Simulated Wound Irrigation Impact Pressures

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Abstract

Objective: Prior studies have estimated wound irrigation impact pressures based on Bernoulli's equation, but they have never been measured directly. We empirically measured surface impact pressures of common irrigation methods used in the emergency department.

Method: Study Design: Experimental study. **Setting:** Laboratory adjacent to Emergency Department. **Participants:** Eight physicians and three students. **Intervention:** Volunteers simulated clinical wound irrigation with NS using various combinations of 10, 35, and 65 ml syringes, 19 and 16 gauge needles, a commercially available plastic splatter shield, and a plastic saline bottle pierced with a 19-gauge needle. The irrigant stream was directed onto a metal bending beam and the force assessed by noting the deflection a laser off the beam onto a calibrated wall scale. The pressure was then derived by dividing the observed force by the cross-sectional area of the stream at the impact site. Wound impact pressures were also calculated based on the velocity of the irrigant stream and Bernoulli's equation. **Data Analysis:** Repeated measures ANOVA was used to compare pressure across the irrigation methods, controlling for individual variability. The Wilcoxon's signed-ranks test was used to compare between these measured pressures and those calculated via an adaptation of Bernoulli's equation.

Results: There were significant differences across irrigation methods ($p < 0.05$) and between measured and calculated impact pressures ($p < 0.05$). The highest pressures were found when using the splatter shield. The lowest pressure was obtained with the IV bottle. The greatest differences between calculated and measured pressures occurred in the most commonly used syringe/needle combinations.

Conclusions: Actual impact pressures as measured by our system are different from those calculated by Bernoulli's equation. A need for revision of the current nomenclature is suggested as well as a move away from the dependence on Bernoulli's theorem. This will allow standardization of future research in wound irrigation.

Introduction

Prior to closure, debridement and irrigation are necessary to clear wounds of contaminating particles and bacteria. Given the large number of traumatic skin wounds seen in emergency departments (1) and the long accepted role of irrigation in their proper treatment (2-4), it is surprising that there are still many unresolved questions.

A review of the literature regarding pressure, the most important irrigation variable thus far identified, illustrates this well. Early on, Madden *et al.* (5) found that continuous flow irrigation at a high pressure provided optimal wound decontamination and significant protection against the development of clinical infection. Their results confirmed even earlier studies (2-4,6). Stevenson et al. (7) note that the advocated high-pressure irrigation can be achieved with simple syringe/needle combinations, such that cumbersome and expensive options are not necessary. They recommend a 35cc syringe/19-gauge needle combination to provide an optimal surface pressure of 8 pounds per square inch (psi) (7). However, high-pressure irrigation must be used carefully, as it can have unwanted side effects. Most importantly, it can result in mechanical injury that would actually increase the wound's susceptibility to infection (8-10).

Even though these clinically orientated studies have noted the importance of carefully controlling impact pressure, the derivation of the latter has been restricted to calculations based on Bernoulli's equation:

$$p + \tfrac{1}{2} \rho V^2 + \rho gz = constant \qquad (*)$$

This equation uses the measured indices of flow velocity (V) and irrigant density (r) to give an approximation for the pressure (p) difference between the nozzle tip and the impact point (gz is a term for gravitational acceleration that is negligible for small distances). It is well known that Bernoulli's equation is idealized and based on the rather stringent requirements of one-dimensional, steady, inviscid (no viscous forces, shear work, and heat transfer), incompressible flow, with no mechanical work (11). However, a less obvious, but equally important, assumption is that the flow must be laminar. This can be appreciated by examining the Navier-Stokes equations - the more general, governing equations of fluid flow motion (12):

$$\rho \frac{\partial V}{\partial t} + \nabla (p + \tfrac{1}{2} \rho V^2 + \rho gz) = \rho V \times \omega - \mu \, curl \omega \qquad (**)$$

This equation is derived by placing (on the left) the terms for stress in a Newtonian fluid (such as saline) into the differential equations of motion and expressing these (on the right) in terms of velocity gradients and fluid properties (μ is viscosity, and ω is a measure of rotation). This equation can be reduced to the traditional form of the Bernoulli equation (*) only if the there is no rotation ($\omega = 0$) - such that the right-hand side of the Navier-Stokes equation disappears. Since this condition can never be satisfied in turbulent flow, Bernoulli's equation is not applicable under such circumstances.

Returning to our irrigation problem, the Reynolds number for a standard syringe needle setup (velocity of 9 m/s, diameter of 6.9×10^{-4} m, and kinematic viscosity of 1×10^{-6} m^2/s) turns out to be 6,210. Since any number above 2,000 implies turbulent flow, Bernoulli's equation cannot be applied to this system. This is further supported by experimental ***in vivo*** and ***in vitro*** studies in stenosed arteries in which turbulent flow conditions distal to the throat of the stenosis were generated. The turbulence caused an irrevocable pressure loss that continued past the throat of the stenosis (13-16). As made clear above, the simplified Bernoulli equation will not account for this secondary pressure loss and hence will underestimate the stenosis severity. Experimental studies (13,15,17) of stenotic heart valves have also shown that for severely stenosed valves (>85%) in which turbulent flow conditions are generated, the simplified Bernoulli equation will underestimate the pressure gradient. These theoretic and experimental studies indicate that the loss coefficient is a function of the severity of the stenosis, which is directly related to the turbulence intensity.

Given the clear importance of pressure, it seems worthwhile to empirically test the impact pressures. The purpose of this study then, was to take a first step toward understanding the tissue-level fluid dynamics of wound irrigation by empirically measuring and comparing impact pressures of common wound irrigation methods.

Methods

Study Design

A prospective experimental laboratory study was conducted to measure the surface impact pressure of various wound irrigation systems commonly used in the ED. All subjects gave informed consent and the study was approved by the Institutional Review Board.

Setting

The study was conducted in a functional laboratory set up in the Department of Emergency Medicine at the State University of New York at Stony Brook.

Participants

Volunteer subjects included 8 ED resident or attending physicians as well as 3 students. Their mean age was 30 (±12) and 4 (36%) were females. All had experience with wound irrigation.

Experimental Setup

The experimental setup consisted of the design shown in **Figure 1**. A metal bending beam was chosen with the appropriate material properties to accommodate the expected range of forces. A laser pointer was fixed at a slight distance to allow the light to fall along the center of the beam. An optical grade mirror was attached at the point where the laser light hit. A second mirror was attached further along the path of the beam to reflect the laser light toward a wall scale. Using known weights, this scale was calibrated to vary from a range of 0-14 grams. By calibrating the scale using known weights applied directly to the site where the irrigant would be directed, further external validation was deemed unnecessary. To ensure that the calibration was maintained throughout testing, the weights were once again applied periodically to test

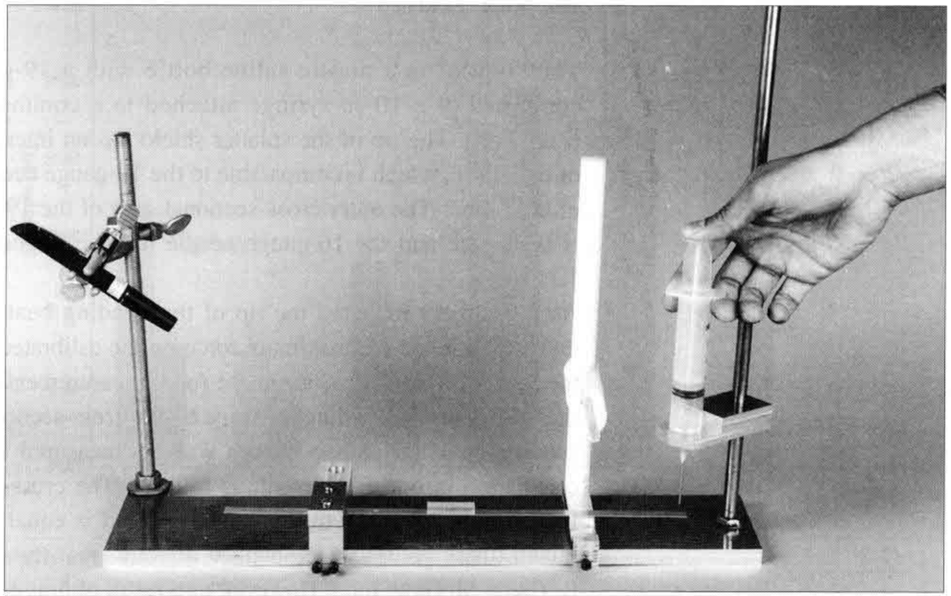

Figure 1. Experimental setup

the system. In fact, further recalibration was never required. Lastly, the syringe was placed in a secure holder that positioned the needle tip a distance (8 mm) away from the beam that was chosen to approximate the distance the needle would be kept from a real wound during irrigation.

Study subjects were told to simulate wound irrigation - that is to use an amount of force to depress the syringe equal to what they would if they were actually irrigating a wound, and not necessarily the greatest amount of force they could generate. Each subject irrigated with each method once and the mean force at the impact site on the beam was calculated.

The various forms of irrigation chosen for this study are shown in **Table 1**. Not every combination of syringe/needle was studied because trends are already known (i.e., that flow velocity is directly related to the gauge size of the needle and indirectly related to syringe volume). The specific irrigation combinations were chosen since they are commonly used and as examples to compare with calculated measures. Novel irrigation techniques described recently such as the port or cap were excluded from this study because they are not commonly used in ED's nationwide.

Table 1. Measured and calculated irrigation values

	|--------Calculated---------		||-----------Measured---------|		
Method (syringe/needle)	Cross-sectional area (mm^2)	Flow velocity (m/s)	Pressure (psi)	Force (g)	Pressure (psi)	p-value
35-cc/19-G	0.37	10.41	7.85	4.1 +/- 0.8	15.7 +/- 3.1	< 0.0001
35-cc/16-G	1.11	8.84	5.66	5.8 +/- 2.0	7.4 +/- 2.6	0.04
65-cc/19-G	0.37	9.39	6.39	3.5 +/- 0.7	13.4 +/- 2.7	< 0.0001
10-cc/Zerowet	0.40	18.43	24.63	6.2 +/- 2.4	22.0 +/- 8.5	0.51
35-cc/Zerowet	0.40	17.38	21.91	6.3 +/- 2.9	22.4 +/- 10.3	0.85
65-cc/Zerowet	0.40	16.46	19.63	5.4 +/- 2.2	19.2 +/- 7.8	0.88
Saline bottle	0.90	N/C	N/C	2.0 +/- 0.7	3.2 +/- 1.1	N/C

N/C = not calculated

The "bottle" is a plastic saline bottle with a 19-gauge needle hole. The "kit" is composed of a 10-cc syringe attached to a commercially available splatter shield (Zerowet®). The tip of the splatter shield has an internal (luminal) cross-sectional area of 0.40 mm^2, which is comparable to the 19-gauge needle's internal cross-sectional area of 0.37 mm^2. The outer cross-sectional area of the 19-gauge needle (saline bottle hole) is 0.90 mm^2 and the 16-gauge needle has the largest luminal cross-sectional area of 1.11 mm^2.

As the subject irrigated the tip of the bending beam, an observer (always the same individual) noted the maximum force on the calibrated wall scale that was stable during the length of the irrigation. These force measurements were then converted to pressure measurements by dividing the force by the cross-sectional area of the impact stream. The actual area of the impact stream was not measured and therefore constitutes the only calculation in our experiment, as follows. The cross-sectional area of the stream as it leaves the irrigation setup is known since it is equal to the cross-sectional area of the lumen (these values were obtained directly from the companies: Becton-Dickinson and B. Braun McGaw, Inc.). However, as a result of gravity, a fluid stream tends to narrow as it descends vertically. This narrowing effect is directly related to the change in height (e.g., from needle exit to impact point) and indirectly related to velocity. Given the high fluid velocities (range: 8.84-18.43 m/s), and the small change in height (approximately 8 mm) between needle tip to impact, the gravitational effects leading to cross-sectional area narrowing are negligible. Therefore, the cross-sectional area at the impact site was said to be equal to the cross-sectional area of the respective exit lumens.

The method by which we collected this force data (bending beam) technically provides moments rather than vertical force values. However, this complication was circumvented by simplifying the setup and calibrating a wall scale with known gram weights rather than using the traditional strain gauges to measure the bending of the beam.

Data Analysis

Repeated measures ANOVA were used to compare pressure across the irrigation methods controlling for individual volunteer variability. In addition, the Wilcoxon's signed-ranks test was used to compare between these measured pressures and those calculated via an adaptation of Bernoulli's equation. Note that the saline bottle was excluded for comparison in this second part of the study as the pulsatile nature of its flow is not suitable for comparison with Bernoulli's equation.

Results

The outcomes are shown in **Table 1** and **Figure 2**. In comparing the measured to the calculated values, there are clear inequalities with overall significant differences ($p = 0.03$) between the two groups. The greatest difference between measured and calculated pressures lies with either the 16-G ($p = 0.04$) or especially the 19-G needle combinations ($p < 0.0001$), while the differences with the Zerowet attached to any size syringe were not significant ($p = 0.51, 0.85, 0.88$). It is also of note that the variance between measures in any of the Zerowet setups was much higher than with the needle setup or the bottle.

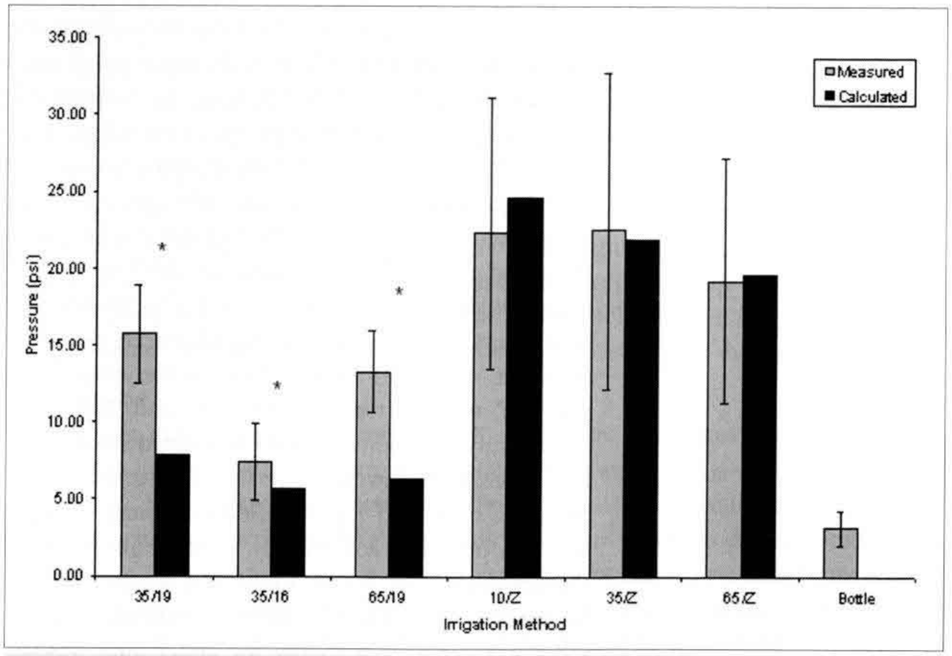

Figure 2. Comparison of measured and calculated pressures across irrigation methods
Note: Bars denote one standard deviation. Stars indicate a significant difference ($p < 0.05$)

Secondly, comparing the measured pressures of the different methods, the expected relation of syringe and needle gauge effects generally held as noted by Stevenson et al (7). Overall, there were significant pressure differences across methods ($p = 0.04$). All except the saline bottle gave pressures in the range traditionally considered to be high pressure (> 7 psi). And of these, only the 35cc/16-G combination gave a pressure below 10 psi.

Discussion

Irrigation has long been used to treat traumatic wounds before closure. Of the many variables to consider when deciding on irrigation specifics, pressure has (so far) been most correlated to removal of bacteria and thus better treatment outcomes (5-9). This variable, however, is problematic. Given a uniform irrigant volume, higher pressures are generally more efficacious than lower ones, but if the pressure becomes too high, irrigation can actually cause tissue damage and thereby reduce its ability to withstand contaminants (10).

Although researchers have long understood that the tissue impact pressures have to be carefully controlled, they have so far depended wholly on Bernoulli's equation to calculate these impact pressures using flow velocity and irrigant density. This methodology has generally not been questioned, except (to the best of our knowledge) by two authors. Morse et al.(18) suggest that these calculations might be difficult as the proximal conditions within an irrigation setup are complex - composed of laminar, transitional, and turbulent flows. This would lead to "friction within the system [which] may significantly reduce the effective irrigation pressure" and make it deviate from being "strictly Bernoulli-like." Such worries are misdirected because Bernoulli's equation estimates the change in pressure *after* the irrigant leaves the system so that proximal system effects are irrelevant. Singer *et al* (19). measured the pressure between the syringe and needle but state that "ideally, the irrigation impact pressure on the surface of the wound should be measured. However, measurement of pressures in an open system is complex." As mentioned above, the real problem is that irrigation streams are turbulent and, as such, don't fulfill one of the basic requirements of the application of Bernoulli's equation. As confirmed by this study, the calculated and empirically observed impact pressures are not necessarily equal.

Therefore, it is fortunate that the existant research has been so clinically oriented, for their theoretical explanations and subsequent nomenclature adaptations can no longer be supported. For instance, the fact that the 35-ml/19-G combination actually leads to twice the expected impact pressures (15.7 vs. 7 psi) doesn't change the fact that the setup, as shown by Stevenson et al. (7), provides a pressure that is more efficacious than others for removing bacteria. However, in terms of research and theory, the results are quite important as it contradicts the entire terminology which considers "high pressure" to be in the range of 7 psi, and "low pressure" to be in the range of 1 psi. Historically, this nomenclature is adopted from work by Madden (5), Rodeheaver (6), and especially Stevenson et al (7). The latter group noted that calculated impact pressures of around 7 psi should be considered "high pressure" to differentiate it from the "low pressure" achieved by asepto (bulb type) syringes (calculated to be 0.05 psi). Furthermore, since it was found that setups yielding calculated impact pressures any higher (20 psi by the 12-ml/19-G combination) didn't provide significantly improved reduction in bacterial counts, the upper limit was set at 7 psi. During the ensuing 30 years, all literature in this field of wound irrigation have adopted their terminology and the method of Bernoulli's equation to calculate impact pressures - including some of the most recent work (1,12). Our results indicate a need to clarify this ambiguous nomenclature. We suggest the following terminology. If a 35-ml/19-G combination truly provides the most effective bacterial removal, and such a combination gives true impact pressures of around 15 psi, then that should be considered "optimal pressure." That in turn will be differentiated from setups that provide "low pressure" (and ostensibly lower bacterial removal) in the range of below 10 psi, such as a 35-ml syringe with a 16-G needle, or a saline bottle with a 19-G needle hole. Lastly, setups providing higher than necessary irrigation, such as anything with the Zerowet attached, will be considered "high pressure."

The Zerowet setups are interesting for a few additional reasons: the measured and calculated pressures were not significantly different for this group; they consistently provided very high pressures even though their luminal cross-section was only 0.03 mm^2 larger than the 19-G needle; and they had a much higher variance across users than the other setups. We believe the reason for the latter two characteristics has to do with the small length of the Zerowet lumen compared to the needles. The longer length of the needles requires a larger force by the user to maintain high ejection velocities and, at the same time, this allows the Zerowet setup to be more sensitive to user input thereby resulting in a higher variance in measurements. The higher variance may additionally be explained by the fact that the splatter shield of the Zerowet blocks clear visibility to the irrigation site (in our case the end of the bending beam) and thus causes users to be more variable in their use of this setup. It is not immediately clear why the calculated and measured values for the Zerowet setups are so close, but this may have to do again with the small luminal length resulting in a more even flow of the irrigant fluid. In any case, since these setups provide higher than optimal pressures, they should generally not be used in preference to the more typical syringe-needle combinations.

Limitations and Future Questions

Our study has several limitations. We measured surface impact pressures using a highly controlled and simulated wound irrigation set up. However, we do not feel that measurements in the clinical setting would differ greatly. Furthermore, the number of subjects in the current study was small. It is possible that this sample may not generalize to all practitioners who irrigate wounds. Future studies should measure wound impact pressures during actual irrigation of wounds in the clinical setting. At the same time, our empirically measured pressure values were the average of the dynamic flow situation actually occurring during irrigation. Future work can attempt to control this in two separate ways: a fixed load can be applied to the setups to minimize fluctuations in the flow, and a transducer (i.e., a load cell or strain gauge) can be used in place of the bending beam to directly capture the dynamic flow during irrigation.

Conclusions

Clearly, our results have raised more questions than they have answered. The bottom line is that the application of Bernoulli's equation to wound irrigation is misdirected. Fortunately, most of the past work in this field had a clinical focus (i.e., which setup provides optimal bacterial removal) and only secondarily tried to calculate the impact pressures of their setup. Therefore, our results do not negate their clinical conclusions, but do suggest a need for revision of the nomenclature derived from this constant dependence on the idealized Bernoulli's equation. Trying to understand true factors at play behind the fluid dynamics of wound irrigation should be a goal of future research.

References

1. Pronchik D, Barbar C, Rittenhouse S. Low - versus high-pressure irrigation techniques in Staphylococcus aureus-inoculated wounds. Am J Emerg Med 1999;17:121-124
2. Edlich RF, Custer J, Madden J, et al. Studies in management of the contaminated wound: III. Assessment of the effectiveness of irrigation with antiseptic agents. Am J Surg 1969;118:21
3. Falconer B, Liljedahl S, Olovson T. On the effect of treatment of traumatic wounds with soap solution. An experimental study. Acta Chir Scand 1952;103:222
4. Casten DF, Nach RJ, Spinzia J. An experimental and clinical study of the effectiveness of antibiotic wound irrigation in preventing infection. Surg Gynec Obstet 1964;118:783
5. Madden J, Edlich RF, Schauerhamer R, et al. Application of principles of fluid dynamics to surgical wound irrigation. Curr Top Surg Res 1971;3:85-93
6. Rodeheaver GT, Pettry D, Thacker JG. Wound cleansing by high pressure irrigation. Surg Gynec Obstet 1975;141:357-362
7. Stevenson TR, Thacker JG, Rodeheaver GT, et al. Cleansing the traumatic wound by high pressure syringe irrigation. JACEP 1976;5:17-21
8. Edlich RF, Rodeheaver GT, Morgan RF, et al. Principles of emergency wound management. Ann Emerg Med 1988;17:1284-1302
9. Edlich RF, Thacker JG. Wound irrigation. Ann Emerg Med 1994;24:88-90
10. Wheeler CB, Rodeheaver GT, Thacker JG, et al. Side-effects of high-pressure irrigation. Surg Gynec Obstet 1976;143:775-778
11. Fox RW, McDonald AT: Introduction to Fluid Mechanics, ed 5. New York: John Wiley & Sons, Inc., 1998:246
12. White FM. Viscous fluid flow, ed 2. NY: McGraw-Hill, 1991
13. Marx GR, Allen HD: Accuracy and pitfalls of Doppler evaluation of the pressure gradient in aortic coarctation. J Am Coll Cardiol 1986;7:1379-85
14. Rijsterborgh H, Roeland J. Doppler assessment of aortic stenosis: Bernoulli revisited. Ultrasound Med Biol 1987;13;241-8
15. Yoganathan AP, Valdes-Cruz LM, Schmidt-Dohna J, et al. Continuous-wave Doppler velocities and gradients across fixed tunnel obstructions: studies in vitro and in vivo. Circulation 1987;76:657-66
16. Popp RL, Teplitsky I. Lessons from in vitro models of small, irregular, multiple and tunnel-like stenoses relevant to clinical stenoses of valves and small vessels. J Am Coll Cardiol 1989;13:716-22
17. VanAuker MD, Hla A, Meisner JS, et al. Simultaneous doppler/catheter measurements of pressure gradients in aortic valve disease: a correction to the Bernoulli equation based on velocity decay in the stenotic jet. J Heart Valve Dis 2000;9:291-8
18. Morse JW, Babson T, Camasso C. Wound infection rate and irrigation pressure of two potential new wound irrigation devices: the port and the cap. Am J Emerg Med 1998;16:37-42
19. Singer AJ, Hollander JE, Subramanian S, et al. Pressure dynamics of various irrigation techniques commonly used in the emergency department. Ann Emerg Med 1994;24:36-40