS\right) dx - \int_{x_0}^{xmax} \frac{1}{A^3}\left(\int_{x_0}^{x} dS\right)^2 \frac{dA}{dx} dx\right] \quad (1)$$

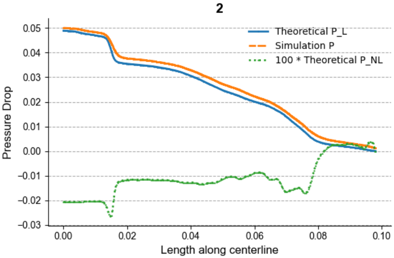
- K_R is resistance parameter.
  Consider Poiseuille flow, $K_R = 8\pi\nu = 8\pi\frac{\mu}{\rho}$. For water, $\mu = 8.9 \times 10^{-4}$ (Pa · s)
- $\dot{M}_T$ (kg/s) is the **total mass source**, means the total mass flow in rate of surface.
- S_T (m^2) is the total surface area of the duct
- $\dot{m}$ ($kg/(s \cdot m^2)$) is $\frac{\dot{M}_T}{S_T}$, which is the mass source per unit area
- $\Delta S(x)$ (m^2) is the round surface area for each segment of the centerline.
- $A(x)$ (m^2) is the cross-sectional area of the duct

$$P = -[\frac{\alpha}{\rho}F_{NL}(A(x), S(x))]\dot{m}^2 - [K_R F_L(A(x), S(x))]\dot{m} \quad (2)$$

In this equation, as we could obtain A(x), S(x) as pancreatic duct shape parameters, we could obtain the coefficient of $\dot{m}$ for each duct.

Analytical Approach: Compare with CFD Data





Analytical Solution:

$$P = -\left[\frac{\alpha}{\rho} F_{NL}(A(x), S(x))\right] \dot{m}^2 - [K_R F_L(A(x), S(x))]\, \dot{m}$$

Correlation of pressure drop linear part with CFD result:

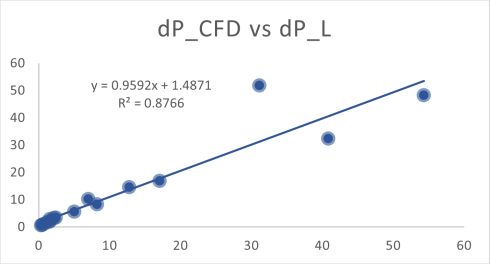


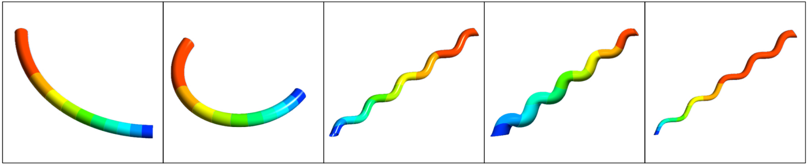
Figure: dP_{CFD} correlation with dP_L among 17 cases

dP	1	2	4	6	8	13	14	15	16	17	18	19	20	21	24	26	27
0.01	20%	2%	5%	1%	25%	15%	39%	11%	-43%	35%	-35%	24%	16%	-9%	22%	-13%	-2%
0.05	27%	6%	25%	21%	32%	20%	43%	14%	-35%	42%	-23%	26%	24%	-5%	27%	-7%	5%
0.1	33%	11%	40%	35%	38%	26%	46%	18%	-26%	48%	-13%	31%	31%	0%	31%	-1%	13%

Table: Origional Error of Theoretical Result

Analytical Approach: Curvecture Effect

As the curvature of the PD varies across locations and differs for each case, we also discussed the curvature results derived from the analytical approach:



$\dot{M}$	**90-degree-pipe**	**180-degree-pipe**	**sin-curved-pipe**	**sin-dilation-pipe**	**sin-structure-pipe**
0.01	12%	2%	-7%	-14%	7%
0.05	6%	-2%	-12%	-17%	-2%
0.1	0%	-8%	-18%	-20%	-12%
0.2	-11%	-18%	-29%	-28%	-28%

We observed that the Sin-dilation pipe exhibits the largest error among different mass sources.

Which may suggest that, in **low-pressure drop scenarios, curvature could have a greater i nfluence** on the error in the analytical approach.

Analytical Approach: Road Map For Pressure Prediction

As we already have PD strcuture parameters, linear and non-linear term dP result, and CFD dP result, next phase is to deploy PINN to obtain pressure drop prediction:

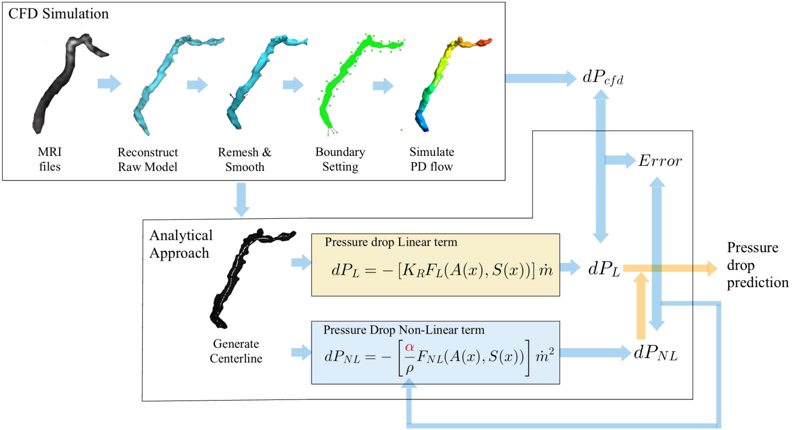


Figure: Road map for pressure prediction
Blue arrow: internal calculation and α iteration
Orange arrow: Obtain Prediction

Speaker Info

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I am a master's student focusing on Computational Fluid Dynamics (CFD) combined with biofluid mechanics at Johns Hopkins University, under the guidance of Dr. Rajat Mittal and Dr. Jung-Hee Seo.

My current research involves theoretical and numerical modeling of Pancreatic Duct flows.

I completed my bachelor's degree at Southern Illinois University and Shenyang Aerospace University, where I specialized in Aircraft Powerplant Engineering.

My research interests include applying computational algorithms to real-world problems, particularly in fluid dynamics, biofluids, and aerodynamics.