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Characterizing Pressure and Flow Rate for Aqueous Immersion Surgery (AIS)

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Characterizing Pressure and Flow Rate for Aqueous Immersion Surgery (AIS)

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ABSTRACT

A major clinical challenge during surgery is management of hemorrhaging which has affects on surgical efficiency and patient survival. A novel surgical method, known as Aqueous Immersion Surgery (AIS), is capable of sustaining a clear surgical field to reduce operating time and simultaneously promote hemostasis for patient blood volume conservation. AIS is able to sustain a bloodless surgical field by providing a controlled hydraulic pressure (immersion pressure) on the bleeding site. Together with the replenishment of an immersion fluid (immersion flow rate), AIS maintains optical clarity of the surgical field. This numerical study was undertaken to investigate the influence of the rate exchange of the immersion fluid on the concentration of blood, hence optical clarity therein. A 3-dimensional multicomponent simulation was performed to evaluate the mixing of blood from an idealized arterial bleeding vessel under pulsatile conditions. With an increase in immersion pressure to the bleeding site, bleeding was reduced and increased perfusion was observed. Additionally, the magnitude and direction of the flow field impacted the deflection of the bleeding trajectory and in turn, impacted the removal rate of blood from the surgical field. For an idealized case of AIS, an optimal immersion flow rate was found for immersion pressures of 100 and 110 mmHg. From this study, fluid dynamic guidelines are postulated to support future development of AIS.

Keywords - Hemostasis, Surgical System, Surgical Fluid Management, Multicomponent Flow, CFD, Blood Management, Hemodynamics, Aqueous Immersion Surgery, Fluid Surgery
1. Introduction

Uncontrolled bleeding produces many challenges during surgery, which may impact patient safety and visualization of the surgical field [1]. Bleeding occurs when an incision is made into tissue that disrupts blood vessels. This does not further the progress of surgery but rather requires the procedure to be halted and hemostatic efforts take precedence. Occasionally, surgical bleeding occurs and there are several adverse effects that can impact patient safety. These include visual obstruction of the surgical field and need for blood transfusion. In extreme situations, these complications can lead to hypothermia, thrombocytopenia, and hypovolemic shock. Although infrequent, the surgical complications can be immense [1, 2]. In addition, it is estimated that proper hemorrhage management during surgery can result in a significant increase in surgical time [3].

Over the years, a variety of methods to halt surgical bleeding have been utilized. Conventional hemostatic techniques include mechanical methods (i.e. direct pressure, gauze pads, sponges, sutures, and staples), thermal/energy-based methods (i.e. electrosurgery, ultrasound, and laser), and topical pharmacological hemostatic agents [1, 2]. One of the more intriguing and effective ways of creating a hemostatic environment is to staunch bleeding by immersing a fluid within the surgical field and providing a hydrostatic pressure. By producing a hydrostatic environment, a reduction in transmural pressure (pressure gradient between inside and outside of blood vessel) occurs at the bleeding site. This decrease in transmural pressure creates a reduction in bleeding and thus allows continued perfusion and tissue preservation. Although this is quite an effective method of hemostasis, it has been limited to only naturally occurring enclosed cavities within the body. These include the bladder and urinary system [3-5], the uterus [6, 7], joint capsules [8, 9], and intracranial endoscopic surgery [10].
However, the application of hydrostatic hemostasis can be extended to open surgery by hermetically sealing the operative field with an enclosure, thereby creating an artificial body cavity. This enclosure technique was recently introduced by Oberdier and Hayden et al. [11, 12] and permits the surgeon to operate in an analogous method to closed laparoscopic surgery inasmuch as similar surgical instruments are used and introduced through sealed access ports.

![Fig. 1. An artist's rendition of a surgical containment system in the context of spinal surgery.](image)

Traditional methods of hydrostatic hemostasis are conceptually simple, however due to the static fluid environment, maintaining a completely bloodless surgical field is a complex problem due to variation of pressure in time and throughout the cardiovascular system. Due to an uncontrolled hydrostatic pressure, exuberant elevation of pressures may also embarrass local tissue perfusion. Another challenge in maintaining a hydrostatic pressure is introduced by the use of surgical suction to help remove expended blood that has not been hydrostatically maintained. This however, has the potential of creating a negative pressure within the surgical field, thereby exacerbating bleeding. Consequently, with the uncontrolled nature of traditional methods, maintaining a bloodless surgical field may be challenging, if not impossible.
We propose a hemostatic technique, known as Aqueous Immersion Surgery (AIS), which is capable of maintaining a bloodless surgical field and simultaneously providing hemostatic efforts. This is achievable by incorporating a feedback-controlled system to maintain a set point hydraulic pressure (immersion pressure) and a controlled flow rate (immersion flow rate) within the surgical field. This study was undertaken to establish guidelines to help prescribe the appropriate immersion flow rate at two set point immersion pressures for an ideal surgical scenario.

2. Methods

An idealized 3-dimensional computation model (CM) was developed (using ANSYS CFX) comprised of a containment chamber enclosing a blood vessel (4.5 mm in diameter) with a circular side hole (2.5mm) representing the bleeding site. (See Figure 2.) The fluid domain was partitioned accordingly, comprised of 302,000 volume elements for the enclosure and 108,000 elements for the blood vessel. Two additional ports (each 6.35 mm in diameter) were provided to transport the immersion fluid (i.e. isotonic saline) in to and out of the chamber. The latter port was extended into a suction nozzle, placed in proximity of the bleeding site. The supply port for immersion fluid was placed at a more distant location.

Fig. 2. Entire fluid domain with surgical field and bleeding vessel.
A. Computational Model

Since blood will rapidly mix with the immersion fluid as it exits the bleeding site, a multicomponent mixture model was chosen, wherein blood and immersion fluid share the same velocity and pressure fields, however the density and viscosity of mixture was allowed to vary in space. The continuity equation and momentum equations are expressed by their non-conservative form in (1) and (2), respectively as:

$$\rho(\nabla \cdot \mathbf{U}) = 0$$

$$\rho(\frac{D\mathbf{U}}{Dt}) = -\nabla p + \mu \nabla^2 \mathbf{U}$$

where $\mathbf{U}$ is the velocity field, $p$ is the pressure field, the density and viscosity of the mixture are $\rho$ and $\mu$ respectively, are given by:

$$\rho = r_\alpha \rho_\alpha + r_\beta \rho_\beta$$

$$\mu = r_\alpha \mu_\alpha + r_\beta \mu_\beta$$

where $r_\alpha$ and $r_\beta$ are the mass fraction of the blood and isotonic saline, respectively. Due to incompressibility, these are related by:

$$r_\alpha + r_\beta = 1$$

B. Fluid Properties

For this analysis it was assumed that the temperature of both fluids were equal, and uniform throughout the domain. The immersion fluid was treated as a Newtonian fluid with the viscosity and density of water. Blood was modeled as a shear thinning fluid with viscosity described by the Carreau-Yasuda model:

$$\left[\frac{\mu_\alpha - \mu_\infty}{\mu_0 - \mu_\infty}\right] = 1 + \left(\frac{\dot{\gamma}}{\lambda}\right)^n$$

where $\mu_\alpha$ is the blood viscosity, $\mu_\infty$ is the asymptotic viscosity (0.0035 Pa s), $\mu_0$ is the zero-shear viscosity (0.1600 Pa s), $\lambda$ is a time constant (8.2 s), $\dot{\gamma}$ is the shear rate, $n$ is the power law index.
(0.2128) and $a$ is the Yasuda constant (0.64), obtained from [15] and the density (1056 kg/m$^3$) from [16].

C. Boundary Conditions

The inlet flow rate and outlet pressure of the blood vessel were prescribed using a time varying function that represented central arterial pressure defined by a five term Fourier series with a heart rate of 60 beats/min [18]. The magnitude of the blood mass flow rate was 6.5 g/s, chosen to achieve a systolic Reynolds number of 500, which is typical for an artery [19] (See Figure 3). The mass fraction, $r_a$ was set to 1 at the blood vessel inlet.

![Fig. 3. Simulation pressure and flow rate conditions.](image)

The immersion inlet to the fluid domain was prescribed with a constant velocity condition to achieve a range of volumetric flow rates from 0.2 to 3 LPM in increments of 0.2 LPM. The immersion outlet boundary was set to an average static pressure and the simulations were performed for two different immersion pressures, 100mmHg and 110mmHg, resulting in a total of 30 simulations. Steady state solutions were first obtained for the immersion fluid domain, whereupon the outlet pressure condition was adjusted so as to achieve the desired immersion
pressure at the bleeding site. Once steady state results were obtained, the multicomponent simulations were evaluated over two cardiac cycles.

3. Results

Representative mass fraction fields at the end of systole are illustrated in Figure 4a-f for five different immersion flow rates. The corresponding mass flow rate of blood within the surgical field is summarized in figure 5 for 110mmHg immersion pressure and all immersion flow rates.

Fig. 4. Mass Fraction of blood at end of systole with an immersion pressure of 110 mmHg at various immersion flow rates (a = Visualization Plane, b = Streamlines, c = 0.6, d = 1.2, e=1.8, f = 2.4 (LPM)).
The images in figure 4 characterize the deflection of blood into the suction exit at different immersion flow rates. The deflection of blood exiting the bleeding vessel was influenced by the direction and magnitude of the flow field.

In figure 5, Blood Accumulation represents the difference between the influx of blood (Bleeding) from the bleeding site and the efflux from the suction exit (Blood Removal). The blood removal rate was found to exhibit a unimodal relationship to immersion flow rate. At the optimal point, blood accumulation is minimized. The bleeding rate, however, exhibited a monotonically decreasing function of immersion flow rate. This phenomenon corresponded to the observation of a localized high-pressure zone in the region of the bleeding site caused by cross-flow [20, 21].

![Blood exchange in AIS at an immersion pressure of 110 mmHg](image)

**Fig. 5.** Blood exchange in AIS at an immersion pressure of 110 mmHg. The corresponding mass flow rate of blood, inside the surgical field, is plotted versus the immersion flow rate. The mass flow rates were averaged after two cardiac.

Figure 6 demonstrates the influence of an applied hydraulic immersion pressure on the bleeding rate and perfusion (blood flow rate through blood vessel outlet). A 10mmHg decrease of immersion pressure (from 110 to 100 mmHg) causes bleeding to increase (by 15.7%) and blood
perfusion to decrease (by 14.5%). The relationship between bleeding and perfusion to immersion flow rate was observed to follow a similar pattern for both immersion pressures studied.

![Graph of Mass Flow Rate vs. Immersion Flow Rate](image1)

**Fig. 6.** Bleeding and perfusion at varying immersion pressures and flow rates. The corresponding mass flow rates are plotted versus immersion flow rate at immersion pressures of 100 and 110 mmHg. The mass flow rates were averaged over two cardiac cycles.

The variation of immersion pressure was found to have a minimal effect upon blood removal for lower immersion rates, and a much more pronounced effect at higher flow rates. (See Figure 7.)

![Graph of Blood Removal Rate vs. Immersion Flow Rate](image2)

**Fig. 7.** Blood removal rate at two immersion pressures. Blood removal rate is plotted versus immersion flow rate at immersion pressures of 100 and 110 mmHg. The mass flow rates were averaged over two cardiac cycles.
The optimal immersion flow rate was observed to be increased (by 3.9%) for the lower immersion pressure. (See Figure 8.)

![Figure 8](image)

**Fig. 8.** Accumulation rate at two immersion pressures. Blood accumulation rate is plotted versus immersion flow rate at immersion pressures of 100 and 110 mmHg. The mass flow rates were averaged over two cardiac cycles.

### 4. Discussion

The objective of AIS is to minimize bleeding, to maintain a bloodless field and preserve blood, while maintaining perfusion. From this idealized simulation, a general relationship between bleeding, blood accumulation, and perfusion was observed. Both the immersion pressure and the immersion flow rate can manipulate bleeding rate and trajectory inside the surgical field. It was observed that bleeding rate was reduced at increasing immersion pressures and the deflection of blood into the suction exit was dictated by the direction (flow field within the surgical site) and magnitude (immersion flow rate) of the flow field.

Optimum performance of AIS transpires at an immersion flow rate that minimizes the accumulation of blood inside the surgical field. This optimum point of performance is dictated by immersion pressure, immersion flow rate, and geometric configuration of the system. In
practice, the suction configuration and the surgical field will vary in size and geometry significantly. Thus, the optimum point will change with different flow field conditions based on surgical field geometry, suction tip location and orientation. With improved flow fields and better suction configurations, it is likely the optimum point will shift in favor of lower immersion flow rates and will require less immersion fluid volume. This is significant for the reason that the surgical system may need to have adaptable fluid ports and accommodating fluid controls during surgery. When a containment chamber is used in open procedures, its design must consider surgical location and range of motion. Similarly, with cases involving minimally invasive surgeries or natural body cavities, simulations of this nature would be a valuable asset for preoperative surgical planning. For these reasons, further research should be conducted to evaluate how the optimum point will be affected in an in vitro and in vivo scenario with a feedback-controlled system.

5. Conclusion

At each set point immersion pressure of 100 and 110 mmHg, an optimal immersion flow rate was observed. This provided important insight into the fluid dynamical trends of AIS. In general, the deflection of the bleeding jet, was influenced by the magnitude of the immersion flow rate and the direction of the flow field (based on the geometric configuration of surgical field). At relatively higher flow rates, the accumulation of blood within the surgical field can be minimized. At increasing immersion pressures, optimal performance was achieved at lower immersion flow rates and thus minimized consumption of immersion fluid volume. Furthermore, with a decrease in transmural pressure, bleeding is reduced and increased perfusion is observed. The results of this study provide guidelines for future development of AIS.
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7. References