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ORIGINAL RESEARCH

Pressures of Wilderness Improvised Wound Irrigation Techniques: How Do They Compare?

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Objective.—Compare the pressures measured by improvised irrigation techniques to a commercial device and to prior reports.

Methods.—Devices tested included a commercial 500-mL compressible plastic bottle with splash guard, a 10-mL syringe, a 10-mL syringe with a 14-ga angiocatheter (with needle removed), a 50-mL Sawyer syringe, a plastic bag punctured with a 14-ga needle, a plastic bottle with cap punctured by a 14-ga needle, a plastic bottle with sports top, and a bladder-style hydration system. Each device was leveled on a support, manually compressed, and aimed toward a piece of glass. A high-speed camera placed behind the glass recorded the height of the stream upon impact at its highest and lowest point. Measurements were recorded 5 times for each device. Pressures in pounds per square inch (psi) were calculated.

Results.—The syringe and angiocatheter pressures measured the highest pressures (16–49 psi). The 50-mL syringe (7–11 psi), 14-ga punctured water bottle (7–25 psi), and water bottle with sports top (3–7 psi) all measured at or above the commercial device (4–5 psi). Only the bladder-style hydration system (1–2 psi) and plastic bag with 14-ga needle puncture (2–3 psi) did not reach pressures generated by the commercial device.

Conclusions.—Pressures are consistent with those previously reported. All systems using compressible water bottles and all syringe-based systems provided pressures at or exceeding a commercial wound irrigation device. A 14-ga punctured plastic bag and bladder-style hydration pack failed to generate similar irrigation pressures.

Introduction

Traumatic wounds are common, with an estimated 10 million wounds cared for in emergency departments annually in the United States.[1] Wound irrigation in acute wound care serves to remove bacterial contaminants, debris, and dirt. Since the 1950s, observational studies have supported the finding that irrigation itself, regardless of the pressure, provides benefit to wound healing and patient outcomes.[2] Despite this early observation, there is a lack of consensus in the literature regarding an optimal irrigation pressure for acute traumatic wounds, in part due to conflicting definitions and techniques reported.

Many techniques have been suggested to improvise wound irrigation for treatment of acute wounds in resource-poor or wilderness settings. Improvised methods include puncturing holes in compressible water reservoirs, such as a water bottle cap or a Ziploc plastic bag,[3] squeezing water out of bladder-style hydration systems, or simply pouring water from a known clean source (commercial bottled water) into contaminated wounds. Additionally, first aid kits often are equipped with a 1-mL syringe that can be used as a tool for wound irrigation. These improvised wound irrigation strategies have not previously been studied in a systematic way.

A standard approach to estimating the pressure of a wound irrigant at the surface of the wound has not been

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consistently reported in the literature. Prior investigations of irrigation pressures include a laboratory benchtop model that measured pressures inside a closed system,[4] a model using an in-line pressure gauge with devices compressed by volunteers,[1] and a force transducer placed in the wound surface.[5] All of these methods have limitations noted by the authors, the most notable of which is the availability of expensive benchtop models, pressure gauges, and force transducers for investigators looking to reproduce results previously reported. Furthermore, none of these experiments tested improvised wound irrigation methods. Calculating water pressure using measurements of water displacement striking a "wound surface" has not been reported previously.

We propose the use of a reproducible model based on utilizing fluid mechanics equations and compare methods of improvised wound irrigation with a commercially available device (500-mL plastic bottle with splash guard used in many emergency departments) and to pressures previously reported in the literature.

Methods

STUDY DESIGN

This is a study of simulated wound irrigation pressures from improvised devices that could be used in a remote, prehospital setting. Devices that were included in the study include a commercially distributed wound irrigation system consisting of a compressible plastic 500-mL normal saline bottle with attached irrigation nozzle spray guard (splash guard), a 10-mL syringe found commonly in backpacking first aid kits (10-mL syringe), a 10-mL syringe with a 14-ga angiocatheter with the needle removed (10-mL syringe + 14 ga catheter), a 50-mL Sawyer water filter cleaning syringe (50-mL Sawyer syringe), a Ziploc sandwich-sized plastic bag with punctures from a 14-ga needle (Ziploc + 14-ga holes), a Smartwater water bottle with multiple punctures from 14-ga needle in the flat plastic cap (water bottle + 14-ga holes), a Smartwater water bottle with sports top (sports-top water bottle), and an Osprey 3-L backpack bladder-style hydration system (bladder hydration system). Punctures were made approximately 3–5 mm apart with a 14-ga angiocatheter needle, with approximately 12–14 per water bottle cap or dependent corner of a plastic bag. This water bottle cap fenestration can be prepared in advance with a small nail, as the punctured cap + water bottle also functions as a "backcountry bidet" for travel in areas that ban the use of buried toilet tissue. Examples of the improvised devices tested can be seen in Figure 1.

Each device was filled with water to its maximum capacity. The irrigation device was then placed on a support and leveled. Maximum manual pressure was exerted on the device by the same individual for every trial and aimed toward a piece of clear glass in order to consistently obtain the highest possible generated pressure. A high speed camera (Panasonic Lumix DMC-FZ28) recorded the height of the top of the stream upon impact with the glass, through video recordings using VLC Media Player and still images taken from video (Figure 2). The height of the support where the stream was produced was measured (Y_0). The stream splash height of displacement was measured (Y_1). The distance between the irrigation device support and the glass was measured (X). The experimental setup with the measured components is diagrammed (Figure 3).

To calculate the range of pressures produced by the irrigant stream, the water displacement height was recorded at initial impact reflecting the maximum pressure

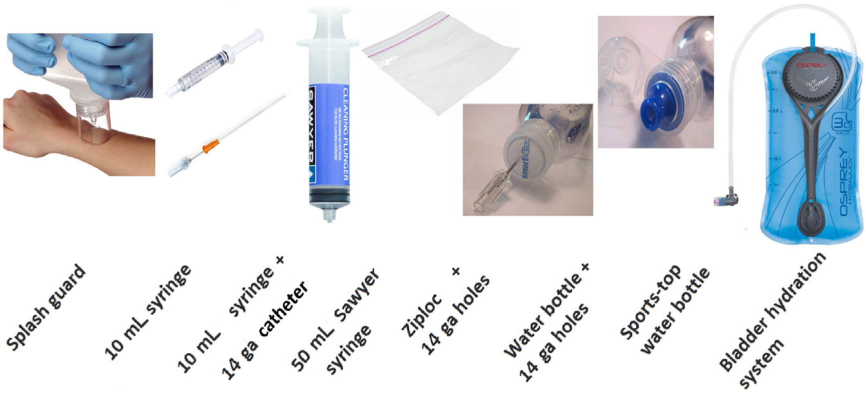

Figure 1. From left to right, devices tested included commercial 500-mL compressible plastic bottle with splash guard (splash guard), a 10-mL syringe, a 10-mL syringe with a 14-ga catheter (10-mL syringe + 14-ga catheter), a 50-mL Sawyer water filtration cleaning syringe (50-mL Sawyer syringe), plastic bag punctured with a 14-ga needle (Ziploc + 14-ga holes), a water bottle cap punctured with holes from a 14-ga angiocatheter (water bottle + 14-ga holes), a sports-top water bottle, and an Osprey 3-L bladder hydration system (bladder hydration system).

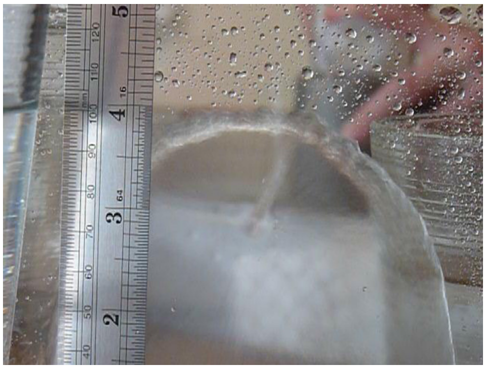

Figure 2. Using a ruler for reference and still images captured from the VLC Media Player, the stream impact was measured.

and during steady state compression of the irrigant device representing the minimum pressure measurement. These measurements of the splash height maximum and minimum were taken 5 times for each tested device.

DATA ANALYSIS

Each of the 5 measurements taken for maximum and minimum heights of water displacement was averaged to produce a minimum and maximum of the range of values for Y_1 created by each tested device. Using projectile motion equations, the velocity of the stream of water can be calculated using the difference of the height of the water column leaving the device and the height of the water column striking the glass barrier over a known distance and constant gravitational force. The gravitational acceleration was approximated to 9.81 m/s^2. The velocity equation was the product of the distance of the fluid trajectory before striking the glass barrier with the square root of the gravitational acceleration divided by 2 times the distance the water

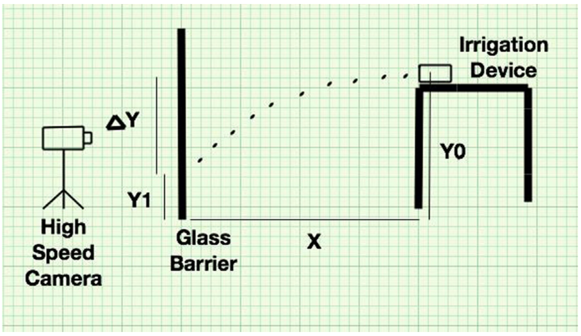

Figure 3. Experimental setup with Y_0 representing the height of the support of the irrigation device. X represents the distance between the support and the glass barrier, and Y_1 marks the height of the irrigant stream striking the glass as recorded by the high speed digital camera. ΔY is the calculated difference between Y_0 and Y_1 to be used in data analysis described in the methods.

trajectory dropped in its flight from initial expulsion to the glass barrier.

Calculated velocity was converted into a pressure measurement. Static fluid pressure was calculated by dividing the product of the weight of water by the squared velocity calculated in the previous step with the gravitational acceleration. The weight of water was obtained by multiplying the density of water (value used was 1000 kg/m^3) with the gravitational acceleration (9.81 m/s^2). After pressure was calculated, units were converted from Pascals to pounds per square inch (psi). Because nearly all commercial instruments are specified to display in psi, the authors chose to report results in psi to facilitate comparison to previously reported irrigation pressures in the literature. One psi equals 6894.76 Pascals.

One-way analysis of variance testing was planned to analyze whether there were any significant differences among the experimental groups. The results of our calculated data analysis for improvised devices were compared post hoc with reports of commercial irrigation devices of similar size and caliber previously measured through benchtop and force meter methodologies.

Results

The individual trials for each device were internally consistent, as measured by the small amount of variance seen in the 5 separate measurements for maximum and minimum heights of water displacement. Intradevice maximum height measurements (on impact) between the 5 trials varied by less than 1 cm for 5 of 8 devices tested: the splash guard, 10-mL syringe, 50-mL Sawyer syringe, Ziploc + 14-ga holes, and the water bottle + 14-ga holes. Steady state measurements (minimum height measurement) varied most with the smallest devices, but still had very similar intradevice height measurements within trials (Table). The splash guard, 50-mL Sawyer syringe, and sports-top water bottle trials all had values in an intradevice range of less than 1 cm. All maximum and minimum height values measured within each device varied by less than 2.5 cm within the range of values obtained.

The individual variable values used for calculations of pressure are in the Table. The highest pressures on impact were recorded for the 10-mL syringe (48.7 psi), 10-mL syringe + 14-ga catheter (24.1 psi), and the water bottle + 14-ga holes (25.7 psi). The 50-mL Sawyer syringe (10.9 psi), sports-top water bottle (6.7 psi), and splash guard (4.6 psi) were the next most powerful irrigant streams. The least pressurized devices were the bladder hydration system (3.3 psi) and the Ziploc + 14-ga holes (1.9 psi).

Table. The individual variables values used in calculating pressure

	Splash guard	*10-mL Syringe*	*10-mL syringe + 14 ga Catheter*	*Sawyer 50-mL cleaning syringe*	*Ziploc + 14-ga holes*	*Water bottle + 14-ga holes*	*Water bottle sports top*	*Bladder hydration system*
Gravity (m/s^2)	9.810	9.810	9.810	9.810	9.810	9.810	9.810	9.810
Density (kg/m^3)	1000	1000	1000	1000	1000	1000	1000	1000
X (m)	0.503	1.010	0.935	0.708	0.310	0.620	0.530	0.395
Y_0 (m)	0.110	0.098	0.098	0.105	0.130	0.115	0.110	0.100
Y_1	0.073	0.083	0.060	0.064	0.092	0.105	0.068	0.070
Y_2	0.075	0.083	0.065	0.074	0.090	0.102	0.085	0.060
Y_3	0.073	0.080	0.085	0.074	0.092	0.101	0.075	0.065
Y_4	0.074	0.083	0.075	0.072	0.097	0.105	0.090	0.060
Y_5	0.073	0.087	0.077	0.074	0.098	0.110	0.085	0.080
MAX Mean of 5 trials (m)	0.074	0.083	0.072	0.071	0.094	0.104	0.080	0.067
MAX Velocity (m/s)	5.8	18.3	12.9	8.6	3.6	13.3	6.8	4.8
MAX Pressure (Pa)	34026	335811	165963	73094	12936	177249	46489	23025
MAX Pressure (psi)	4.935	48.705	24.071	10.601	1.876	25.708	6.743	3.340
Y_1	0.065	0.055	0.055	0.050	0.085	0.085	0.045	0.055
Y_2	0.068	0.075	0.060	0.058	0.080	0.075	0.050	0.050
Y_3	0.065	0.065	0.063	0.060	0.080	0.070	0.045	0.040
Y_4	0.065	0.065	0.055	0.055	0.065	0.075	0.045	0.045
Y_5	0.065	0.075	0.060	0.055	0.070	0.080	0.055	0.045
MIN Mean of 5 trials (m)	0.065	0.067	0.058	0.055	0.076	0.077	0.048	0.047
MIN Velocity (m/s)	5.3	12.7	10.4	7	3	7	4.7	3.8
MIN Pressure (Pa)	27747	160179	108182	49533	8760	49310	22138	14375
MIN Pressure (psi)	4.024	23.232	15.691	7.184	1.271	7.152	3.211	2.085

MAX, maximum; MIN, minimum.

The minimum pressures were similarly ranked, with the 10-mL syringe (23.2 psi) and 10-mL syringe + 14-ga catheter (15.7 psi) producing several times the pressure seen with other devices. The 50-mL Sawyer syringe and the water bottle + 14-ga holes were similarly pressured (7.2 psi), and the splash guard was very consistent in its stream (4.0 psi) with a narrow pressure range (4.6–4.0 psi). The sports-top water bottle (3.2 psi) fell off in pressure by more than 50% (6.7–3.2 psi). The lowest pressure devices again were the bladder hydration system (2.1 psi) and the Ziploc + 14-ga holes (1.3 psi).

One-way analysis of variance analysis demonstrated the experimental groups were significantly different from each other with an F ratio ($P < .001$). However, this analysis was not valid for our data sets due to the violation of the "homogeneity of variances" assumption for all data value (levenes); in addition, the splash guard data subset lacked a normal distribution (Shapiro-Wilks). Nonparametric testing was then performed with the Kruskal-Wallis test, which also showed at least 1 or more of the groups are significantly different from each other with a χ^2 of 31.5 ($P < .001$). Post hoc analysis of the individual test groups was performed using Tukey's honest significant difference test to see which test groups were significantly different from the others. Numerous differences between groups were significant, enough to state the groups are different, but not in any recognizable group patterns. The significantly different groups in post hoc analyses includes the following: splash guard vs water bottle + 14-ga holes ($P = .004$); 10-mL syringe vs bladder hydration system ($P = .024$); 10-mL syringe + 14-ga catheter vs Ziploc + 14-ga holes ($P = .012$); 10-mL syringe + 14-ga catheter vs water bottle + 14-ga holes ($P = .0003$); Sawyer 50-mL cleaning syringe vs Ziploc + 14-ga holes ($P = .004$); Sawyer 50-mL cleaning syringe vs water bottle + 14-ga holes ($P = .0001$); Ziploc + 14-ga holes vs water bottle sports top ($P = .0057$); Ziploc + 14-ga holes vs bladder hydration system ($P = .0001$); water bottle + 14-ga holes vs water bottle sports top ($P = .0001$); and water bottle + 14-ga holes vs bladder hydration system ($P < .00001$). In short, the devices each provided different pressures upon compression and are generally not comparable to each other.

Discussion

The pressures measured by the methodology used in this study are mostly consistent with previous reports of similar, but not identical, devices tested in a both a human subject model using flow meters and a benchtop experimental landmark study. All systems using compressible water bottles and all syringe-based systems provided pressures meeting or exceeding those measured with a commercial wound irrigation device. A 14-ga punctured plastic bag and bladder-style hydration pack failed to generate irrigation pressures similar to the commercial device, which raises the question of what irrigation pressure is needed to irrigate acute traumatic wounds.

The pressures measured are mostly analogous to pressures published on similar (but not identical) experimental devices using different experimental methods. The 10-mL syringe + 14-ga catheter pressure range of 14–24 psi shows similarity to the 20 psi from a 12-mL syringe + 19-ga needle measurement by Stevenson et al.[4] The low-pressure bladder hydration system pressures (2.1–3.3 psi) are higher but similar to the low-pressure asepto bulb syringe (0.05 psi) also tested in a benchtop model by Stevenson et al.[4] In comparison to studies using human volunteers to compress devices manually, the Ziploc + 14-ga holes measured in ranges similar to a 250-mL intravenous fluid bag + 19-ga holes by Singer et al (1.3–1.9 psi vs 2–5.5 psi).[1] In contrast, Singer et al showed significantly lower pressures with a punctured plastic bottle (16.5 psi vs 2.3 psi), perhaps related to the more compressible nature of a Smartwater bottle in comparison to a medical grade normal saline commercial bottle.[1] These results can be seen visually and in comparison to similarly tested commercial devices previously reported (Figure 4).

The ideal pressure with which to irrigate acute wounds is still under academic debate, in no small part related to a

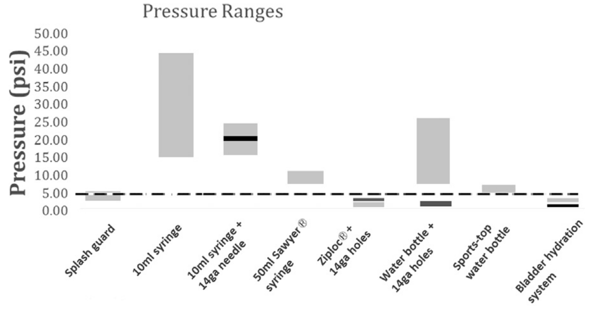

Figure 4. Pressure ranges from the maximum and minimum pressures for each device tested are shown in light gray. Black lines are pressures measured by Stevenson et al[4] on a benchtop model of a 12-mL syringe + 19-ga needle (20 psi) and a 50-mL asepto bulb syringe (0.05 psi). Dark gray lines reflect pressures measured by flowmeter by Singer et al using a pierced 250 mL intravenous fluid bag + 19-ga needle (4 psi), and a water bottle +19-ga holes (2.3 psi). The dashed line is the benchmark: the minimum pressure measured by a commercial device used in a level 1 trauma center (a compressible 500-mL normal saline bottle with splash guard).

lack of agreement regarding what constitutes high and low irrigation pressures. A 2005 review of the literature concluded that the selection of which irrigation technique (high vs low pressure) that would be most beneficial and least harmful to the patient is not possible.[6] The prevailing thought is that constant high-pressure irrigation would be most beneficial for large wounds to dislodge bacteria, and low-pressure irrigation would be better for smaller, clean, noncontaminated wounds.[7] The concern is that if the pressure of the irrigation fluid is too high, destruction of vital tissue may occur, and the end cosmetic result may be affected.[8] The definition of high-pressure irrigation is dependent on the source. The American College of Surgeons defines high pressure as irrigant delivery of 35–70 psi and low pressure irrigation as 1–15 psi.[9] The Wilderness Medical Society latest practice guideline on basic wound management recommends high-pressure irrigation (6–15 psi), especially in the case of open fractures.[10] Low pressure, in this expert consensus, was <6 psi and very high pressures were >15 psi. A 2015 study investigating irrigation of open fractures categorized 3 pressure groups based on the pulsed lavage and handheld, battery-operated irrigators used in the operating room: high pressure (>20 psi), low pressure (5–10 psi), and very low pressure (1–2 psi).[5] A 2010 review on acute wound care noted the paucity of well-supported literature as to the deliverable irrigant pressure as many types of pressure measuring models of varying complexity have been used.[7] Despite the academic debate on what pressure is best, it is agreed that the benefits to wound irrigation are time dependent and the sooner the wound can be irrigated, the better.[11]

The volume of irrigation recommended was not addressed by this study model. There is no current consensus on the volume of irrigant to use with 3–10 L recommended in the literature.[12] A complex wound model utilizing bioluminescent *Pseudomonas* bacteria suggests that higher pressure irrigation (commercial pulsed lavage) achieves the same bacterial wound clearance in 3 L as low pressure methods (bulb syringe) can in 9 L of irrigant solution.[13] Practitioners should keep this rough guideline of 3–10 L of irrigant fluid in mind when approaching acute traumatic wounds with an improvised irrigation technique.

The finding that 2 of the tested improvised devices, the Ziploc + 14-ga holes and the bladder hydration system, failed to meet pressures obtained by a commercial wound irrigation device used in many emergency departments casts doubt on these methods providing sufficient pressure to be recommended for emergency use. However, a potentially practice-changing finding published in 2015 by the Fluid Lavage of Open Wounds (FLOW) investigators reported no change in outcome of complication rates, including infection, regardless of whether high, low, or very low (gravity-pressure irrigation 1–2 psi) was used.[5] In this study, participants enrolled in the study had open extremity fractures and were blinded to the irrigation arm they were assigned. This large, multicenter study concluded the rates of reoperation were similar regardless of irrigation pressure and that very low pressure (gravity pressure 1–2 psi) is an acceptable, low-cost alternative for irrigation. If this is the case, then all of the improvised irrigation techniques tested in this study would be useful for irrigation of wounds in the wilderness setting.

A limitation to our study is that the grip strength by that individual may change if different people perform the irrigation technique. Our study only had 1 person providing all of the testing of the different irrigation devices. In further testing of irrigation pressure, we should include multiple people and see if differences in grip strength affect pressure.

Conclusion

Both the water bottle improvised systems and all syringe-based systems provided pressures at or exceeding those measured with a commercial wound irrigation device used in an emergency department at a level 1 trauma center. A 14-ga punctured Ziploc plastic bag and bladder-style hydration pack failed to generate similar irrigation pressures; however, recent evidence suggests even very low pressures may be effective in reducing bacterial contamination. With that in mind, the authors recommend carrying any of the equipment tested in this article for the use of emergency irrigation, with a preference for devices that would be a normal part of gear supply. In terms of ease of use, the water bottle with the sport top is ideal, being lightweight, already filled with clean water, and taken by most hikers routinely for water storage purposes.

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References

1. Singer A, Hollander J, Subramanian S, Malhotra A, Villez P. Pressure dynamics of various irrigation techniques commonly used in the emergency department. *Ann Emerg Med.* 1994;1:36–40.
2. Singleton A, Davis D, Julian J. The prevention of wound infection following contamination with colon organisms. *Surg Gynecol Obstet.* 1959;108:389–392.
3. Weiss E. Wounds (cuts and abrasions). In: Weiss E, ed. *Comprehensive Guide to Wilderness and Travel Medicine.* 3rd ed. Oakland, CA: Adventure Medical Kits; 2005:88.
4. Stevenson TR, Thacker JG, Rodeheaver GT, Bacchetta C, Edgerton MT, Edlich RF. Cleansing the traumatic wound by high pressure syringe irrigation. *JACEP.* 1976;5: 17–21.
5. FLOW Investigators, Bhandari M, Jeray KJ, et al. A trial of wound irrigation in the initial management of open fracture wounds. *N Engl J Med.* 2015;373: 2629–2641.
6. Chatterjee JS. A critical review of irrigation techniques in acute wounds. *Int Wound J.* 2005;2:258–265.
7. Nicks BA, Ayello EA, Woo K, Nitzki-George D, Sibbald RG. Acute wound management: revisiting the approach to assessment, irrigation, and closure considerations. *Int J Emerg Med.* 2010;3:399–407.
8. Hollander JE, Richman PB, Werblud M, Miller T, Huggler J, Singer AJ. Irrigation in facial and scalp lacerations: does it alter outcome? *Ann Emerg Med.* 1998;31:73–77.
9. Sullivan SR, Engrav LH, Klein MB. Acute wound care. In: Souba WW, Fink MP, Jurkovich GJ, eds. *ACS Surgery: Principles and Practice.* 6th ed. New York, NY: WebMD Professional Publishing; 2007:102–126.
10. Quinn RH, Wedmore I, Johnson EL, et al. Wilderness Medical Society Practice guidelines for basic wound management in the austere environment: 2014 update. *Wilderness Environ Med.* 2014;25:S118–133.
11. Bhandari M, Schemitsch EH, Adili A, Lachowski R, Shaughnessy SG. High and low pressure pulsatile lavage of contaminated tibial fractures: an in vitro study of bacterial adherence and bone damage. *J Orthop Trauma.* 1999;13:526–533.
12. Anglen JO. Wound irrigation in musculoskeletal injury. *J Am Acad Orthop Surg.* 2001;9:219–226.
13. Svoboda SJ, Bice TG, Gooden HA, Brooks DE, Thomas DB, Wenke JC. Comparison of bulb syringe and pulsed lavage irrigation with use of a bioluminescent musculoskeletal wound model. *J Bone Joint Surg Am.* 2006;88: 2167–2174.