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Effect of intestinal pressure on fistula closure during vacuum assisted treatment: A computational approach

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ABSTRACT

Background: Enterocutaneous fistulae, pathological communications between the intestinal lumen and the abdominal skin, can arise as serious complication of gastrointestinal surgery. A current non-surgical treatment for this pathology involves topical application of sub-atmospheric pressure, also known as vacuum assisted closure (VAC). While this technique appears to be promising, surgeons report a number of cases in which its application fails to achieve fistula closure. Here, we evaluate the fistula's physical properties during the vacuum assisted closure process in a computational approach exploring the relevance of intraluminal intestinal pressure.

Methods: A mathematical model formulated by differential equations based on tissue elasticity properties and principles of fluid mechanics was created and forcing functions were integrated to mimic intestinal pressure dynamics. A software to solve equations and to fit the model to experimentally obtained data was developed. This enabled simulations of vacuum assisted fistula closure under different intestinal pressure.

Results: The simulation output indicates conditions, in which fistula closure can or cannot be expected suggesting favoured or impeded healing, respectively. When modifications of intestinal pressure, as observed in fistula accompanying pathologies, are integrated, the outcome of fistula closure changes considerably. Rise of intestinal pressure is associated with delay of fistula closure and temporary fistula radius augmentation, while reduction of intestinal pressure during sub-atmospheric pressure treatment contributes to a faster and direct fistula closure.

Conclusion: From the model predictions, we conclude that administration of intestinal pressure decreasing compounds (e.g. butylscopolamine, glucagon) may improve VAC treatment, while intestinal pressure increasing drugs should be avoided.

1. Introduction

Enterocutaneous fistulae (ECF) represent one of the most apprehensive complications of gastrointestinal surgery. This pathology is significant in terms of the high health risk it implies and the elevated economic cost it entails to the health care system.[1] Chapman and co-workers[2] rose the awareness that in the majority of cases the basis of ECF treatment should be, preferably, of conservative nature and emphasized the importance of nutritional and sepsis control. Though fistulae management experienced progress, treatment remained unsatisfactory calling for new therapeutic strategies. In 1992 Fernández and co-workers designed a vacuum-compaction device that applies sub-atmospheric pressure at the external extreme of the enterocutaneous fistula to achieve its closure.[3] This therapeutic approach, also referred to as vacuum assisted closure (VAC), has been implemented in 91 patients during the last years with promising results.[4] Under sub-atmospheric conditions, enterocutaneous fistula showed a reduced output and spontaneous closure was attained for a high percentage of patients. Recently, we successfully developed the first

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deterministic mathematical model to describe the closing mechanism of fistula under vacuum assistance.[5] The model assumed the fistula as a flexible tube with a Newtonian fluid circulating inside under a laminar regime and the intestine having constant atmospheric pressure during the treatment.

While in physiological state the average intraluminal pressure has been shown to be close to atmospheric pressure, forces vary under pathological conditions.[6–10] Patients presenting ECF are often in circumstances that are associated with high intestinal pressures. Intraluminal pressures may be increased due to various reasons including postoperative increased bowel wall tension, persisting bowel obstruction, stasis, bacterial overgrowth and malfunctioning of the ileocecal valve.[11,12] In a number of patients the fistula is complicated by inflammatory bowel syndrome. Under these circumstances the bowel smooth muscle may show higher intraluminal pressures.[13,14] There is a 25% failure of ECF closing using VAC treatment and the aforementioned conditions have been described as possible hindrance factors.[15] In this light, it appears relevant to study the influence of intestinal pressure on the outcome of ECF treatment using vacuum assistance. We performed computational simulations and developed a mathematical model comprising different functions describing intestinal pressure dynamics.

The obtained results suggest that during sub-atmospheric pressure treatment, increments in intestinal pressure may hinder or even preclude fistula closure, whereas a diminution of intestinal pressure may accelerate the closing process and facilitate the preservation of tissue integrity.

2. Vacuum applying methodology

Enterocutaneous fistulae are pathological communications between the lumen of the intestine and the external abdominal skin (Fig. 1). The objective of the VAC methodology is to achieve fistula closure without surgery and without immobilizing the patient. After cleaning the patient's abdominal skin, the surgeon describes a circular area from the abdominal extreme of the enterocutaneous fistula with Karaya paste (a biological adhesive for skin protection).[4] A polymeric foam is placed on this circular area, which is then covered by a low-density, highly malleable polythene film (18–21 μm) constituting the compaction chamber. A catheter, long enough to allow the patient to move, connects this chamber to a vacuum pump. When the pump is turned on, vacuum is applied. The compaction chamber volume decreases and the fistula can achieve its transitory closure. Depending on the evolution, this closure may be permanent.

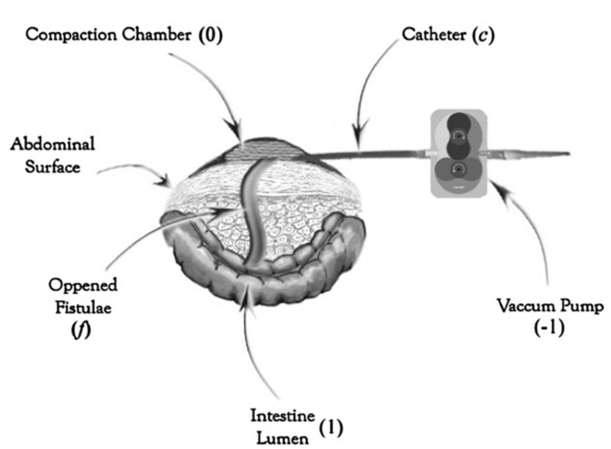

Fig. 1. Scheme of the computational model. The schematic representation depicts the intestine (1) connected to the compaction chamber (0) by the fistula (*f*). The compaction chamber in turn is connected to the vacuum pump (−1) by the catheter (*c*). An equivalent volume flux enters and leaves the fistula, the compaction chamber and the catheter connected to the vacuum pump.

3. Computational model incorporating intestinal pressure dynamics

In order to simulate the behaviour of the fistula during VAC application and evaluate the effect of intestinal pressure on the efficacy of this treatment, a model of five serial compartments was developed (Fig. 1). A complete description of the employed assumptions and equations can be found in the Supplementary information section. Briefly summarized, the fistula is simulated as a flexible cylinder of constant length (L_f) and variable radius as function of time ($r_f(t)$) with an incompressible fluid circulating through the fistula, once the vacuum pump is turned on. The flux through the system, described by the Poiseuille law, is conserved. The negative pressure generated by the vacuum pump (P_{-1}) follows an exponential decay kinetics.[5] The fistula radius depends on the pressure at the middle part of the fistula (P_f) and the inverse of fistula compressibility (D_f). The fistula extreme communicating with the intestine is exposed to the intestinal pressure which is a function of time ($P_1(t)$). Following these assumptions a computational model, describing the behaviour of the fistula radius during VAC as a function of time, was developed. This model is determined by the following expression which relates the rate of fistula radius change ($\dot{r}_f$) with the radius of fistula (r_f):

$$\dot{r}_f = \frac{a_6 r_f^6 + a_4 r_f^4 + a_0}{a_1 r_f} \tag{1}$$

where a_6, a_4, a_1 and a_0 depend on the physical properties of fistula, intestine and vacuum system and are given by:

$$a_6 = -\frac{\pi^2 D_f}{4\eta} \tag{2}$$

$$a_4 = \frac{\pi(P_1 - P_a)}{8 L_f \eta} + \frac{\pi^2 D_f r_0}{4\eta} \tag{3}$$

$$a_0 = -Q_B - \frac{\dot{P}_1}{D_0} \tag{4}$$

$$a_1 = L_f \pi \left(1 + 4\frac{D_f}{D_0}\right) \tag{5}$$

where D_f, D_0, η, L_f, r_0, Q_B, P_a, P_1, $\dot{P}_1$ represent the inverse of fistula compressibility, the inverse of the compaction chamber compressibility, the fistulous fluid viscosity, the length of fistula, the initial fistula radius, the flux generated by the vacuum pump, the atmospheric pressure, the intestinal pressure, and the rate of intestinal pressure change, respectively.

At initial time ($t = 0$) the pressure within the system, which includes the intestine, fistula, compaction chamber and catheter connected to the vacuum pump, is assumed to be atmospheric (P_a). The effect of intestinal pressure on the fistula behaviour can be observed in the factors a_4 and a_0. The influence of intestinal pressure (P_1) and the rate of change of intestinal pressure ($\dot{P}_1$) on the rate of change of the fistula radius ($\dot{r}_f$) are reflected in expressions (3) and (4).

The behaviour of the model represented by Eqs. (1–5) is directly related to the intestinal pressure through expressions a_0 and a_4. The