Water Decontamination Products for Wound Irrigation in Austere Environments

Benchtop Evaluation and Recommendations

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ABSTRACT

Background: Irrigation is used to minimize infection of open wounds. Sterile saline is preferred, but potable water is becoming more widely accepted. However, the large volumes of water that are recommended are usually not available in austere environments. This study determined the long-term antimicrobial effectiveness of military purification powder compared with currently available civilian methods. The study also compared the physical characteristics and outcomes under the logistical constraints. **Methods:** Six commercially available water decontamination procedures were used to decontaminate five different sources of water (pond water, river water, inoculated saline, tap water, and sterile saline). Each product was evaluated based on six different parameters: bacterial culture, pH, turbidity, cost, flow rate, and size. **Results:** All methods of treatment decreased the bacterial count below the limit of detection. However, they had variable effects on pH and turbidity of the five water sources. Prices ranged from $7.95 to $350, yielding 10–10,000L of water, and weighing between 18 and 500g. **Conclusion**: In austere settings, where all equipment is carried manually, no single decontamination device is available to optimize all the measured parameters. Since all products effectively reduced microbial levels, their size, cost, and production capability should be evaluated for the intended application.

Keywords: *infection; wound care; prehospital care*

Introduction

Readily available potable water is required for soldiers on the battlefield.[1–4] Purified and potable drinking water is routinely transported via air or ground to forward tactical staging areas. However, far-forward and prolonged casualty care scenarios may require civilians or soldiers in austere settings to rely on rucked-in or available groundwater.[5] Soldiers are issued small survival kits, which contain essential survival tools and equipment needed for the austere battlefield, including water purification tablets. These CHLOR-FLOC tablets have not changed since the 1940s and are used to decontaminate water for drinking and washing out wounds.[6] Wound irrigation with a large volume of decontaminated water is a critical step in reducing the risk of infection and preserving tissue function following combat injury.[1–5]

When treating a heavily contaminated combat wound in the prehospital setting, especially if evacuation is delayed, it is crucial to generate large amounts of potable water for irrigation from any available source. Conventionally, open wounds are irrigated with sterile saline, which is usually not available due to size and weight constraints in the far-forward or austere environment. According to preclinical studies and a recent Cochrane review, potable water with similar infection-related outcomes as sterile saline can be used as a substitute.[1–4,7] Commercially available off-the-shelf products can be used to convert contaminated groundwater into drinkable water.[5] In some cases, these products may be quicker and more effective and rugged than CHLOR-FLOC, the traditional standard powder used for military water purification. Herein, we performed a comprehensive search to identify products with appropriate size, weight, price, and rate of decontamination for potentially viable generation of large volumes of water to irrigate wounds in austere environments. This study was conducted to determine how the current military method for decontaminating a water source compares with currently available civilian methods and whether any of the commercial devices would be suitable for the far-forward environment.

Methods

Four portable, commercially available, water purification systems were evaluated along with boiling water and the standard method of personal purification specified by the Army. These systems were organized based on seven key variables to determine their optimal use in an austere environment (Table 1). The tested systems can be categorized into two main mechanisms of purification: chemical methods and filtration/ultraviolet light. Chemical purification techniques use chemicals to kill the bacteria within the water.[8] Several methods of chemical purification are available. Aquamira® Water Treatment drops (Aquamira Technologies, Logan, UT) use chlorine dioxide to kill bacteria. Potable Aqua® Water Purification Germicidal Tablets (Pharmacal, Jackson, WI) release both free iodine and hypoiodous acid into the water to inactivate microorganisms.

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TABLE 1 *Key Criteria for Water Purification Systems Evaluated*

	Method of purification	Volume/ unit or case	Time/ unit-volume	Flow rate	Cost	Effective against					Cube
						Bacteria	Viruses	Protozoa	Chemicals & toxins	Particulate	
Boiling	Thermal	Dependent on container	Boiling once for 3 min, followed by cooling	Dependent on container	none	Yes	Yes	Yes	No	No	Container size
CHLOR-FLOC	Chemical	10L	12–20 min	12–20min/ container	$21.99	Most	Most	Most	Not specified	Yes*	18g
Potable Aqua tablets	Chemical	22.7L	35 min	35 min/ container	$7.95	Yes	Yes	Yes*	Not specified	Not specified	85g
Aquamira Water Treatment drops	Chemical	113.6L	15–30 min	15–30 min	$14.99	Yes	Yes	Yes	Not specified	Not specified	2×28.3g bottles
Steripen FitsAll Filter & Ultralight	Filtration/ UV	20 uses per charge (8000 uses per life)	90 seconds	3L/1.5 min	$114.90	Yes	Yes	Yes	Not specified	Yes (FitsAll filter)	65g (4×3×4in) & 140g (7×2×1in)
Guardian purifier	Filtration	10,000+L	Instant	2.5L/min	$350	Yes	Yes	Yes	No	Yes	0.49kg (8×5×3in)

Source: Public domain information and individual manufacturers' claims.
*Not effective against cryptosporidium.
†Forced sedimentation of particulates suggesting filtration through cloth.
UV = ultraviolet.

The CHLOR-FLOC water purification sachets (Deatrick & Associates, Inc., Haymarket, VA), the long-standing military purification method, use chlorine, a flocculating agent, along with a coagulating agent to promote rapid sedimentation of water pollutants. Filtration/ultraviolet light purification methods use physical filtration to remove the bacteria from the water source and/or ultraviolet light to destroy bacteria. The filtration/ultraviolet methods tested include the Steripen Ultralight combined with the Steripen FitsAll™ Filter (Katadyn Group, Kempttal, Switzerland) to destroy bacteria, protozoa, cysts, and viruses with ultraviolet (UV) light after large particulates are removed through a bottle/canteen-adaptable filter. The Guardian™ Purifier (MSR, Cascade Designs, Inc., Seattle, WA) uses a 0.02μm filter media to remove particulates, bacteria, protozoa, and viruses from water. Each system was used as directed by the manufacturer. Laboratory testing was performed accurately according to the manufacturers' specifications. Boiling (100°C for 30min) was the sixth method evaluated and was used as the gold-standard technique for water disinfection.

Five water samples were collected from local sources for analysis. Fresh water samples, obtained from both pond (Bexar Co., TX) and river (Guadalupe Co., TX), were used to replicate possible water types available in austere environments. Softened tap water (Fort Sam Houston Water Treatment Plant, Fort Sam Houston, TX) was used to represent available municipal water. Sterile normal saline (0.9% NaCl) was used as a negative control. Positive control was sterile normal saline (1L) inoculated with 10^8 colony-forming units (CFU) for a final concentration of 10^5CFU/mL of a clinical *Escherichia coli* strain, a common fresh-water bacterial contaminate that is also known to cause wound infection.

Outcomes

Bacterial Contamination

Bacterial contamination burden was quantified using standard enumeration techniques.[9] Before and after the use of the six methods of purification, aliquots of the five water samples (100μL, 3 each) were spread evenly onto 5% sheep's blood agar (ThermoFisher Scientific, Waltham, MA). Plates were incubated at 37°C overnight and the total CFU count was determined and normalized to volume.

pH

The pH levels of the five water samples (3 technical replicates) were tested at room temperature before and after using the purification method (pH 5+ meter, Oakton Instruments, Vernon Hills, IL).

Turbidity

Water turbidity was measured (3 samples, 6 technical replicates) via spectrophotometry, a quantitative technique used to measure the concentration of a substance based on how much light passes through it.[10] Aliquots of water samples (200μL) at room temperature were analyzed at 750nm (BioTek [Agilent], Santa Clara, CA).

Statistical Analysis

For each product, paired *t* tests were used to compare outcomes before and after product use; where appropriate non-parametric (e.g., signed rank) tests were employed, and *p*-values of ≤.05 (two-sided) were considered statistically significant.

Results

Water from both pond and river carried a pre-treatment bacterial burden of 9.7×10^2 (SD 2.2×10^2) CFU/mL and 9.2×10^2 (SD 2.3×10^2) CFU/mL, respectively. The inoculated saline had a starting concentration of 1.0×10^5 CFU/mL of *E. coli*. Tap water and sterile saline, as expected, did not show any bacterial growth prior to treatment and therefore were excluded from further microbiological assessment. All treatments except the Steripen device with filter and UV light significantly ($p \le .05$) reduced the CFU count of the river water, pond water, and inoculated saline (Table 2). The Steripen device significantly

TABLE 2 *Classification of Recovered Aerobic Bacterial Burden*

	pre-TX	BW	CF	PA	AQ	SP	MSR
Pond water	+	0	–	–	–	–	–
River water	+	–	0	–	+	–	0
Inoculated saline	+	0	0	0	0	–	0

Notes: No growth (0); below limit of detection (–) (<102 CFU); above limit of detection (+) (>102CFU). Sterile saline and tap water post-treatment is not indicated; the pre-TX value was 0.

Pre-TX = CFU before purification; BW = boiling water; CF = CHLOR-FLOC Army purification powder; CFU = colony-forming units; PA = Potable Aqua iodine tablets; AQ = Aquamira drops; SP = Steripen (filter and ultralight); MSR = MSR Guardian purifier.

decreased the CFU count in only the river water (p=.02) and inoculated saline (p=.01) samples. Notably, the Steripen device reduced the bacterial load to levels below the detectable limit, although no statistically significant decrease in bacterial level was observed in the pond water.

As anticipated, the chemical methods of purification altered the pH of the water sources (Figure 1). CHLOR-FLOC, a chlorine purification method, significantly decreased the pH of pond, river, and tap water ($p \leq .05$), while it did not affect the pH of saline or inoculated saline. Potable Aqua and Aquamira, both chlorine purification methods, significantly decreased the pH of all five water sources ($p \leq .05$). Boiling significantly increased the pH of pond and tap water but decreased that of river water ($p \leq .05$). The Guardian filtration device significantly decreased the pH of tap water ($p \leq .05$). The filtration and UV methods of purification had negligible effects on pond and river water or saline pH. The Steripen device, which combines a filter and UV light, did not change the pH of any water source ($p > .05$).

Initially, the water sources were not significantly turbid, with UV values equivalent to 50–100 nephelometric turbidity units (NTU).[10] The three chemical methods of purification increased the turbidity of several water sources ($p \leq .05$; Figure 2) (Table 1). Interestingly, boiling water did not significantly change the turbidity of any water source. As expected, the Guardian filtration device reduced the turbidity of both pond and river water significantly ($p \leq .05$), while the Steripen device did not change the turbidity of any water source.

In addition to determining the decontamination characteristics, unit cost, cube, flow rate, and total volume of purified water per unit were ascertained (Table 1).

Discussion

Large-volume wound irrigation is a critical step in reducing infection risk following combat injury.[1–4,7] However, large volumes of saline or clean water may not be available in the far-forward environment, especially in the austere setting.[5] While the U.S. Military has traditionally utilized water purification tablets, several civilian devices are used currently for

FIGURE 1 *pH of saline/water before (black bar) and after chemical purification (blue bars) or filtration/ultraviolet purification (red bars).*

Horizontal gray bar indicates physiological pH ± 1. Horizontal green bar represents the pH range of sterile, surgical normal saline used for irrigation. Signed rank tests were employed.

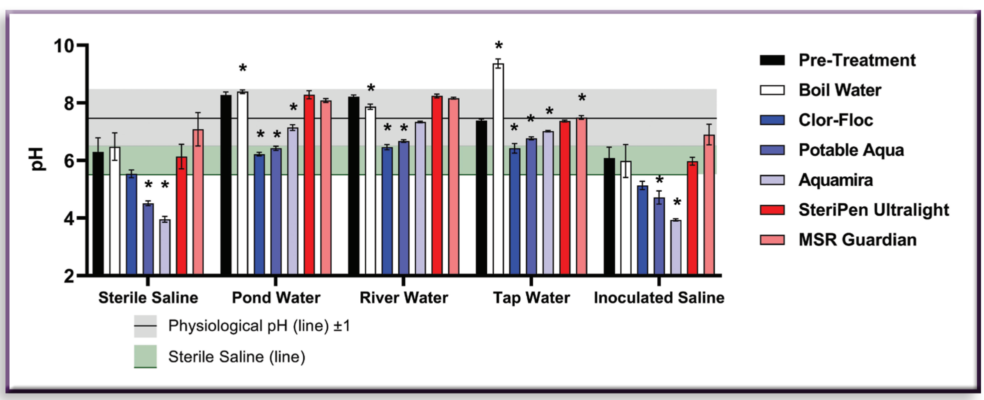
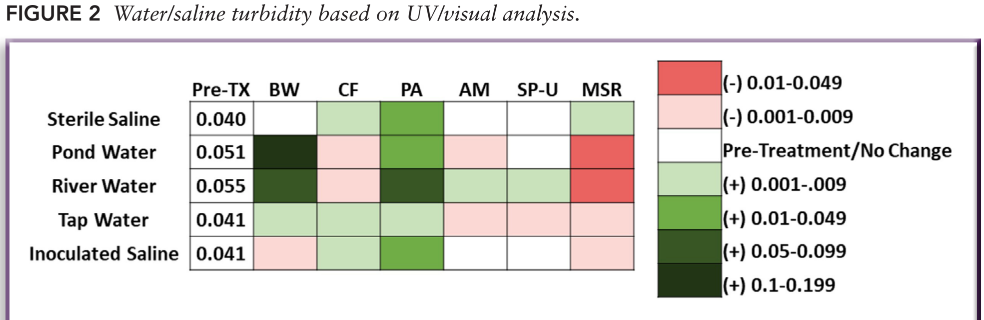


FIGURE 2 *Water/saline turbidity based on UV/visual analysis.*



The red color indicates decrease in turbidity compared with pre-treatment level (pre-treatment). The green color indicates an increase in turbidity compared with pre-treatment level.

Empty boxes = no change in turbidity; red colors = decrease in turbidity; green colors = increase in turbidity. Signed rank tests were employed.

BW = boiling water; CF = CHLOR-FLOC Army purification powder; PA = Potable Aqua iodine tablets; AQ = Aquamira drops; SP = Steripen (filter and ultralight); MSR = MSR Guardian purifier. Pre-TX = turbidity (absorbance at 750nm) before purification.

similar purification tasks. These commercially available devices vary greatly in size, weight, cost, and volume of water throughput. Six different methods of water purification were evaluated and found to effectively reduce the bacterial burden in water. However, no single device was perfect, as each device had both perceived strengths and weaknesses.

Severe, open, battlefield wounds are inherently prone to infection because of their exposure to the environment, contamination with dirt and debris, and blood loss/transfusion.[11] Irrigation with fluids is a primary strategy to remove debris and reduce infection.[12] Accordingly, it is crucial to ensure that no additional bacteria are introduced via contamination with dirty water. All the evaluated products significantly decreased the CFUs of all contaminated water sources (pond and river water and inoculated saline), but only the Steripen device reduced bacteria levels to below detectable limits.

It is generally understood that human pathogenic bacteria thrive in alkaline environments; as such we measured pH in the pond, river, and tap waters used in this study.[13] The use of filtration or boiling decreased the already alkaline pH of the pond, river, and tap water, whereas chemical purification methods raised the acidity of the water. Accordingly, chemical purification may be preferred to filtration.

Turbidity reflects the "cloudiness" or individual particles in any water source and generally indicates the presence of pathogenic microorganisms.[14] As expected, pre-treatment turbidity measurements indicate that only pond and river water sources were more turbid than saline or tap water sources. The Guardian and CHLOR-FLOC methods decreased the turbidity of both river and pond water.

Given the lack of conclusive data from high-quality clinical trials, the optimal combination of CFU count, turbidity, and pH for high-volume wound irrigation is unknown. A multicenter, randomized, prospective clinical study of 634 patients with lacerations identified no differences in infection outcomes between saline and tap water irrigation.[15]

Characteristics, such as flow rate, cost, volume, and size/weight of purification devices, are important metrics to consider for use in austere military and civilian settings. These vary greatly in the products we evaluated. Current recommendations for wound irrigation specify using up to 10L per wound.[4] The Guardian purifier had the highest capacity; however, it was the most expensive and the largest of the methods evaluated. At the other end of the spectrum, the Aquamira was inexpensive and lightweight but delivered a high volume of fluid, which would facilitate treatment of multiple casualties. Other products fall between these devices in terms of desirable features. Balancing flow rate, cube, and cost of the selected device depends on tactical and logistical considerations.

Limitations

The results of the current study should be interpreted in light of several limitations. It was not possible to test the water sources for viruses, protozoa, chemicals, and toxins. Instead, we relied on the manufacturers' descriptions. Notably, the product claims were evaluated and found accurate. The most important limitation was that this study only evaluated in vitro results and not in vivo or clinical outcomes, thus only assumptions can be made about the products' clinical effectiveness.

Conclusion

Based on the results of this study and the feedback received from experienced military physicians, we conclude that a layered approach to water purification is optimal. Notably, CHLOR-FLOC, the product the U.S. Military has used since WWII, has many desirable characteristics and effectively reduces microbial load in contaminated water. In austere settings where all equipment is manually carried, given its high-volume throughput, low cost and cube, and positive effects on pH and water decontamination, the Aquamira drops appear superior to the other small, lightweight products. When weight, cost, and cube are less important (vehicle availability), the Guardian purifier appears to be a superior device.

Author Contributions

NM, DJS, and JCW conceived the study. IBH and SMS coordinated, collected, and analyzed the data. IBH, SMS, JBH, and JCW wrote the first working drafts of the manuscript. All authors read, edited, and approved the final manuscript.

Disclaimer

The views expressed in this article are those of the author(s) and do not reflect the official policy or position of the U.S. Army Medical Department, Department of the Army, DoD, or the U.S. Government.

Disclosures

Dr. Holcomb is a consultant with BARDA, Aspen medical and DoD, is Co-founder, Co-CEO and a Member of the Board of Directors of Decisio Health, the Board of Directors of Hemostatics, QinFlow, Zibrio, and Oxyband. He is also a Co-inventor of the Junctional Emergency Tourniquet Tool.

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