Pulsed Lavage in Wound Cleansing

Wound cleansing is an essential component of wound management used to facilitate the wound healing process.[1,2] Several methods are available for use by the physical therapist to achieve wound cleansing.[1–4] This update reviews the research examining the effects of pulsed lavage in wound cleansing and comparisons with more traditional methods of wound cleansing.

The Necessity of Wound Cleansing

Normal wound healing is characterized by 3 overlapping phases: inflammatory, proliferative or fibroplastic, and remodeling.[5,6] Vascular and cellular responses to trauma occurring during the inflammatory phase remove infectious microorganisms, foreign materials, and necrotic tissue from the wound's surface. During the proliferative phase, tissue granulation and reepithelialization occur.[5,6] Collagen fibers are deposited in the dermis of the skin during the remodeling phase to strengthen the healing wound.

If the body's inflammatory response is inadequate to overcome surface microorganisms, a wound is predisposed to infection, delaying wound angiogenesis and granulation.[7] In the 1950s, Liedberg et al[8] showed that when bacterial concentrations of streptococci, pseudomonas, or staphylococci were greater than 100,000 organisms per gram in tissues, skin grafts on rabbits were destroyed. In 1969, Robson and Heggers[9] summarized military and civilian studies examining the critical level of bacterial burden necessary to produce wound sepsis and failure to heal. They concluded that wound healing is possible only when bacterial counts are maintained at a concentration of 100,000 organisms per gram or less.

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Impediments to healing are not limited to the presence of microorganisms on the wound's surface. Winter,[10] for example, suggested that the presence of eschar or scab in a dry wound delays wound epithelialization and contraction. Likewise, Constantine and Bolton[11] surmised that the presence of necrotic tissue or eschar, within the wound or at the wound's margin, impedes wound contraction and closure. Elek[12] concluded that necrotic tissue in a wound provides an environment that facilitates wound infection. Current medical practice includes wound cleansing and debridement to remove impediments to the healing process to facilitate the progression from the inflammatory phase to the proliferative phase of wound healing.

The most common terms used to describe the actions taken to remove impediments to wound healing are "cleansing" and "debridement." Although frequently used interchangeably, these terms are differentiated in this article as follows. *Cleansing* involves the use of a fluid to remove loosely attached cellular debris and surface pathogens contained in wound exudate or residue from topically applied wound care products.[1,3,4,13] *Debridement* refers to the use of mechanical or chemical means to remove adherent material from a wound.[2,13] Common wound adherents include necrotic tissue and foreign matter, such as residual topical agents. This article focuses on methods of wound cleansing rather than debridement in wound management.

How do the effects of pulsed lavage compare with more traditional methods?

In the Agency for Health Care Policy and Research's (AHCPR) *Treatment of Pressure Ulcers: Clinical Practice Guideline No. 15*,[2] Bergstrom et al stated that the process of wound cleansing involves 2 steps: (1) selection of a wound cleansing solution and (2) selection of a mechanical means for delivering that solution to the wound. Bergstrom et al recommended the use of normal saline for cleansing most pressure ulcers. Our review of the literature confirms that normal (isotonic) saline is the most common irrigating solution (irrigant) used in research. Of the 21 studies examining the cleansing effects of pulsed lavage reviewed for this article, normal saline or saline with antibiotic preparations was used in 15 studies, tap water was used in 3 studies, and surfactants were used in 2 studies. For 1 study, the type of irrigant used was not described. Although solutions other than isotonic saline are used in wound cleansing, a detailed discussion of them is beyond the scope of this article.

Mechanical force used in wound cleansing may be produced through lightly "scrubbing" with gauze or sponges or by using mechanical irrigation. The AHCPR guideline recommends irrigation pressures ranging from 4 to 15 psi.[2] It suggests that irrigation pressures of less than 4 psi may be insufficient to remove surface pathogens and debris and that irrigation pressures greater than 15 psi may cause wound trauma and drive

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Table 1.
Commonly Used Wound Cleansing Methods, Associated Pressures, Effects, and Limitations

Method	Pressure (psi)	Effects	Limitations
Pour bottle	0–1	Removal of loose surface pathogens and debris	Insufficient pressure to achieve wound cleansing[14,18–26]
Bulb syringe	0–1	Removal of loose surface pathogens and debris	Insufficient pressure to achieve wound cleansing[14,18–26]
Piston syringe	8	Effective cleansing of traumatic wounds[27,28]	Small reservoir requires repeated filling; may prove time-consuming Single stream of fluid delivered
Piston irrigation system[a]	4–8	No controlled studies available	Output pressures are at lower end of cleansing efficacy[2]
Whirlpool agitation	Unknown	Removal of surface pathogens from intact skin[29] Limited removal of bacteria from burn wounds[30]	Clinicians unable to calibrate output or impact pressures Immersion may cause: · increased systemic demands on patients' cardiovascular and respiratory systems[31–35] · periwound skin maceration[36,37] · dependent edema[3,38,39] · cross-contamination[40–43]
Whirlpool hose sprayer	Unknown	Removal of surface pathogens from intact skin[29] Limited removal of bacteria from burn wounds[30]	Clinicians unable to calibrate output or impact pressures

[a] Canyons Wound Irrigation System, Canyons International, 1226 E 2nd Ave, Salt Lake City, UT 84103.

bacteria into wounds. These pressure range recommendations were derived from studies conducted by Brown et al,[14] Rodeheaver and colleagues,[15,16] Wheeler et al,[17] and Stewart et al,[18,19] and a series of studies performed at Walter Reed Army Hospital.[20–23]

Commonly used wound cleansing methods include the use of pour or squeeze bottles, bulb syringes, piston syringes (a 35-mL syringe attached to a 19-gauge needle or angiocatheter), piston irrigation systems, whirlpool agitation, and a whirlpool hose sprayer attachment. Table 1 summarizes these methods' resultant pressures, effects, and limitations.[2,3,14,18–43]

Pulsed Lavage in Wound Cleansing

Pulsed lavage is defined in this article as the delivery of an irrigating solution (or irrigant) under pressure that is produced by an electrically powered device. Irrigation under pressure may be delivered concurrently with suction, removing the irrigating solution from the target area. In wound cleansing, pulsed lavage is used to remove infectious agents and debris from a wound's surface. This method of wound cleansing is known by various names, including "lavage," "jet lavage," "mechanical lavage," "pulsatile lavage," "mechanical irrigation," and "high-pressure irrigation."

During the 1960s, military medical personnel recognized that bacterial concentrations greater than 100,000 organisms per gram on the wound's surface predispose the wound to sepsis and delayed wound healing and sought an effective method to achieve wound cleansing and debridement in combat settings in Vietnam.[23,24] Cleaning and debriding traumatic, contaminated combat wounds using pulsed lavage was the subject of a series of studies conducted at the United States Army Institute of Dental Research at Walter Reed Medical Center.[20–23,25] Studies examining the efficacy and safety of pulsed and constant-stream irrigation in wound cleansing and debridement were conducted in civilian settings.[14–19,26] These studies form the basis for this update.

Physical Properties of Pulsed Lavage

In establishing the rationale for pulsed lavage in wound cleansing, researchers first described the forces holding bacteria and other contaminants on the wound's surface and opposing forces necessary to remove foreign matter from the wound. Madden et al[24] identified 3 adhesive forces holding bacterial particles on the wound's surface: capillary, molecular, and electrostatic. They proposed 3 types of forces that could be used to remove bacteria from the wound's surface: direct mechanical contact (eg, scrubbing), inertial forces, and fluid dynamic forces. Fluid dynamic forces are the effective forces in wound irrigation using pulsed lavage.

Rodeheaver et al[15] quantified both the output and impact pressures produced by "high-pressure" irrigation using Bernoulli's equation:

$$P/p + gz + V^2/2 = \text{constant}$$

where P equals pressure (in pounds per square inch), p equals fluid density (in pounds per cubic inch), V equals fluid speed (in inches per second), g equals acceleration of gravity (in inches per second squared), and z equals elevation height (in inches). Rodeheaver et al began their evaluation of irrigation pressures by calculating the fluid's pressure at the point of exit from the orifice of the irrigating device, or its *output pressure*. After calculating the fluid's speed and assuming that zero energy is gained from changes in elevation from the irrigation nozzle to the wound's surface, the researchers applied Bernoulli's equation to yield the *impact pressure* at the wound's surface:

$$P = V^2 p/2$$

where P equals pressure at the tissue surface (in pounds per square inch), V equals speed of fluid at the nozzle (in inches per second), and p equals fluid density (in pounds per cubic inch) (constant for a given fluid).

Although the study by Rodeheaver et al[15] is commonly referred to in subsequent research and in manufacturers' literature, it is unclear whether their method of calculating irrigation impact pressures is accepted as absolute or as a "gold standard." Quantification of impact pressures provides researchers with a method of measuring the effects of pulsed lavage at varying pressure levels. Other researchers did not use uniform methods of reporting pressures as either the output pressure measured at the nozzle or the impact pressure measured at the tissue's surface. Wherever appropriate, output or impact pressures are reported.

Animal Studies Using Pulsed Lavage

In the bulk of the studies reviewed for this article, the use of pulsed lavage in wound cleansing was examined using animal models in controlled settings. In the earliest studies, researchers sought to establish the minimum pressure necessary to remove debris and bacteria from the wound's surface. Several authors[18–23] found irrigation at pressures of ≤1.0 psi to be ineffective for removing debris and preventing infections in artificially contaminated wounds. Madden et al[24] studied the ability of irrigation at output pressures of 0.5, 10, and 25 psi to cleanse artificially produced wounds on rats contaminated with *Staphylococcus aureus* and *Escherichia coli*. Impact pressures were not reported. The authors concluded that although gentle irrigation at both 0.5 and 10 psi reduced the number of surface bacteria, these output pressures were ineffective in preventing development of clinical infection. *Clinical infection* is defined as the presence of bacteria or other microorganisms in sufficient concentration (100,000 organisms per gram of tissue) to overwhelm the tissue defenses and produce the inflammatory signs of infection (ie, purulent exudate, odor, erythema, warmth, tenderness, edema, pain, fever, and elevated white blood cell count).[2] However, wounds irrigated at an output pressure of 25 psi were found to develop clinical infections at lower rates.

Rodeheaver et al[15] studied the effect of irrigation on the removal of *S aureus* and soil particles from experimentally contaminated wounds in 4 groups of rats. Each group was exposed to 1 of 4 impact pressures: 1, 5, 10, or 15 psi. Impact pressures of both 1 and 5 psi, although removing 48.6% and 50.3% of the contaminants, respectively, were ineffective at preventing infection. The animals in both groups developed clinical wound infections. The groups exposed to impact pressures of 10 and 15 psi experienced removal of 75.7% and 84.8% of wound contaminants, respectively. The infection rates of these groups were lower than incidence rates for the group exposed to irrigation at an impact pressure of 1 psi.

Stevenson et al[27] compared bacterial removal between "low-pressure" irrigation produced by a bulb syringe (0.5 psi) and "high-pressure" irrigation using 12- and 35-mL piston syringes through 19-gauge needles (20 and 7 psi, respectively). They reported that piston syringe irrigation, at both pressure levels, removed greater amounts of bacteria than did the bulb syringe method. Actual rates of bacterial removal between wounds receiving irrigation at 20 and 7 psi were not reported.

In addition to investigating the effects of varied output and impact pressures on removal of contaminants and infectious agents, researchers have also compared the effects of continuous and pulsed irrigation. *Continuous irrigation* is the delivery of an uninterrupted stream of irrigant to the wound's surface. Continuous irrigation may be produced by a variety of methods, including the use of a pour bottle, bulb syringe, piston syringe, whirlpool, and a hose sprayer attachment to the whirlpool. In addition, selected mechanical irrigation devices may be set to deliver a continuous stream of irrigant. *Pulsed irrigation* refers to the intermittent or interrupted delivery of irrigant to the wound's surface. Although pulsed irrigation may be manually interrupted using the methods mentioned, this term is most frequently reserved for irrigation produced by an electrically powered irrigation device. The number of pulses per second, or frequency, produced by mechanical irrigation varies among manufacturers.

Table 2.
Summary of Cleansing Effects of Pulsed Lavage at Varying Pressure Levels

Pressure (psi) Output	Impact	Removes Debris	Prevents Infection	Decreases Surface Bacteria	Side Effects	Investigator
0.5			Ineffective	Limited		Madden et al[24]
	≤1.0	Ineffective	Ineffective	Ineffective		Brown et al,[14] Rodeheaver et al[15]
	2.2	Ineffective				Grower et al[21]
	4.0	Effective				Grower et al[21]
	5.0	Ineffective	Ineffective	Ineffective		Rodeheaver et al[15]
	5.8		Effective		No bacteremia[25]	Grower et al,[21] Gross and colleagues[23,25]
	5.8 (w/streptomycin and penicillin)		Effective			Gross et al[25]
	5.8–8.8 (w/vancomycin and streptomycin)		Effective			Cutright et al[22]
	10	Effective	Effective	Effective		Rodeheaver et al[15]
	15	Effective	Effective	Effective		Rodeheaver et al[15]
25 (continuous irrigation removed more bacteria than pulsed irrigation)		Effective				Green et al,[19] Madden et al[24]
	25	Effective	Effective	Effective		Rodeheaver et al[15]
42		Ineffective	Effective			Saxe et al[45]
	50		Effective			Brown et al[14]
>50					No bacteremia	Tamimi et al[44]
60 (no statistical difference in debris removal between pulsed and continuous lavage)		Effective				Green et al[19]
70			Ineffective		Dispersion of irrigant No bacteremia Impaired wound infection defenses	Wheeler et al[17]
90		Effective				Green et al[19]

Rodeheaver et al[15] compared the cleansing efficacy of pulsed and continuous irrigation at 10 and 15 psi. They concluded that when pulsed and continuous irrigation are delivered at equal pressures, they are equally effective in the removal of bacteria. Similarly, Stewart et al[18] found that when equal volumes of irrigant were delivered at an output pressure of 60 psi, no difference existed between the amounts of bacteria removed by pulsed irrigation and constant irrigation. In the companion study, Green et al[19] found no difference in quantities of debris (iron filings) removed between pulsed and constant-stream irrigation at 60 psi. However, when Madden et al[24] compared bacterial removal between pulsed and continuous irrigation at an output pressure of 25 psi and equal volumes of saline, they concluded that continuous irrigation at 25 psi removed greater amounts of *S aureus* bacteria than did pulsed irrigation at the same pressure. Based on the available studies using animal models, the amount of irrigation pressure appears to be the determining factor in successful wound cleansing, whereas the effects of continuous and pulsed irrigation appear equivocal. Table 2 summarizes the cleansing effects of pulsed lavage at varying levels of pressure.[14,15,17,19,21–25,44,45]

Clinical Efficacy of Pulsed Lavage

One of the earliest references to the clinical application of pulsed lavage in wound cleansing was a 1978 clinical note in *Physical Therapy*, in which Nourse and Myers outlined the use of a dental irrigating device to cleanse a pressure ulcer.[46] In 1984, Diekman reported the healing rates of pressure ulcers that either were irrigated using a dental irrigating device or received "routine care."[47] Diekman matched 8 subjects according to wound surface area and assigned them to 2 groups. The experimental group received twice-daily treatments

using the dental irrigating device for 2 weeks, and the control group received twice-daily treatments using "routine care" for the same length of time. Neither output nor impact pressures of the irrigating device were reported, nor was "routine care" defined. Although the experimental group demonstrated greater average decreases in wound dimensions, statistical analysis of the changes in wound surface areas did not indicate differences between the 2 groups.

Given the dearth of clinical studies examining the effects of whirlpool and pulsed lavage individually, it is not surprising that clinical studies comparing whirlpool and pulsed lavage are similarly scant. In 1975, Niederhuber et al[29] compared the effects of whirlpool immersion with spray irrigation produced by the whirlpool spray hose attachment in their abilities to reduce normal bacteria on intact skin. The authors compared the effects of whirlpool agitation with 3 alternative treatments: (1) spray irrigation alone, (2) the combination of whirlpool agitation followed by spray irrigation, and (3) soaking without agitation. Spray irrigation output pressure was 500 dynes/mm^2, or 7.25 psi, applied for 30 seconds, with the spray head positioned 15 cm from the skin's surface. Impact pressures were not reported. The authors found whirlpool agitation alone to be a better technique of bacterial removal than either spraying or soaking. More importantly, they found that agitation followed by spray irrigation had the greatest effect, rinsing away 70% of the remaining contaminants and removing 95% of bacteria that were present on the skin's surface at the start of the treatment.

Using a single-subject repeated-measures design, Bohannon[48] compared the effects of whirlpool agitation alone with whirlpool agitation followed by spray irrigation on the removal of bacteria from a venous insufficiency ulcer. Bacterial counts were measured indirectly by taking bacteria from the water in the whirlpool before whirlpool treatment, after the whirlpool treatment, and after the whirlpool followed by spray irrigation of the ulcer. Water pressure during irrigation was not measured. Instead, the pressure was increased to patient tolerance for 30 to 90 seconds. Mean values for bacterial colonization from the water samples following whirlpool alone and whirlpool followed by irrigation were compared. Bohannon found that whirlpool plus irrigation removed 4.1 times more bacteria from the wound's surface than did the whirlpool treatment alone.

Haynes et al[49] compared the effects of pulsed lavage and whirlpool on the rate of formation of granulation tissue in 13 subjects with a variety of chronic open wounds. Seven subjects received pulsed lavage, and 6 subjects received whirlpool. The rate of granulation tissue formation for patients receiving pulsed lavage (12.2% per week) was greater than the granulation rate of patients receiving whirlpool (4.8% per week).

Safety of Pulsed Lavage in Wound Care

Concerns have been raised regarding potential hazards associated with using "high-pressure" pulsed lavage in wound cleansing. Several researchers have investigated the potential risks, which include the development of bacteremia following lavage of contaminated wounds, traumatization of wounds, and dissemination of particulate matter or bacteria through the wound to surrounding tissues. For example, Tamimi et al[44] studied whether human subjects developed bacteremia following the use of an oral irrigation device (Water-Pik*). Participants were 10 subjects with gingivitis, 10 subjects with periodontitis, and 10 subjects in a control group who were free of periodontal disease. All subjects brushed their teeth twice daily. The subjects in the groups with gingivitis and periodontitis followed brushing with irrigation using a water irrigation device with the pressure control set at 6 on the dial (>50 psi output pressure). Blood samples were drawn from all subjects before and after the first exposure to water irrigation. Subsequent blood samples were collected 15, 45, and 60 days later. Analysis of the blood samples provided no evidence that subjects in the control group or those with periodontal disease developed bacteremia after exposure to high-pressure oral irrigation.

Gross et al[50] used an animal model to examine whether lavage causes bacteremia. They artificially contaminated wounds on 75 rats with samples of *S aureus, Pseudomonas aeruginosa, Klebsiella pneumoniae,* and *Proteus mirabilis* at a concentration of $3 \times 10^7/0.03$ cc of soil. Thirty minutes after contamination, the wounds were lavaged at an output pressure of 70 psi (impact pressure of 5.88 psi) for 30 seconds. Samples of blood were obtained 2, 5, 10, 20, and 30 minutes after lavage and cultured for 10 days. Although isolated samples contained growth of *S epidermidis,* Gross et al found that none of the bacteria used in wound contamination were isolated in blood cultures. They concluded that the isolated bacterial growth of *S epidermidis* resulted from contamination with indigenous skin bacteria and that under the controlled circumstances of their study, the probability of bacteremia was negligible.

Beasley[51] examined whether tissue damage and particle penetration could be induced in intact tissues with pulsed lavage. Using suspensions of spherical polymer beads in water, Beasley lavaged the intact oral mucosa of albino rats at output pressures of 50, 60, 70, 80, and 90 psi. The rats were exposed to irrigation for 30 seconds at a distance of 1.9 to 2.54 cm from the irrigation source.

* Teledyne Water-Pik, 1730 E Prospect Rd, Fort Collins, CO 80553-0001.

Effects on tissues irrigated with polymer suspensions were compared effects on tissues irrigated at identical pressure levels using only tap water. Beasley found that, regardless of pressure level, pulsed lavage only inconsistently pushed surface contaminants into the mucosal epithelium. Furthermore, he found no evidence of contaminants reaching the underlying tissues. However, irrigation with the polymer suspension produced increased epithelial damage and edematous changes at all pressure levels when compared using irrigation with tap water. Irrigation with tap water alone produced only occasional epithelial and connective tissue disruption, regardless of pressure level. In a similar study using lower output pressures, O'Leary et al[52] demonstrated that high-pressure irrigation (20 and 40 psi) using tap water alone did not push surface contaminants through intact epithelial surfaces.

Wheeler et al[17] studied the potential tissue damage and particle penetration produced by pulsed irrigation in artificially produced wounds. They examined (1) whether high-pressure irrigation leads to dissemination of foreign bodies and irrigant through wound surfaces and (2) whether high-pressure irrigation results in impaired resistance of the wound to infection. Wheeler et al compared the effects of piston syringe irrigation at an output pressure of 8 psi and pulsed irrigation at 70 psi (impact pressures were not reported) with a control group receiving no irrigation. Standardized surgical wounds in Yorkshire pigs, contaminated with *Serratia marcescens*, were subjected to either piston syringe or pulsed irrigation, or no irrigation. They found that high-pressure irrigation spread fluids 14±1 mm laterally from the wounds and 3±1 mm beneath the wounds, whereas low-pressure irrigation produced only 3±1 mm of lateral dissemination and negligible penetration. Analysis of tissues surrounding the wounds revealed that bacteria did not accompany the dispersed fluids in either experimental group. Although effectively removing bacteria from the wounds' surfaces, Wheeler et al reported that wounds irrigated with both high-pressure and piston syringe irrigation demonstrated comparable infection rates (71% and 69%, respectively) that were greater than that of the control group (12.5%). The authors surmised that both pulsed lavage and syringe irrigation result in tissue trauma that makes wounds more susceptible to infection. Although these results reduce concerns about high-pressure irrigation of wounds disseminating contaminants into adjacent tissues, Wheeler et al warned that high-pressure irrigation might impede tissue defenses against infection. Based on the results of their study, Wheeler et al cautioned that high-pressure irrigation should not be used indiscriminately. Rather, its use should be reserved for heavily contaminated wounds.

Summary and Conclusions

The literature suggests that the amount of pressure used in irrigation is the key variable to achieve effective wound cleansing. Pressures of 1 psi or less have been found to be of little clinical value for wound cleansing. Although surface bacterial counts are reduced by irrigation in general, the literature indicates that higher pressures are more effective. Surface debris, such as loose necrotic tissue and wound exudate, has been shown to be most effectively removed using pressures between 5 and 10 psi. Irrigation pressures above 10 psi protect the wound from gross infections. Inconsistencies in reporting output and impact pressures, described previously, create confusion in performing a meta-analysis of research results. Future research examining the efficacy of pulsed lavage must demonstrate consistency in reporting impact pressures at the tissue's surface.

Research comparing the efficacy of continuous or intermittent (pulsed) lavage procedures has produced less clear results. The results of one study[15] suggest that both methods are effective at removing surface bacteria when using pressures of 10 to 15 psi, whereas another study[24] suggests that continuous irrigation is more effective than pulsed irrigation at removing bacteria at 25 psi. Clearly, additional research is needed that compares the effects of pulsed and continuous irrigation at a variety of pressure levels, before suggesting a preferred method. Until there is definitive evidence, it may be advisable to eliminate the use of the phrase "high-pressure irrigation" when referring to pulsed lavage because "pulsed lavage" refers only to the application of an intermittent stream of fluid regardless of the pressure level.

Research comparing the effectiveness of whirlpool and pulsed lavage on wound cleansing is scant. Two studies[29,48] suggest that pulsed lavage following whirlpool agitation is more effective at removing bacteria than lavage alone. In a recent study,[49] however, pulsed lavage was found to be more effective than whirlpool in promoting wound healing. Additional clinical studies comparing the effects of pulsed lavage and whirlpool on wound cleansing and healing are needed. Recognizing the progressive financial restrictions facing the clinician, future comparisons should also include cost analyses of the 2 methods. Total costs per incident, number of treatments required to achieve wound closure, and per-treatment costs should be included.

Pulsed lavage appears to be a safe method for wound cleansing. Research has demonstrated no evidence of bacteremia following lavage applications, regardless of pressure. Concerns that "high-pressure" (output pressure of 70 psi) lavage may disseminate contaminants to surrounding tissues appear to be unwarranted, but more

research needs to be conducted in order to confidently apply pulsed lavage to all types of wounds at all stages of the healing process. Until more convincing controlled studies are performed, establishing safe levels of irrigation pressure in wound cleansing, Rodeheaver's[4] suggestion needs to be heeded: continue to use the AHCPR guideline of irrigation pressures between 4 and 15 psi.

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