A commentary by Thomas G. Harris, MD, and Casey Pyle, DO, is linked to the online version of this article at jbjs.org.

Wound-Healing Following Negative-Pressure Wound Therapy with Use of a Locally Developed AquaVac System as Compared with the Vacuum-Assisted Closure (VAC) System

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Investigation performed at CLMMRH, Bacolod City, Philippines

Background: Negative-pressure wound therapy (NPWT) gained widespread clinical use after its introduction in the 1990s because of its many beneficial effects on the wound environment. However, high treatment costs have limited its use in third-world countries. The present study compares a low-cost, locally developed NPWT system with a commercially available system in terms of efficacy, reliability, ease of application, and safety.

Methods: This prospective, randomized controlled trial involved 36 patients who were managed with NPWT with either a low-cost, locally developed system (AquaVac) or a commercially available Vacuum-Assisted Closure Advanced Therapy System (VAC ATS; KCI). The low-cost NPWT system described consists of a converted aquarium pump as a reusable vacuum source and a dressing system that can be found in the hospital supply room: food plastic wrap as an occlusive drape, surgical gauze as wound filler, nasogastric tubes as tubing, and used intravenous (IV) bottles as effluent canisters. The purpose of the study was to compare the 2 systems in terms of (1) time to apply the dressing, (2) exudate levels, (3) amount of granulation tissue, (4) wound size reduction, (5) average cost of treatment, (6) visual analog scale (VAS) pain scores, and (7) complications.

Results: The experimental low-cost system had a small but statistically insignificant advantage over the commercially available system in terms of application time, pain during dressing changes, and wound contraction percentage. The 2 systems were comparable in terms of the amount of exudate, granulation tissue coverage, and VAS scores during the course of treatment. No wound or periwound complications were observed. The systems were significantly different in terms of cost, with the AquaVac system being 7 times less expensive than the VAC ATS system ($63.75 compared with $491.38 USD).

Conclusions: The low-cost AquaVac system was shown to be comparable with the commercial VAC ATS system, suggesting that it is an effective and safe alternative method for NPWT in resource-challenged settings.

Level of Evidence: Therapeutic Level I. See Instructions for Authors for a complete description of levels of evidence.

Negative-pressure wound therapy (NPWT) involves the application of subatmospheric pressure into a closed, sealed system of dressing[1-3]. Since its introduction in the 1990s, it has rapidly become an important tool in wound management. However, NPWT's cost has limited its use, especially in third-world countries[4-6]. Worse, many patients

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with devastating soft-tissue injuries live in resource-challenged environments, further compounding the problem[7-9].

The mechanisms of NPWT include macrodeformation of the wound, with the wound edges being brought closer together. Microdeformation of the wound surface produces a 5% to 20% strain across the healing tissues, which promotes cell division and proliferation, growth factor production, and angiogenesis. Extraction of edema fluid and exudate from the extracellular space improves recovery of damaged tissues. The maintenance of a warm and moist environment prevents desiccation of the wound and enhances the formation of granulation tissue[10-12].

NPWT improves the outcomes of wound care, significantly shortening the duration of hospitalization[13-15]. Previous studies have demonstrated no significant differences between foam-based and gauze-based dressings[16-18]. In previous studies, a homemade foam-based NPWT system has been found to be cost-effective and economically viable in comparison with the commercially available vacuum-assisted closure (VAC) system[19,20]. A plethora of NPWT modifications have been tried in an attempt to reduce cost without compromising efficacy and safety[21-26]. These modifications of the NPWT system were not inferior to the patented VAC system[27-31]. A bedside suction machine also has been utilized to apply negative pressure intermittently[32-34]; however, that machine can be intolerably loud and overheats quickly, necessitating intermittent use.

Regimens combining NPWT with repetitive debridement, irrigation, and antibiotics have been shown to reduce the bacterial load and the rate of infection[35-37]. The use of NPWT decreased time to wound closure, the length of hospitalization, and the number of surgical procedures. The locally developed AquaVac system was developed with adherence to the principles of NPWT. This system consists of an inexpensive, reusable vacuum source (a converted aquarium pump equipped with a pressure gauge and pressure regulator) and a dressing system that can be easily found in the hospital supply room (including food plastic wrap as an occlusive drape, surgical gauze as wound filler, nasogastric tubes as tubing, and used intravenous [IV] bottles as effluent canisters). This system ensures that a surgical unit does not

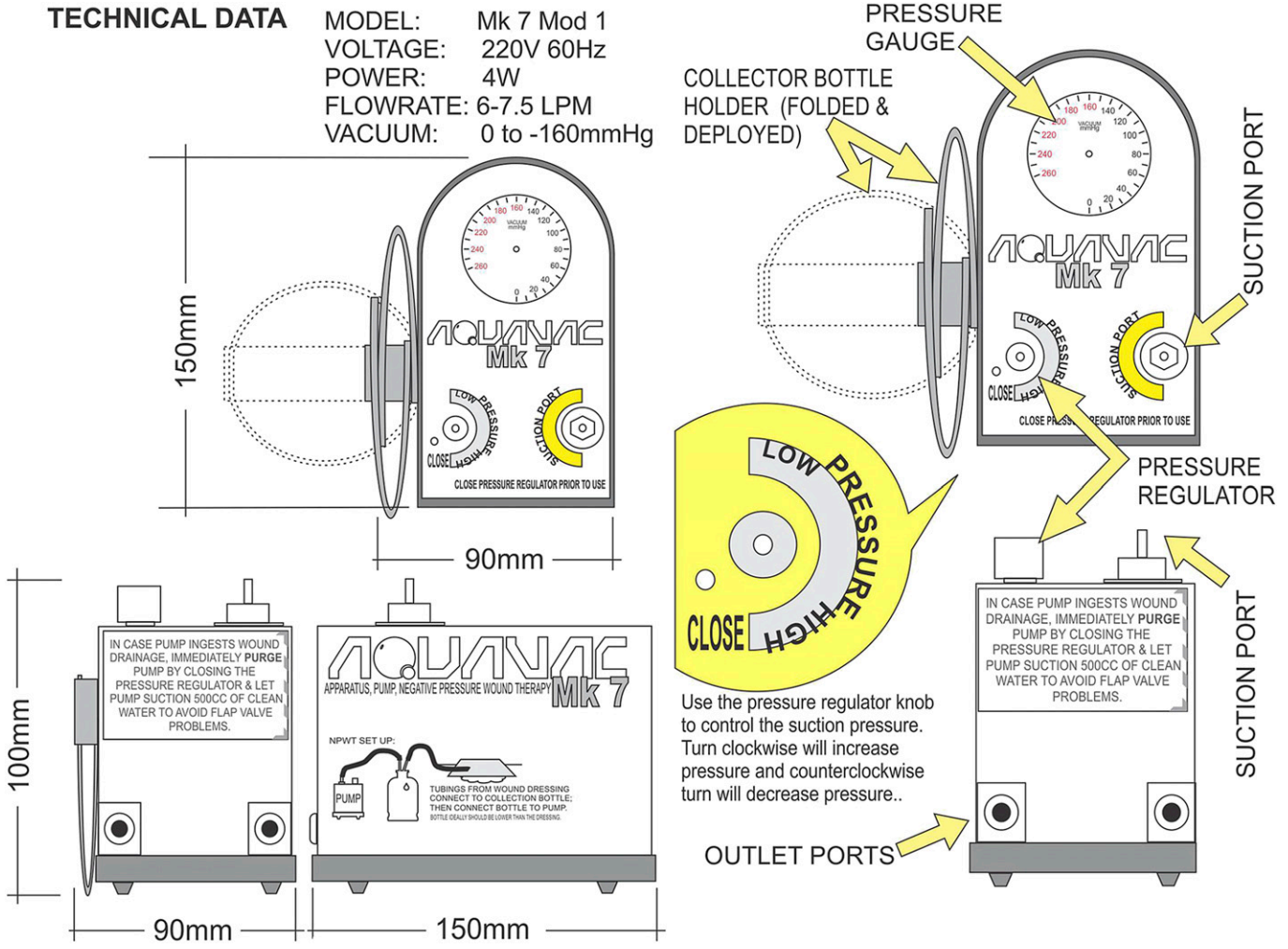

Fig. 1
The AquaVac system machine.

have to be dependent on a supply of expensive and model-specific NPWT dressings.

Materials and Methods

The present prospective, randomized controlled trial was conducted in a tertiary hospital in Bacolod City, Philippines, and was approved by the hospital's research ethics review committee. The study involved 36 patients who were managed with NPWT with either a low-cost, locally developed system (AquaVac) or a commercially available system (Vacuum-Assisted Closure Advanced Therapy System [VAC ATS]; KCI) for 7 days. All patients were admitted from March 1, 2018, to October 31, 2018, for the treatment of acute traumatic injuries to the upper or lower limbs with substantial soft-tissue involvement and skin loss that was not amenable to primary closure. Patients who had surgical contraindications because of medical conditions, chronic wounds, implant exposure, and multiple injuries or polytrauma were excluded from the study. All patients who were included were randomly allocated into treatment groups utilizing the random "fish bowl" method with 50% chance. (Specifically, 100 rolled papers were placed inside a container, 50 of which were marked as AquaVac group and the other 50 were marked as VAC ATS group. A random rolled paper was picked to determine the treatment group and then was returned to the container to maintain the 50% chance.)

Interobserver variability was assessed by having a third, blinded person evaluate outcomes by verifying the results and measurements. The wounds were measured with use of a clear 5 × 5-mm grid sheet and photographed. The dressing materials for the low-cost NPWT (AquaVac) group were sterilized in the institution's central supply section. The AquaVac system machine and dressing setups are shown in Figures 1 and 2. The VAC ATS machine and dressing materials were used according to their specifications. In both groups, a splint was applied to the extremity for immobilization, and continuous negative pressure (−120 to −125 mm Hg) was applied[38]. The outcome measures were collected from the patient charts and were recorded by the principal investigators. The outcome measures included (1) dressing application time (time recorded), (2) exudate levels (amount measured in the canister), (3) area of wound bed covered by healthy tissue (measured with use of a 5 × 5-mm grid), (4) size reduction (determined by comparing the measurements before and after application of NPWT), (5) cost (average costs for all the materials used per patient), (6) visual analog scale (VAS) pain scores (recorded as scheduled monitoring), and (7) the presence of complications such as infection (noted at the end of the treatment or dressing change).

Statistical analysis was performed with use of SPSS software (version 20; IBM). Descriptive statistics (frequencies, percentages, cross-tabulations) were used for summarizing the data for each group. The statistical tools used were the independent t test (with the Levene test for equality of variances), Pearson product moment correlation coefficient, and Spearman rank correlation coefficient.

Results

From March 1 to October 31, 2018, a total of 38 eligible patients were seen; 2 were excluded (1 did not meet the inclusion criteria, and the other declined to participate). The remaining 36 patients were included in the study and were randomly allocated into 1 of the 2 treatment groups. No patient was lost to follow-up or withdrew from the study (Fig. 3).

The majority of patients were male, were 18 to 34 years of age, and had avulsion-type soft-tissue injuries due to road traffic accidents, mostly involving the leg. The 2 groups did not differ in terms of age, sex, mechanism of injury, and extremity involved.

The AquaVac dressing was faster to apply (5.5 minutes) than the VAC ATS dressing (7.5 minutes), but the difference was not significant (t = 1.730, degrees of freedom [df] = 34, p = 0.093) (Table I). There was moderate and significant correlation between wound size and the time needed to apply the dressing in the VAC ATS group (r = 0.636, p = 0.006) but not in the AquaVac group (r = 0.277, p value = 0.250). That is, in the VAC ATS group, the bigger the size of the wound, the longer the time it took to apply the dressing. In the AquaVac group, however, the wound size did not influence the time that it took to apply the dressing.

With regard to exudate levels, the 2 groups did not differ significantly from each other, with the average amounts in the

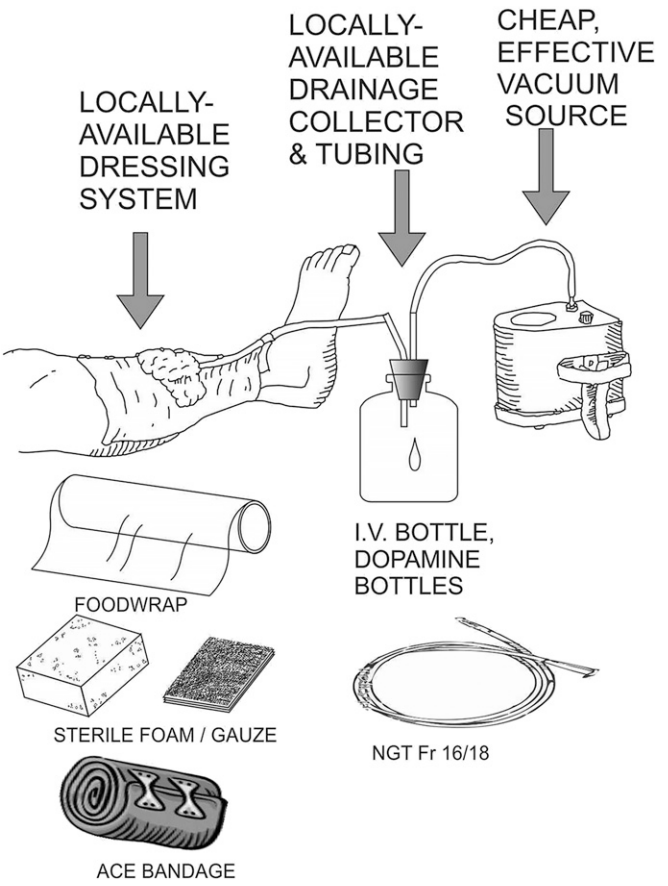

Fig. 2
The AquaVac system dressing set-up.

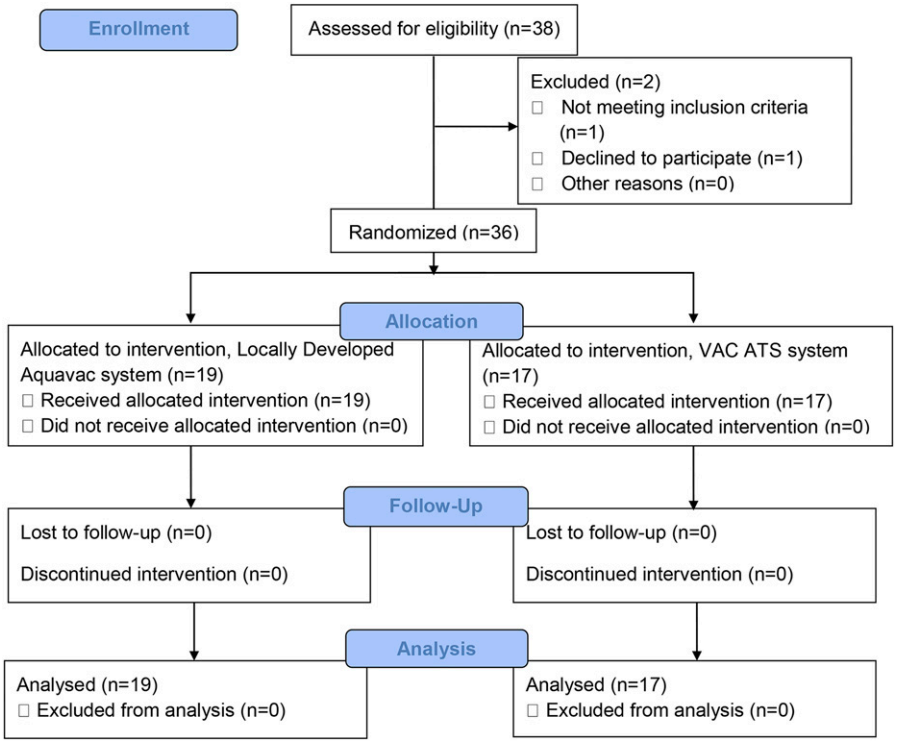

Fig. 3

CONSORT (Consolidated Standards of Reporting Trials) flow diagram.

VAC ATS and AquaVac groups being 198 and 161 mL, respectively. There was a significant correlation between the exudate level and wound size in both the VAC ATS group ($r = 0.898$, $p = 0.000001$) and the AquaVac group ($r = 0.601$, $p = 0.006$), implying that the bigger the size of the wound, the higher the amount of the exudate.

In all wounds, a large part of the wound bed area was covered by healthy granulation tissue in both the VAC ATS and AquaVac groups (98.01% and 97.16%, respectively). The average reduction in wound size was greater in the AquaVac group than in the VAC ATS group (19.50% compared with the 14.99%, respectively). The results related to the amount of granulation tissue and reduction of wound size were not significantly different between the 2 treatment groups (Table II). Representative photographs of wounds involving the leg, foot, and forearm in the 2 groups are shown in Figures 4 and 5. Wound photographs for all 36 patients who were enrolled in the study are shown in the Appendix.

Patients in both groups reported mild pain during the duration of NPWT treatment (VAS score, 3 to 4). The VAS scores on Day 7 (during dressing changes) showed that majority of patients (9 patients; 52.9%) in the VAC ATS group reported moderate pain (VAS score, 5 to 7), whereas the majority of patients in the AquaVac group (10 patients; 52.6%) reported mild pain (VAS score, 1 to 2). However, the cross-tabulation showed no significant difference at the 0.05 level (Table III). There was a significant correlation between pain and wound size on Days 1 to 7 in both the VAC ATS group ($r_s = 0.494$, $p = 0.044$) and the AquaVac group ($r = 0.790$, $p = 0.00006$). On Day 7, the correlation between pain and wound size was significant in both the VAC ATS group ($r_s = 0.641$, $p = 0.006$) and the AquaVac group ($r = 0.615$, $p = 0.005$), suggesting that, even when the wound had reduced in size, the intensity of the pain was still directly related to the would size.

There were no deep infections involving wounds or periwound complications in either of the 2 groups. No pump in

TABLE I Independent Sample Tests for Time Required to Apply Dressing*

Levene Test for Equality of Variances		T Test for Equality of Means				
F	Significance of Variances	T	df	P Value (2-Tailed)	Mean Difference *(min)*	Standard Error of Difference *(min)*
0.752	0.392	1.730	34	0.093	1.98427	1.14677

*The AquaVac dressing was faster to apply (5.5 minutes) than the VAC ATS dressing (7.5 minutes), but the difference was not significant ($t = 1.730$, $df = 34$, $p = 0.093$). df = degrees of freedom.

TABLE II Amount of Exudate, Granulation Tissue, and Wound Size Reduction*

Variable	Treatment Group	Mean	Standard Deviation	Mean Difference	T	df	P Value (2-Tailed)
Approximate amount of exudate *(mL)*	VAC ATS	197.647	181.160	36.858	0.696	34	0.491
	AquaVac	160.790	135.567				
Percentage of granulation tissue	VAC ATS	98.012	4.209	0.853	0.532	34	0.598
	AquaVac	97.159	5.279				
Wound size (granulated) after NPTW *(cm^2)*	VAC ATS	159.635	137.159	68.901	2.018	17.714	0.059
	AquaVac	90.735	33.551				
Wound size (not granulated) after NPTW *(cm^2)*	VAC ATS	2.750	6.177	0.090	0.046	34	0.963
	AquaVac	2.660	5.500				
Wound size before NPWT *(cm^2)*	VAC ATS	188.647	158.694	73.831	1.867	17.791	0.079
	AquaVac	114.816	39.679				
Wound size after NPWT *(cm^2)*	VAC ATS	162.427	139.843	69.032	1.979	17.847	0.063
	AquaVac	93.395	35.514				
Wound size reduction *(cm^2)*	VAC ATS	26.221	19.858	4.800	0.896	34	0.377
	AquaVac	21.421	11.657				
Wound size reduction *(%)*	VAC ATS	14.987	3.549	−4.515	−1.839	22.893	0.079
	AquaVac	19.501	10.022				

*The results related to the amount of exudate, granulation tissue, and wound size reduction showed no significant difference between the 2 treatment groups at the 0.05 level. df = degrees of freedom.

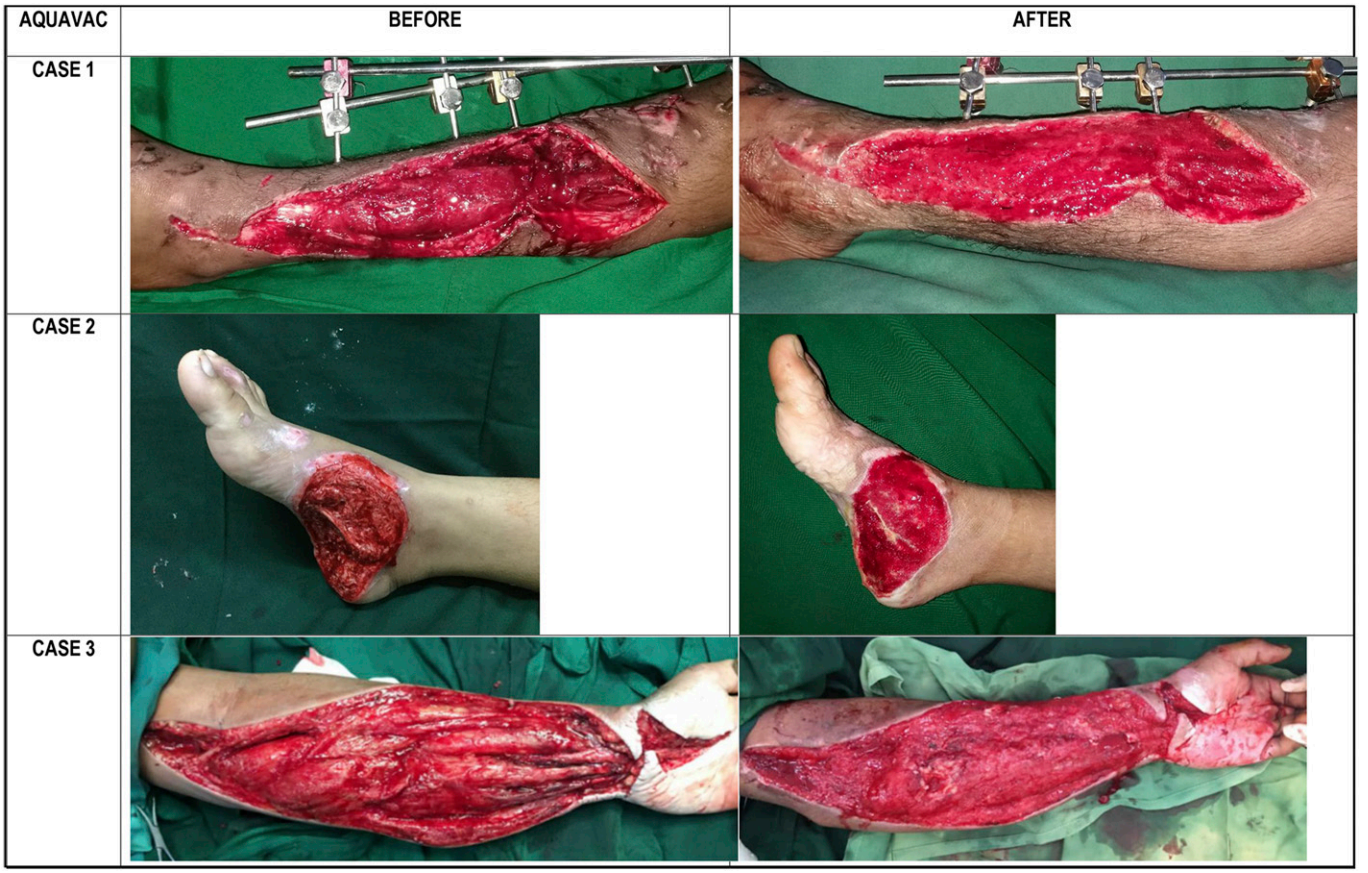

Fig. 4

Representative wound photographs of the leg, foot, and forearm of patients in the AquaVac group before and after application of NPWT.

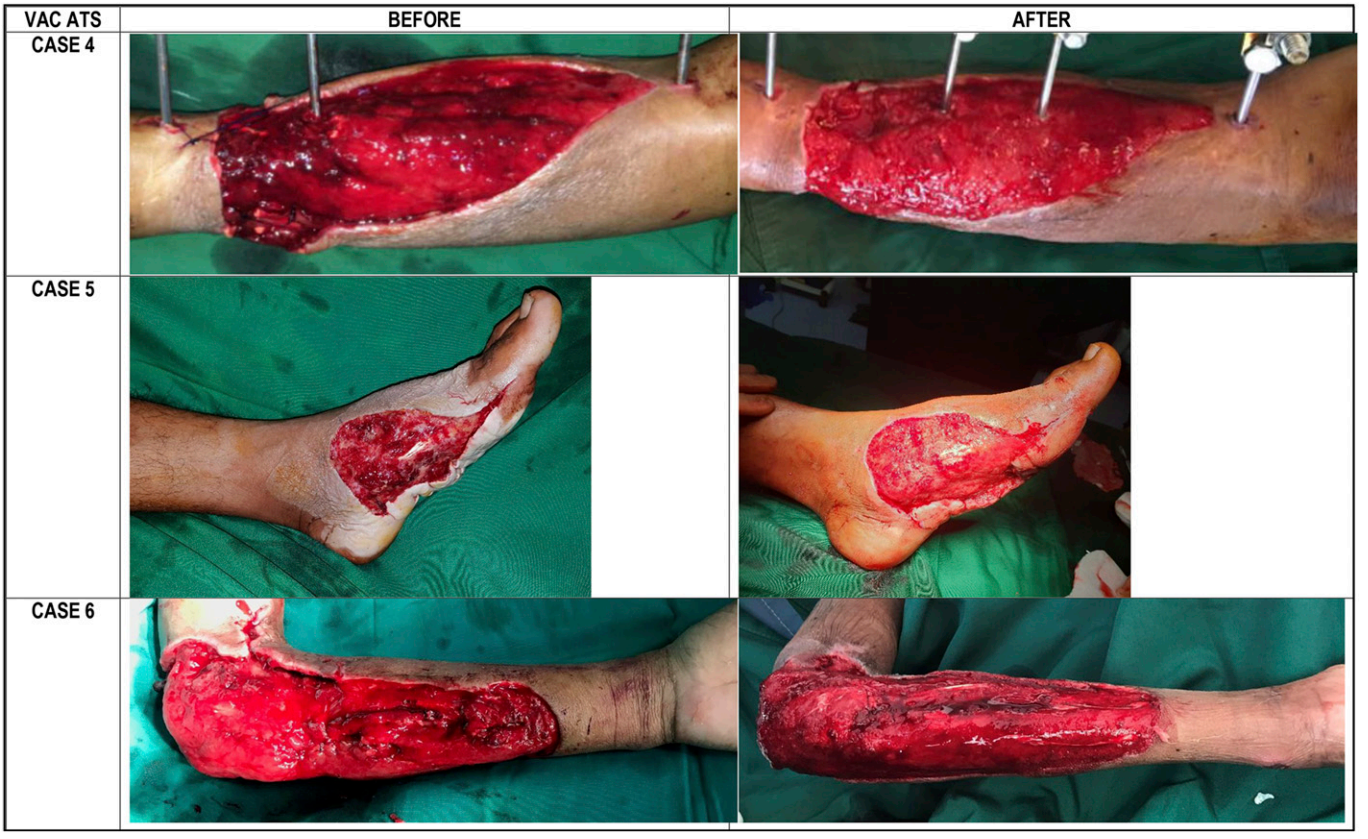

Fig. 5

Representative wound photographs of the leg, foot, and forearm of patients in the VAC ATS group before and after application of NPWT.

either group failed or malfunctioned during the 7-day treatment period.

The average cost for a 7-day NPWT treatment regimen was $491.38 USD per patient for the VAC ATS group (including the local price for the pump rental, dressing, and canister) and $63.75 USD per patient for the AquaVac group (with the pump being considered single-use; if the pump were to be used several times, the costs would be considerably lower). The cost analysis showed that the AquaVac system was at least 7 times cheaper than the VAC ATS system.

TABLE III Average VAS Scores Measured on Days 1 to 7 and Day 7*†

Level of Pain‡	VAC ATS Group (N = 17)	AquaVac Group (N = 19)	Total (N = 36)
Days 1-7			
None (1-2)	5 (29.4%)	8 (42.1%)	13 (36.1%)
Mild (3-4)	10 (58.8%)	9 (47.4%)	19 (52.8%)
Moderate (5-7)	2 (11.8%)	2 (10.5%)	4 (11.1%)
Severe (8-10)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Total	17 (100.0%)	19 (100.0%)	36 (100.0%)
Day 7			
None (1-2)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Mild (3-4)	4 (23.5%)	10 (52.6%)	14 (38.9%)
Moderate (5-7)	9 (52.9%)	7 (36.8%)	16 (44.4%)
Severe (8-10)	4 (23.5%)	2 (10.5%)	6 (16.7%)
Total	17 (100.0%)	19 (100.0%)	36 (100.0%)

*Cross-tabulation shows that there was no significant difference between columns of the same row at the 0.05 level. †The values are given as the number of patients, with the percentage in parentheses. ‡The VAS pain scores associated with each pain category are shown in parentheses.

Discussion

The present study showed that the low-cost AquaVac NPWT system was not inferior to the commercial VAC ATS system. There were no significant differences between the systems in terms of application time, exudate levels, wound size reduction, and granulation tissue formation. These results agree with the findings of previous studies regarding granulation formation, edema control, and facilitation of wound closure[11,39-43]. Adequate surgical debridement until viable tissues are present in the wound base is needed. Both systems were comparable in terms of reducing the edema and wound exudate, which agrees with previous findings[44-46]. The study involved a 7-day continuous application of NPWT and demonstrated no significant difference between the 2 groups in terms of the reduction of wound size. These observations were promising and demonstrated a positive response of the wound, with reduction of the wound surface area, in agreement with previous studies[47-49].

While there were differences between the groups in terms of pressure fluctuations during the first 72 hours of treatment, these fluctuations may have been due to the fact that the converted aquarium pump's pressure had to be regulated manually, whereas the VAC ATS pump had an automated pressure regulation system and thus had no fluctuations.

The low-cost AquaVac NPWT system consists of (1) a vacuum source and (2) modified dressings. The vacuum source is a modified aquarium aerator pump. An oscillating coil moves a magnetic lever back and forth, which in turn operates a bellows or diaphragmatic pump. This mechanism is quiet, can continuously operate for days or weeks without overheating, and consumes a small amount of electricity (4 W). A pressure regulator and pressure gauge were added to enable the user to manually regulate the suction from 0 to −160 mm Hg. The pump cost $60.00 USD to modify. While inexpensive enough to be disposable, the pump can be reused up to 20 times. In comparison, the average cost of commercially available NPWT pumps range from $2,500 to $6,000 USD. These modified pumps are assembled with use of basic industrial tools and semi-skilled labor.

The second component of the system is the modified dressing. Food wrap (e.g., Cling Wrap [Glad] or Saran Wrap [SC Johnson]) is used as an occlusive drape, sterile surgical gauze is used for wound filler, Vaseline (Unilever)-impregnated gauze (e.g., Bactigras [Smith & Nephew]) is used as a barrier dressing for exposed tendons or bone, nasogastric tubes are used as tubing, and empty IV bottles are used as effluent canisters. All of these materials can be easily found in the operating room (anesthesiologists routinely use food wrap for temperature regulation in limbs of pediatric patients), and 1 dressing change costs only $3.65 USD. In comparison, 1 VAC dressing set costs $57.69 USD and a disposable canister costs $52.88 USD, for a total of $110.57 USD.

The use of food wrap (Cling Wrap, Saran Wrap) as an occlusive dressing may not be ideal but is adequate for this purpose. Its lack of adhesive produces some air leakage, leading to minor pressure fluctuations shortly after application. The seal is tenuous in the area where the tubing exits the occlusive drape. Sealing this area with surgical tape usually solves the problem. The presence of body hair and dry, scaly skin also present problems with the seal, but not so much as to cause inadequate pressure. Applying petroleum jelly (e.g., Vaseline) on the periwound skin helps in sealing the dressing. The presence of external fixator pins also presents a challenge; utilizing multiple sheets and tape around the pins helps. The key is an adequate flow rate of the pump. If the suction flow is greater than the air leakage (which, in this case, it is), the seal and pressure are maintained.

Improvising canisters from IV bottles is fairly straightforward. A rubber stopper with 2 metal tubes is used; 1-cc syringe barrels also work. In fact, even soda or beer bottles can be used, and they can be easily steam-autoclaved.

Adequate surgical debridement was done when necessary. Once the wounds had a good granulating bed and were amenable to skin, the 2 NPWT dressing systems were used as skin-graft bolsters.

The AquaVac group had lower pain scores during dressing changes than the VAC ATS. This may be due to the granulation tissue ingrowth into the foam used by VAC ATS system.

The limitations of the present study included the low number of patients and the 7-day treatment period. The potential for selection bias was addressed through randomization, and the potential for detection bias was addressed by having third blinded person verify and measure the variables.

Patient comfort is one of the benefits associated with the use of NPWT[50]. There was no significant difference between the 2 treatment groups, and VAS pain scores were highly correlated with wound size, indicating that greater wound size was associated with greater pain. In the present study, we did not observe any cases of infection or periwound complications. This observation agrees with the findings of previous studies[51-55].

Traditionally, the use of NPWT has been thought to be associated with higher costs. Today, however, the use of NPWT is more practical and inexpensive as the costs of NPWT are offset by a lower number of operations, less-time-consuming dressing changes, and shorter hospital stays[56-59]. Our cost analysis indicated that the locally developed AquaVac system was approximately 7 times cheaper than the VAC ATS system. Our findings suggest that potential savings can be achieved, while maintaining the quality of wound care needed by the patients, especially in areas with limited resources[60-62].

Conclusions

The present study showed that the 7-day results associated with the low-cost AquaVac NPWT system were not inferior to those associated with the commercially available VAC ATS system. There were no significant differences between the

systems in terms of application time, exudate levels, wound size reduction, and granulation tissue formation. In addition, although the difference was not significant, the VAS pain scores were lower in the AquaVac group during dressing changes at Day 7. Other notable findings were that wound size was highly correlated with the amount of wound exudate and the VAS scores.

The main difference between the 2 NPWT systems is the cost: the AquaVac system is at least 7 times cheaper than the commercial VAC ATS system. Such an economical method for delivering NPWT—which is noninferior to the gold standard—greatly impacts surgical units in developing countries, where most patients needing such treatments are those who can scarcely afford it. With such a system in place, cost becomes far less of an issue, and the decision on whether to use NPWT rests on whether the wound requires the benefits of NPWT or not. However, it should be noted that any NPWT system should not be used as a substitute for adequate surgical debridement and, where indicated, prompt definitive closure.

Appendix

eA Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJS/F532). ■

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