Modelling side to side intestinal anastomosis

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Abstract Side-to-side intestinal anastomosis is a surgical procedure where an incision is performed between two parallel segments of gut and then they are sutured together. The purpose of this paper is to investigate if the standard surgical practice diameter used in anastomosis leads to undesirable closed circulatory flows which may be harmful to the gut tissue. A finite element model for the chyme flow in a side by side anastomosis with realistic user configurable parameters is developed and solved in a wide range of situations. We analyze the flow crossing the anastomosis, the normalized pressure difference in the gut section and the streamlines that show the presence or absence of closed flow regions for a set of surgically feasible anastomosis diameter values. In contrast with the findings of simpler analytical models, closed flows do not appear in any of these cases. The study shows that the current standard surgical practice where the anastomosis diameter is similar to the gut diameter does not lead to undesirable effects predicted by some simple analytical models.

Keywords Anastomosis · Surgery · Finite elements · Navier–Stokes · FreeFem

1 Introduction

Side-to-side intestinal anastomosis is a surgical procedure that establishes communication between two parallel segments of gut (Fig. 1). It can be used to bypass a damaged section (e.g. in Crohn’s disease) or to achieve long-term weight reduction. Even though anastomosis is widely used both in planned and emergency situations, there is still some debate in the surgical community regarding several aspects of this procedure [1].

In the established surgical practice the diameter of the anastomosis is approximately the same as the diameter of the corresponding intestinal segments [2]. However, further analysis from a fluid mechanics point of view might be necessary to quantify the effect of changing this parameter (and others).

In [3] a mathematical model is made to find an analytical solution to a model of intestinal side to side (S–S) anastomosis. To obtain this solution it is necessary to assume that the fluid is Newtonian (constant viscosity) and in laminar flow (low Reynolds numbers). These assumptions hold provided that the anastomosis is made sufficiently far from the stomach [4]. The authors model an S–S intestinal anastomosis as a pair of two-dimensional parallel channels connected through an opening in the wall between them. This is justified by clinical practice where the surgical incisions are made in “straight parallel” segments of the gut.

The most interesting clinically applicable finding in [3] is the appearance, when the anastomosis diameter is greater than the gut diameter, of closed circulatory regions which are “potentially damaging to the tissue either by increasing the residence time of toxins or by facilitating the development of infection”. This is especially important in the anastomosis performed in obesity surgery (e.g. gastric

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Fig. 1 Drawing of an anastomosis; its proposed model is shown in the upper left corner

bypass), since reflux of chyme or pancreatic juice can cause the procedure to fail [5, 6, 7].

In this paper we will show that some of the data presented in [3] correspond to situations that would not be possible in real surgical practice and, thus, a more complete anastomosis model is needed. Our model still makes several simplifying assumptions (gut walls in the area static, peristaltic waves used to check the feasibility of the proposed pressure values) so the absence of closed fluxes in our model cannot fully guarantee that they would not occur in a real patient. However the absence of closed fluxes in our model suggests that they may be an artefact caused by the suppositions made in [3].

2 Methods

In this work we model S–S anastomosis using finite element methods. In the upper left corner of Fig. 1 we show the proposed model geometry. In this model we consider that the anastomosis is performed between two “parallel” sections of the gut separated by a “bypassed” section with a length of 15 (or more) gut diameters. We have introduced in the model two clinically meaningful parameters: the anastomosis diameter (measured as a ratio to the mean gut diameter) and the unobstructed ratio defined as $D/N \times 100\%$ where D is the minimum diameter in the bypassed area and N is the mean diameter in the area where the anastomosis is performed. We have also performed experiments extending the model to study the influence of the shape of the obstruction and the bypassed section.

The definition of the unobstructed ratio is complementary to that usually employed for percent arterial stenosis, $(1 - D/N) \times 100\%$ [8].

In our case the fluid in gut follows the Navier–Stokes equation for incompressible fluids at low Reynolds numbers [9].

$$-\vec{\nabla} p + \nabla^2 \vec{u} = 0$$

$$\vec{\nabla} \cdot \vec{u} = 0$$

where $\vec{u} = (u1, u2, 0)$, $\vec{u} = \vec{v}/U$ is the nondimensional velocity, with U being the typical chyme mean velocity (around 1 cm/s); and $p = PN_t/(\mu U)$ is the nondimensional pressure, with N_t being the typical gut diameter (around 2.5 cm) and μ the dynamic viscosity of water (about 0.7 cP at 37 °C).

We will also need to compute the streamlines which are just isovalue lines for the stream function. This function (ψ) should satisfy:

$$\vec{u} = \vec{\nabla} \times \vec{\psi}$$

where $\vec{\psi} = (0, 0, \psi)$.

In our case we find the solution to the Stokes problem through finite element methods. Specifically we use the FreeFem++ (version 3.51-4) [10] environment. **FreeFem++** is a partial differential equation solver. It has its own C++ like language and can be used to solve multi-physics nonlinear systems.

To solve our problem we have to use a variational formulation of the Stokes problem [11]. This is done by multiplying the above equations by adequate test functions and integrating using Green’s theorem. A good discussion of this technique applied to FreeFem++ can be found in [12].

We need to establish the boundary conditions for our problem. The input nondimensional velocity should have a parabolic profile. We conventionally select 1 as the maximum nondimensional input velocity. The remaining boundary conditions are that the velocity should be 0 in the gut walls and that the stream function at the input is fully conditioned by the velocity profile. These conditions allow us to compare our results with [3].

3 Results

We study the behavior of our model considering four different anastomosis diameters: 25, 50, 100 and 200% of the mean gut diameter. For each of these cases we consider four unobstructed gut ratios with minimum gut diameter in the bypassed zone which are 0, 25, 50 or 100% of the mean gut diameter.

In Fig. 2 we show the percentage of the input flow that crosses the anastomosis in for the chosen configurations.

In Fig. 3 we analyze the pressure difference between the input and the output of our model for the selected

Fig. 2 Flow crossing the anastomosis for chosen diameters and obstruction ratios

Fig. 3 Normalized pressure difference between input and output

configurations. The values are normalized so that the value for an unobstructed section without anastomosis is 1. This value corresponds to about 1.5×10^{-3} mmHg. Although this seems very low it agrees very well with the value obtained using Poiseuille's Law [9].

We don't show the pressure values for highly obstructed gut sections without anastomosis as these would make the figure unreadable: for an unobstructed ratio of 10 we would obtain a normalized pressure of 5 and for a ratio of 1 we would obtain about 33.

In Fig. 4 we show the streamlines which are obtained solving our model for anastomosis diameters $1/4 N$, N and $2 N$. For each configuration we include the results for fully obstructed gut, unobstructed gut and 50% gut obstruction ratio.

In order to better validate our model we will consider the influence of the obstruction position, its shape and the length of the bypassed region.

Regarding the effect of the position we study its effects by changing the input and output ports in our model thus moving the obstruction much further from the output. Running the simulations again with this configuration we see no significant change in the bypassed flux percentage or the pressure differences.

To study the effects of the obstruction shape we modify the model to allow for wider obstructions. In Fig. 5 we show percentage of flow through a 25% gut diameter anastomosis for the default obstruction width (10% of the gut diameter) and for widths that are 40 and 80% of the gut diameter. We can see that increasing the width of the obstacle decreases slightly the percentage of flow through the anastomosis but its effect is very small when compared to that of the unobstructed gut ratio. We only show the case with the smallest anastomosis diameter as in all the remaining cases the effect of the obstruction shape is negligible.

To study the effect of the channel length we modify the model to allow the length of the gut section after the obstruction to increase. In Fig. 6 we show the flow lines for a 25% diameter anastomosis when the unobstructed gut ratio is 50%, the obstacle is wide and the bypassed section length is 45 gut diameters. In this figure we used a reversed flow so that the obstacle is far from the input. However, as already mentioned, the bypassed flow percentage and the pressure increment are the same if we change the obstacle position.

In Fig. 7 we show the influence of the channel length on the bypass flow ratio when the anastomosis width is 25% of the gut diameter. It can be seen that in our model the increase in the bypassed section length leads to an increase in the flow of chyme through the anastomosis. We only include in the figure the case of very narrow (25%) anastomosis as for the remaining cases a very high proportion of the chyme will go through the bypass even for the shortest considered bypassed section.

The Freefem++ model can be downloaded from <https://goo.gl/AaqQir>.

4 Discussion

The chyme flow is analysed for anastomosis diameters 100, 200 and 300% of the mean gut diameter considering that either there is no flow through the anastomosis or the flow is evenly divided between the anastomosis and the regular gut path. In Fig. 2 we show that in these situations at least 90% of the chyme will go through the anastomosis even for a fully unobstructed bypassed area. Therefore, the situations studied in [3] would most probably not appear in a real case. As a result, we conclude that using the percentage of flow that goes through the anastomosis as a model parameter, and selecting very low values for it, leads to the appearance of closed fluxes in situations that are not likely to appear in medical practice (only 0 or 50% flow through a wide diameter anastomosis). It is also clear that, according to our model, performing anastomosis which is larger than

Fig. 4 Streamlines for different anastomosis widths and unobstructed gut ratios

Fig. 5 Flow through the anastomosis as a function of obstruction width

Fig. 6 Streamlines for a 45 gut diameter model

the gut diameter has very little impact on the proportion of bypassed chyme.

Regarding the pressure in the input channel Fig. 3 shows that small anastomosis diameters require larger pressure differences. However as $p = p\mu U/N_t$ even the largest pressures required by our model are below 1 mmHg and thus well below the pressures that can be generated by peristaltic movements which are above 25 mmHg [13].

Fig. 7 Influence of the bypassed section length

Thus, in principle, the peristaltic waves would be able to make chyme flow through any of the proposed diameters.

Regarding the position and shape of the obstruction we see very little influence on the bypassed flow percentage as long as we don't modify the unobstructed gut ratio.

Regarding the influence of the length of the bypassed section we can see in Fig. 7 that when the obstruction is important (25 or 50% unobstructed gut ratio) it has a significant influence on the bypassed flow percentage. As would be expected this influence is much smaller as the gut obstruction increases (i.e. unobstructed ratio approaches 0).

Regarding the closed chyme circulation region described in [3] we can see in Fig. 4 that these regions don't appear for any of the proposed anastomosis diameters in our model. These fluxes appear to be related to the choice

of percentage of flow through the anastomosis as a parameter in [3]. The chosen values for this percentage are very low in relation to what should be expected for the selected anastomosis diameters. This selection leads to the appearance of closed fluxes which are probably a mathematical artefact.

Thus, as a general conclusion, we find that the standard surgical practice of performing side by side small gut anastomosis using a diameter similar to that of the intestine in the selected area is fully justified from a fluid dynamics point of view. Furthermore, we believe that this type of models would be interesting for digestive surgery courses. This would provide tools to allow surgeons to select an adequate anastomosis diameter before performing gastric or intestinal bypass surgery thus reducing the chance of possible complications.

It is important to take into account that although the proposed model is more realistic than that used in [3] it is still simplistic as we consider the gut walls in the area static and only make use of the peristaltic pressure waves to assess the feasibility of the pressure values obtained with our model. Thus a more realistic anastomosis model, as well as real experimental measurements, would be useful to further ensure the validity of our conclusions.

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Compliance with ethical standards

Conflict of interest Javier Civit declares that he has no conflict of interest in relation to the work in this article. Fernando de la Portilla declares that he has no conflict of interest in relation to the work in this article. Jose Luis Sevillano declares that he has no conflict of interest in relation to the work in this article. Anton Civit declares that he has no conflict of interest in relation to the work in this article.

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