

Original Article

Ultrasonic debridement promotes wound healing and enhances infection control compared with surgical debridement in diabetic foot ulcers: a propensity score-matched retrospective study

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Abstract: Objective: To compare wound healing rates, infection control, tissue perfusion, and quality-of-life outcomes between low-frequency ultrasonic debridement (UD) and surgical debridement in patients with diabetic foot ulcers (DFUs). Methods: This single-center, retrospective study included 298 DFU patients treated in the Department of Burns and Plastic Surgery at the Central Hospital of Xuzhou from January 2021 to January 2025. Patients were grouped by the first documented debridement method: UD (n=142) or surgical debridement (n=156). Propensity score matching (PSM) at a 1:1 ratio was used to balance baseline confounders, resulting in 230 patients (115 per group). The primary outcome was the 12-week complete healing rate. Secondary outcomes included healing time, wound area reduction, infection control rate, antibiotic use, transcutaneous oxygen pressure (TcPO₂) changes, Wollina Wound Score, safety, and the 36-Item Short Form Health Survey (SF-36) scores. Results: After PSM, baseline characteristics were well balanced. The 12-week healing rate was significantly higher in the UD group than in the surgical debridement group (67.8% vs. 53.9%; P<0.05). Median healing time was significantly shorter in the UD group (15.3 weeks vs. 21.6 weeks; log-rank P=0.003). UD was associated with a greater wound area reduction (81.4% ± 20.7% vs. 70.3% ± 24.5%; P<0.05) and a higher infection control rate (75.7% vs. 60.9%; P<0.05). The cumulative antibiotic days were fewer in the UD group (median 21.0 vs. 28.0 days; P<0.05). Improvements in TcPO₂ and Wollina Wound Score were significantly greater with UD (P<0.001). The SF-36 physical and mental component summary scores improved more in the UD group (both P<0.001). Rates of major amputation and overall adverse events did not differ significantly between the two groups. Conclusion: Weekly low-frequency UD was associated with improved healing, infection control, tissue perfusion, and quality of life compared with surgical debridement in DFU patients, with a comparable safety profile.

Keywords: Diabetic foot ulcer, ultrasonic debridement, surgical debridement, infection control, propensity score matching

Introduction

Diabetic foot ulcers (DFUs) affect approximately 15-25% of patients with diabetes during their lifetime and are a leading cause of non-traumatic lower-limb amputations worldwide [1]. Chronicity in DFUs is driven by persistent biofilm, hyperinflammation, and microcirculatory dysfunction, which render standard wound care insufficient [2, 3]. Therefore, effective debridement that removes biofilm and necrotic tissue

while preserving healthy tissue is pivotal [4]. Surgical debridement remains the reference standard, but it is invasive, may cause bleeding and pain, and is not always suitable for patients with coagulopathy or severe pain sensitivity [5]. Low-frequency ultrasonic debridement (UD) has emerged as a non-invasive alternative that uses cavitation and acoustic streaming to disrupt biofilms and stimulate microcirculation [6]. Although one recent randomized pilot study favored UD over standard care, large-scale real-

world comparisons that adequately control for confounding factors by indication are lacking. The present study innovatively applies propensity score matching (PSM) to balance baseline ulcer severity and vascular status, and comprehensively evaluates not only healing metrics but also infection burden, tissue perfusion, quality of life, and safety, thereby providing robust evidence for clinical decision-making.

With the development of biomedical engineering, debridement technology based on low-frequency ultrasonic energy is gradually being applied to chronic wound management [7]. Low-frequency UD is a non-contact or micro-contact physical debridement method that can selectively remove necrotic tissue and biofilm via cavitation and acoustic streaming. In addition, studies have shown that it may stimulate local microcirculation and promote the release of growth factors [8, 9]. A recent preliminary randomized clinical trial suggested that compared with standard wound care, weekly UD can significantly reduce wound area and improve the wound bed condition [10, 11].

At present, most comparative studies have small sample sizes and do not fully control for key baseline factors affecting wound prognosis, which may lead to bias in the results [12, 13]. This is particularly true in the real-world clinical setting, where the type of debridement that patients receive is often affected by multiple factors such as ulcer severity, infection, vascular status, and resource availability, making it difficult to accurately evaluate the net effect of the debridement technique itself through simple group comparison [14]. Furthermore, the evaluation of debridement efficacy should not be limited to macro measures of healing rates, but should also comprehensively consider multidimensional indicators including infection control, the need for antibiotic use, improvement in local tissue perfusion, and treatment safety. However, such comprehensive evaluation has been incomplete in previous studies [15].

Therefore, this study aims to systematically compare the effects of low-frequency UD and surgical debridement on wound healing rates, infection control indicators, and safety in patients with DFU through a retrospective cohort study, with strict application of PSM to control baseline confounders, so as to provide an evi-

dence-based basis for clinical decision-making using real-world data.

Materials and methods

Patient selection and search methods

This single-center retrospective cohort study identified patients through a systematic search of the electronic medical record system and the wound care database of the Department of Burns and Plastic Surgery, Central Hospital of Xuzhou. The search, performed using structured queries based on diagnostic codes for DFU and procedure codes for debridement, initially retrieved all patients diagnosed with a DFU who underwent professional debridement between 1 January 2021 and 31 January 2025. A total of 410 records were screened. This retrospective study was conducted in accordance with the Declaration of Helsinki and was approved by the Medical Ethics Committee of the Central Hospital of Xuzhou (XZXY-LJ-20250508-051). Because the study involved analysis of existing anonymized clinical data, the requirement for informed consent was waived by the ethics committee.

Patients were consecutively evaluated against pre-specified inclusion and exclusion criteria.

Inclusion criteria were: (1) Age ≥ 18 years; (2) Confirmed diagnosis of type 2 diabetes mellitus; (3) A foot ulcer classified as Wagner grade 2 (ulcer extending to tendon, bone, or joint capsule) or grade 3 (deep ulcer with abscess or osteomyelitis); (4) The first planned, professionally documented debridement at Central Hospital of Xuzhou was either low-frequency UD or surgical debridement; (5) Complete baseline assessment data before debridement and follow-up data for at least 24 weeks, or until a definitive endpoint was reached (ulcer healing, major amputation, death, or loss to follow-up).

Exclusion criteria were: (1) Ankle-brachial index ≤ 0.7 or transcutaneous oxygen pressure ($TcPO_2$) < 30 mmHg, indicating severe limb ischemia requiring revascularization; (2) Clinical or radiographic evidence of Charcot neuro-osteoarthropathy; (3) Radiographic (X-ray or MRI) confirmation of osteomyelitis before the index debridement; (4) Pregnant or lactating women; (5) $> 20\%$ of key baseline or outcome data missing (e.g., missing initial ulcer area, unclear

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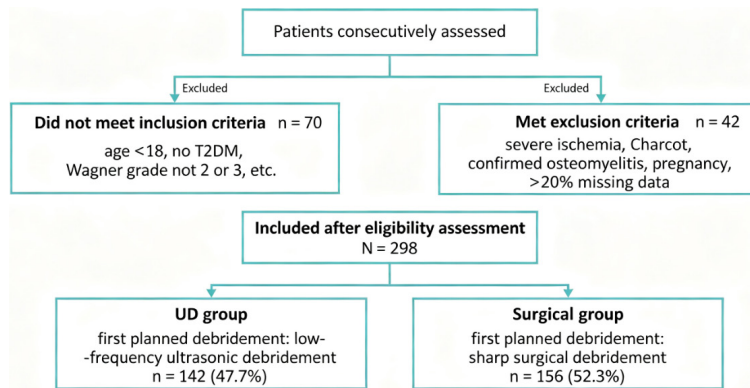


Figure 1. Flow diagram of patient selection and group assignment. Note: UD, ultrasonic debridement; T2DM, type 2 diabetes mellitus.

debridement method, or undocumented healing/amputation status).

After applying the eligibility criteria, 298 patients were included. Based on the first documented planned professional debridement abstracted from the medical record, the cohort was divided into two groups: those who received low-frequency UD (UD group, $n=142$, 47.7%) and those who underwent surgical debridement (surgical group, $n=156$, 52.3%). This distribution reflects the concurrent use of the two techniques in routine clinical practice at the center during the study period.

The exposure was defined as the first planned professional debridement. In the UD group, treatment consisted of low-frequency, non-contact UD administered once weekly using the MIST Therapy® System (Celleration, Inc., Eden Prairie, MN, USA). The device delivers ultrasound at a frequency of 40 kHz with a power output of 0.1-0.5 W/cm², in a non-contact mode with the probe held 1-2 mm from the wound bed and moved slowly to cover the entire ulcer; treatment duration was approximately 1-2 minutes per cm² (total ≤ 20 minutes). In the surgical group, sharp debridement with sterile instruments (scalpel, tissue scissors, curette) was performed in a treatment room or operating theater, aiming to excise all non-viable tissue down to a bleeding, healthy base, typically every 1-2 weeks based on wound status. Both groups uniformly received standard of care: offloading (therapeutic footwear, total contact cast), modern moisture-retentive dressings, comprehensive diabetes management (glycemic control, nutritional support), and infection management according to IWGDF guidelines.

Because this was a retrospective study, the sample size was not based on an a priori power calculation; instead, all eligible patients within the study period were consecutively enrolled. After enrollment, a post hoc power analysis was performed. Assuming 12-week complete healing rates of 65% (UD group) versus 45% (surgical group), based on historical center data, and using a two-sided $\alpha=0.05$ with a chi-square test, the achieved power with 298 patients exceeded 85%,

confirming that the sample was sufficient to detect clinically meaningful differences.

The choice of the initial debridement method was made by a multidisciplinary diabetic foot team comprising an endocrinologist, a podiatric/vascular surgeon, and a wound care specialist. The team discussed the advantages and limitations of each debridement approach (UD vs. surgical debridement) with the patient and/or legal guardian, including expected benefits, risks, and potential need for repetition. Treatment was then determined based on a combination of the patient's clinical condition, the recommendations of the team, and the informed preference of the patient/guardian. Patients were not randomly assigned to treatment groups; the allocation was the result of real-world clinical decision-making, which is why PSM was employed to minimize selection bias (Figure 1).

Data extraction and validation

Data were retrospectively extracted using a pre-designed, pilot-tested standardized electronic case report form. Two diabetic foot specialist nurses, blinded to the study hypotheses, performed independent, back-to-back extraction of all variables from the electronic medical record and wound care database. For continuous variables such as ulcer area, when multiple measurements were recorded, the values closest to the pre-debridement assessment (within 72 hours) and to the scheduled follow-up time points (e.g., 4 weeks, 12 weeks) were extracted.

After extraction, the two datasets were compared. Any discrepancies were resolved by joint

review of the original medical records; if consensus could not be reached, a third senior podiatrist arbitrated. Data consistency was further ensured by random re-abstraction and verification of 10% of the medical records.

Outcome measures

The primary outcome was the 12-week complete healing rate, defined as complete epithelialization of the ulcer with no drainage or crusting, as determined independently by an investigator blinded to group assignment using wound photographs and written clinical records.

Secondary outcomes, each with pre-specified measurement time points, were:

(1) Median time to healing: number of days from the first debridement to complete healing; cases without healing, major amputation, or death were censored.

(2) Relative percentage reduction in wound area at 12 weeks: $[(\text{baseline area} - \text{area at week 12}) / \text{baseline area}] \times 100\%$. Wound area was measured by tracing the outline on sterile transparent acetate film and calculating the area with digital software (ImageJ) or a specialized wound ruler.

(3) Clinical infection control rate at week 4: defined according to IWGDF criteria as complete resolution or marked improvement in at least two clinical signs of infection (erythema, pain, increased skin temperature, purulent discharge) compared with baseline, without escalation of antibiotics or additional surgical intervention for infection progression.

(4) Cumulative days of systemic antibiotic therapy: total number of days on systemic (oral or intravenous) antibiotics for foot-ulcer-related infection from the first debridement until healing, amputation, or the 24-week end of follow-up.

(5) Change in TcPO_2 (ΔTcPO_2): difference between the baseline TcPO_2 (measured within 72 hours before debridement) and the week-4 value, obtained under standardized conditions (probe at 44°C on healthy skin 2-3 cm from the ulcer edge, after a 20-min rest period).

(6) Wollina wound score at week 4: a composite score (0-9) assessing granulation tissue quality

(0-3), epithelialization (0-2), exudate amount (0-2), and necrotic tissue amount (0-2); higher scores indicate a better wound bed. Two raters independently scored the wound using concurrent records and photographs, and the mean value was used.

(7) Incidence of major amputation: proportion of patients undergoing amputation at or above the ankle during follow-up.

(8) Rate of debridement-related adverse events: events directly attributable to the debridement procedure, including significant bleeding requiring compression bandaging or surgical intervention, increase in pain (Visual Analogue Scale increase of ≥ 3 points within 72 hours requiring additional analgesia), and new local signs of infection within 7 days post-procedure.

Statistical analysis

All analyses were performed in R version 4.3.0. Variable distribution was assessed with the Shapiro-Wilk test. In the pre-matched sample, normally distributed continuous data were summarized as mean $\pm$ standard deviation and compared with independent-samples t-tests; non-normally distributed data were summarized as median (IQR) and compared with Mann-Whitney U tests. Categorical variables were reported as frequencies (percentages) and compared with chi-square or Fisher's exact tests.

To reduce selection bias, PSM was conducted. A multivariable logistic regression model estimated each patient's probability (propensity score) of receiving UD, using the following covariates selected for their association with debridement choice and ulcer prognosis: age, sex, diabetes duration, admission HbA1c, natural-log-transformed initial ulcer area, Wagner grade (2 vs. 3), ulcer location (forefoot vs. mid-foot/heel), pre-debridement white blood cell count, and baseline TcPO_2 . Subjects were then matched 1:1 with nearest-neighbor matching without replacement, with a caliper of 0.02 standard deviations of the logit of the propensity score. This yielded 115 well-balanced pairs (all post-matching standardized differences were < 0.1).

In the matched cohort, paired analyses were used: paired t-tests or Wilcoxon signed-rank

tests for continuous variables, and McNemar's test or conditional logistic regression for categorical variables. The primary outcome (12-week healing rate) was compared with the Cochran-Mantel-Haenszel test. Time-to-healing was initially compared between groups using Kaplan-Meier curves and the log-rank test. To further control for residual confounding and competing risks, two models were fitted in the overall (unmatched) cohort: a multivariable Cox proportional hazards regression for healing time, and a Fine-Gray competing risk regression treating major amputation as a competing event. Variables entered into the multivariable models were pre-specified based on clinical relevance and univariable screening ($P < 0.1$ in the pre-matched data). The primary analysis was performed in the matched cohort; analyses of the original unmatched cohort were presented as sensitivity analyses. All tests were two-sided, and $P < 0.05$ was considered statistically significant.

Results

Patient selection and baseline characteristics

Between January 2021 and January 2025, we initially screened 410 patients with DFUs who had undergone debridement therapy. Following the strict inclusion and exclusion criteria, 298 patients were ultimately included in the analysis. Of these, 142 patients (47.7%) were assigned to the low-frequency UD group, and 156 patients (52.3%) were assigned to the surgical group.

To control for potential selection bias, we performed PSM. As shown in **Table 1**, before matching, there were significant differences in multiple baseline characteristics between the two groups. The average age of patients in the surgical group was significantly older ($P < 0.05$), the initial ulcer area was larger ($P < 0.05$), the proportion of Wagner grade 3 ulcers was higher ($P < 0.05$), and the baseline $TcPO_2$ level was lower ($P < 0.05$), indicating that in clinical practice, sicker ulcers with greater ischemic risk were more likely to receive surgical debridement. After 1:1 nearest neighbor matching, we obtained 115 pairs of patients with balanced baseline characteristics (total $n = 230$). After matching, the standardized difference of all covariates were less than 0.1, indicating good comparability between the two groups (**Figure 2**). Subsequent primary analyses were based on this matched cohort.

Primary and secondary clinical outcomes

In the matched cohort ($n = 230$), the primary outcome - the 12-week complete healing rate - was significantly higher in the UD group than in the surgical group (78/115, 67.8% vs. 62/115, 53.9%; $\chi^2 = 4.673$, $P = 0.031$). Regarding secondary outcomes (**Table 2**), the UD group demonstrated a significantly greater relative percentage reduction in wound area ($81.4\% \pm 20.7\%$ vs. $70.3\% \pm 24.5\%$; $t = 3.712$, $P < 0.001$). The Wollina Wound Score assessed at 4 weeks post-treatment was also significantly higher in the UD group (6.72 ± 1.45 vs. 5.81 ± 1.68 ; $t = 4.398$, $P < 0.001$). In terms of infection control, the clinical infection control rate was significantly superior in the UD group (87/115, 75.7% vs. 70/115, 60.9%; $\chi^2 = 5.799$, $P = 0.016$), and the cumulative days of systemic antibiotic use were significantly fewer (median 21.0 [IQR 14.0-35.0] vs. 28.0 [18.0-42.0] days; $Z = -2.353$, $P = 0.019$). No significant difference was observed between the groups in the incidence of major amputation (3/115, 2.6% vs. 4/115, 3.5%; Fisher's exact test, $P = 0.752$).

Time-to-event analysis and competing risk

Kaplan-Meier survival analysis was performed for time to healing in the matched cohort (**Figure 3**). The median time to healing was 15.3 weeks (95% CI: 13.1-17.5) in the UD group, compared with 21.6 weeks (95% CI: 18.8-24.4) in the surgical group. The log-rank test revealed a significantly higher cumulative healing probability in the UD group ($\chi^2 = 8.734$, $P = 0.003$). In the Fine-Gray competing risk model treating major amputation as a competing event, UD remained an independent factor associated with promoted ulcer healing (subdistribution hazard ratio = 1.612, 95% CI: 1.182-2.198, $P = 0.002$). In addition, multivariable Cox proportional hazards regression analysis in the matched cohort (**Table 3**) further confirmed that ultrasonic debridement was independently associated with a significantly higher probability of healing (HR = 1.703, 95% CI: 1.247-2.326, $P = 0.001$) after adjusting for age, ulcer area, Wagner grade, baseline $TcPO_2$, and diabetes duration.

Infection-related microbiological and physiological indicators

We further analyzed specific indicators related to infection control (**Table 4**). One week after

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Table 1. Comparison of baseline characteristics between the ultrasonic debridement and surgical debridement groups before and after propensity score matching

Variable	UD Group (n=142)	Surgical Group (n=156)	Statistic	P-value	Variable	UD Group (n=115)	Surgical Group (n=115)	Std. Diff
Age (years)	61.34 ± 10.27	65.89 ± 9.41	t=3.991	<0.001	Age (years)	63.75 ± 9.82	64.13 ± 9.05	0.040
Male, n (%)	92 (64.8)	98 (62.8)	χ ² =0.136	0.712	Male, n (%)	73 (63.5)	74 (64.3)	0.017
Diabetes duration (years)	12.5 (8.0-18.0)	14.0 (10.0-20.0)	Z=-1.293	0.196	Diabetes duration (years)	13.0 (9.0-19.0)	13.5 (9.3-19.8)	0.066
Admission HbA1c (%)	8.21 ± 1.67	8.45 ± 1.89	t=1.157	0.248	Admission HbA1c (%)	8.33 ± 1.72	8.38 ± 1.81	0.028
Initial ulcer area (cm ²)	3.5 (1.8-6.2)	5.8 (3.1-9.8)	Z=-3.549	<0.001	Initial ulcer area (cm ²)	4.6 (2.3-7.9)	4.8 (2.5-8.1)	0.048
Wagner Grade 3, n (%)	38 (26.8)	72 (46.2)	χ ² =12.013	0.001	Wagner Grade 3, n (%)	42 (36.5)	40 (34.8)	0.035
Heel/Midfoot location, n (%)	47 (33.1)	65 (41.7)	χ ² =2.326	0.127	Heel/Midfoot location, n (%)	43 (37.4)	41 (35.7)	0.035
Ankle-Brachial Index	1.02 ± 0.18	0.98 ± 0.21	t=1.756	0.080	Ankle-Brachial Index	1.00 ± 0.19	0.99 ± 0.20	0.051
Baseline TcPO ₂ (mmHg)	48.32 ± 12.47	42.18 ± 13.86	t=4.005	<0.001	Baseline TcPO ₂ (mmHg)	45.67 ± 12.91	44.92 ± 13.24	0.057
Pre-debridement WBC (×10 ⁹ /L)	9.21 ± 3.14	10.05 ± 3.67	t=2.113	0.036	Pre-debridement WBC (×10 ⁹ /L)	9.53 ± 3.28	9.68 ± 3.41	0.045
Baseline positive culture, n (%)	107 (75.4)	128 (82.1)	χ ² =2.001	0.157	Baseline positive culture, n (%)	89 (77.4)	87 (75.7)	0.040
BMI (kg/m ²)	26.83 ± 4.56	27.41 ± 5.12	t=1.028	0.305	BMI (kg/m ²)	27.12 ± 4.71	27.05 ± 4.89	0.015
Smoking history, n (%)	51 (35.9)	62 (39.7)	χ ² =0.464	0.496	Smoking history, n (%)	42 (36.5)	44 (38.3)	0.037
Hypertension, n (%)	98 (69.0)	118 (75.6)	χ ² =1.639	0.200	Hypertension, n (%)	81 (70.4)	83 (72.2)	0.040
CAD, n (%)	34 (23.9)	45 (28.8)	χ ² =0.915	0.339	CAD, n (%)	29 (25.2)	27 (23.5)	0.040

Note: UD, ultrasonic debridement; Std. Diff., standardized difference; HbA1c, glycated hemoglobin A1c; BMI, body mass index; TcPO₂, transcutaneous oxygen pressure; WBC, white blood cell; CAD, coronary artery disease.

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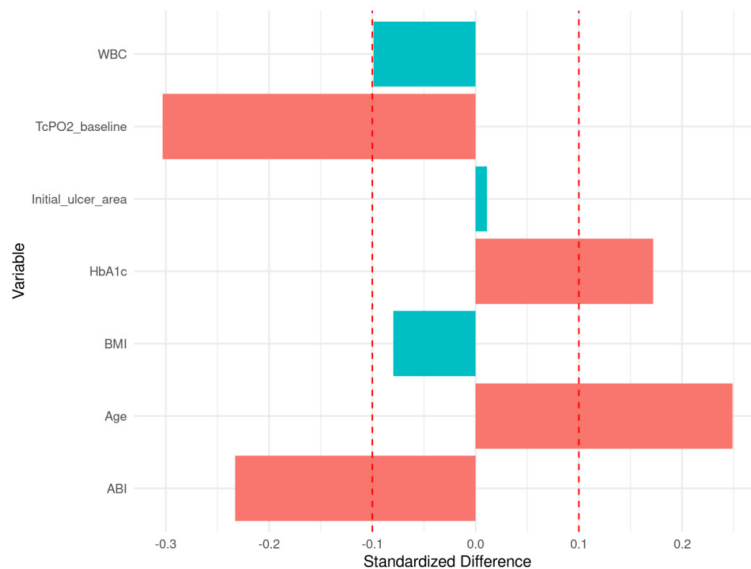


Figure 2. Standardized differences after matching. Note: WBC, White Blood Cell; TcPO₂, Transcutaneous Partial Pressure of Oxygen; HbA1c, Hemoglobin A1c; BMI, Body Mass Index; ABI, Ankle-Brachial Index.

the initial debridement, the rate of positive wound bacterial cultures decreased significantly from baseline in the UD group, whereas no significant change was observed in the surgical group. Between-group comparison revealed a significantly lower post-debridement positive culture rate in the UD group ($P < 0.05$). Regarding physiological indicators of local tissue perfusion, both the absolute TcPO₂ value at 4 weeks post-debridement and the change from baseline (Δ TcPO₂) were significantly higher in the UD group than in the surgical group ($P < 0.05$), consistent with the observed better clinical healing outcomes in this group.

Sensitivity analysis in the unmatched cohort and adverse events

To assess the robustness of the findings, we performed multivariable logistic regression analysis in the unmatched overall cohort ($n = 298$). After adjusting for age, initial wound area, Wagner grade, and baseline TcPO₂, UD remained an independent favorable factor for 12-week healing (adjusted odds ratio = 2.121, 95% CI: 1.269-3.545, $P = 0.004$), consistent with the main findings from the matched cohort.

In terms of safety (**Table 5**), there was no significant difference in the total incidence of debridement-related adverse events between the two groups ($P = 0.337$). However, the distribution of

event types differed: the surgical group had more bleeding events requiring intervention, whereas adverse events in the UD group were mainly temporary pain exacerbation.

Health-related quality of life outcomes

To supplement the clinical efficacy analysis, we used the SF-36 health survey questionnaire to evaluate patients' self-rated health-related quality of life of patients at baseline and 12 weeks post-debridement. As shown in **Table 6**, the SF-36 domain scores in both groups improved from baseline to 12 weeks post-debridement; however, compared with the surgical group, the UD group showed

significantly greater improvement across multiple dimensions. Specifically, the UD group demonstrated significantly greater improvements in physical functioning ($\Delta = 18.42 \pm 8.74$ vs. 12.13 ± 9.21 ; mean difference 6.29, 95% CI: 3.21-9.37; $t = 4.012$, $P < 0.001$), bodily pain ($\Delta = 22.63 \pm 10.31$ vs. 14.82 ± 11.52 ; mean difference 7.81, 95% CI: 4.21-11.41; $t = 4.273$, $P < 0.001$), and vitality ($\Delta = 15.74 \pm 7.92$ vs. 9.28 ± 8.41 ; mean difference 6.46, 95% CI: 3.12-9.80; $t = 3.795$, $P < 0.001$). The physical component summary score improved by 18.64 ± 8.13 points in the UD group compared with 12.91 ± 8.67 points in the surgical group (mean difference 5.73, 95% CI: 2.92-8.54; $t = 4.011$, $P < 0.001$), while the mental component summary score increased by 16.21 ± 8.52 vs. 10.38 ± 9.14 points (mean difference 5.83, 95% CI: 2.61-9.05; $t = 3.562$, $P < 0.001$).

Discussion

This study aimed to compare the effects of low-frequency UD and surgical debridement on wound healing and infection control in the treatment of DFU through a retrospective analysis based on real-world clinical data. The main results showed that after PSM was used to control baseline confounders, patients who received weekly UD had significantly better outcomes than those who received surgical debridement in terms of 12-week complete heal-

Table 2. Comparison of primary and secondary clinical outcomes in the matched cohort (n=230)

Outcome	UD Group (n=115)	Surgical Group (n=115)	Statistic	P-value
12-week complete healing rate, n (%)	78 (67.8)	62 (53.9)	$\chi^2=4.673$	0.031
Relative reduction in wound area, %	81.4 ± 20.7	70.3 ± 24.5	$t=3.712$	<0.001
Clinical infection control rate, n (%)	87 (75.7)	70 (60.9)	$\chi^2=5.799$	0.016
Cumulative antibiotic days, days	21.0 (14.0-35.0)	28.0 (18.0-42.0)	$Z=-2.353$	0.019
$\Delta TcPO_2$ (Week 4-Baseline), mmHg	8.56 ± 6.23	5.21 ± 7.14	$t=3.791$	<0.001
Wollina Wound Score at week 4, points	6.72 ± 1.45	5.81 ± 1.68	$t=4.398$	<0.001
Major amputation, n (%)	3 (2.6)	4 (3.5)	Fisher's exact test	0.752

Note: UD, ultrasonic debridement; $\Delta TcPO_2$, change in transcutaneous oxygen pressure.

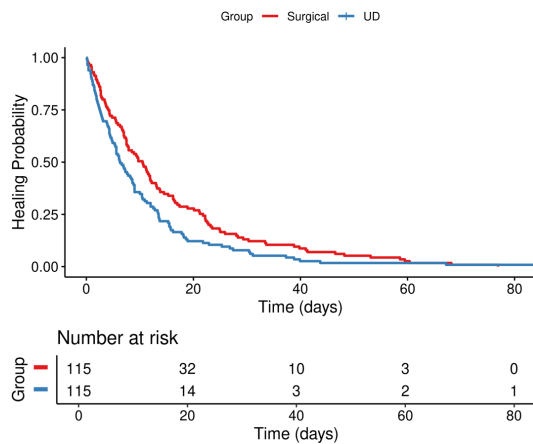


Figure 3. Kaplan-Meier survival analysis. Note: UD, ultrasonic debridement.

ing rate, wound area reduction, clinical infection control, and improvement in local tissue perfusion [16]. These findings suggest that, as a non-invasive or minimally invasive debridement method, regular UD may provide an effective alternative or adjunctive strategy for the comprehensive management of DFU, especially in specific patient populations who are unsuitable for or intolerant of frequent surgical debridement [17].

The baseline analysis before PSM clearly revealed the real-world pattern of clinical decision-making, namely that patients with larger ulcer areas, higher Wagner grade, and relatively poorer local perfusion were more often assigned to the surgical group [18]. This finding is consistent with the conventional practice of prioritizing more active surgical intervention for complex wounds in clinical practice. The balance achieved in the matched cohort provided a scientific basis for subsequent comparisons and effectively reduced the selection bias arising from between-group differences in baseline

disease severity. Therefore, the observed differences in outcomes more strongly reflect the effect of the debridement method itself rather than baseline differences [19].

Regarding core clinical outcomes, the UD group showed a higher healing rate and faster healing time. The significant wound area reduction together with higher Wollina Wound Score collectively confirmed the benefit of UD in promoting wound bed preparation at both quantitative and semi-quantitative levels. The potential mechanism may lie in the cavitation and acoustic streaming produced by low-frequency ultrasound, which can non-selectively remove biofilm, necrotic tissue, and bacteria from the wound surface through physical mechanisms, while simultaneously promoting local blood circulation and cellular activity via micro-mechanical stimulation, thus creating a more favorable microenvironment for granulation tissue growth and epithelialization [20, 21].

In this study, the advantages of UD in infection control were also prominent, as reflected by a higher clinical infection control rate, shorter duration of systemic antibiotic therapy, and a significant decrease in the positive bacterial culture rate after debridement. This result may be related to ultrasound-mediated disruption of biofilm structure, enhanced antibiotic penetration, and improved access of host immune cells to the site of infection [22]. Compared with surgical debridement, which mainly focuses on removal of macroscopic necrotic tissue, the micromechanical effects of ultrasound may be more effective against diffuse biofilm, which is a key driver of non-healing in chronic infected wounds [23]. These findings are consistent with current wound healing theories that emphasize the importance of biofilm management, and provide supporting evidence for the use of UD in DFU infection control [24].

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Table 3. Multivariable Cox proportional hazards regression analysis for time to healing in the matched cohort (n=230)

Variable	Hazard Ratio (HR)	95% Confidence Interval	P-value
Debridement method (UD vs. Surgical)	1.703	1.247-2.326	0.001
Age (per 1-year increase)	0.988	0.973-1.003	0.116
Initial ulcer area (per 1 cm ² increase)	0.932	0.895-0.970	<0.001
Wagner grade (3 vs. 2)	0.712	0.514-0.986	0.041
Baseline TcPO ₂ (per 1 mmHg increase)	1.018	1.005-1.031	0.006
Diabetes duration (per 1-year increase)	0.992	0.976-1.007	0.288

Note: UD, ultrasonic debridement; HR, hazard ratio; CI, confidence interval; TcPO₂, transcutaneous oxygen pressure.

Table 4. Analysis of infection-related microbiological and perfusion indicators in the matched cohort (n=230)

Indicator	UD Group (n=115)	Surgical Group (n=115)	Between-group Statistic (P-value)
Positive bacterial culture, n (%)			
Baseline	89 (77.4)	87 (75.7)	$\chi^2=0.095$ (0.758)
1 week post-debridement	61 (53.0)	78 (67.8)	$\chi^2=5.302$ (0.021)
TcPO ₂ (mmHg)			
Baseline	45.67 ± 12.91	44.92 ± 13.24	t=0.438 (0.662)
4 weeks post-debridement	54.23 ± 11.78	50.13 ± 12.95	t=2.526 (0.012)
ΔTcPO ₂ (Change)	8.56 ± 6.23	5.21 ± 7.14	t=3.839 (<0.001)

Note: UD, ultrasonic debridement; TcPO₂, transcutaneous oxygen pressure; ΔTcPO₂, change in transcutaneous oxygen pressure. Within-group comparisons used McNemar's test (culture) or paired t-test (TcPO₂). Between-group comparisons used chi-square test or independent samples t-test. For the UD group, the decrease in positive culture rate (77.4% to 53.0%) has McNemar's P<0.001; in the surgical group (75.7% to 67.8%), McNemar's P=0.121. For TcPO₂, within-group changes are also reported: UD group, paired t=8.123, P<0.001; surgical group, paired t=4.987, P<0.001.

Table 5. Comparison of debridement-related adverse events in the matched cohort (n=230)

Adverse Event Type	UD Group (n=115)	Surgical Group (n=115)	P-value
Any adverse event, n (%)	13 (11.3)	18 (15.7)	0.337
Significant bleeding requiring intervention, n (%)	1 (0.9)	7 (6.1)	0.067
Pain increase (VAS increase ≥3 points), n (%)	10 (8.7)	8 (7.0)	0.811
New local signs of infection, n (%)	2 (1.7)	3 (2.6)	1.000

Note: UD, ultrasonic debridement; VAS, visual analogue scale. Between-group comparisons used Fisher's exact test.

The time-to-event analysis of ulcer healing time further reinforced the above findings. Even after adjusting for residual confounders in the multivariable model, UD remained an independent factor associated with shorter healing time. More importantly, when considering major amputation as a competing risk, the beneficial effect on healing remained significant [25]. At the same time, the significant improvement in local TcPO₂ offers a potential physiological explanation for the observed clinical benefit, suggesting that UD may support cellular metabolic activity and proliferation by enhancing microcirculation and oxygen delivery in the per-ulcer tissue [26].

The safety analysis revealed that the overall incidence of adverse events was comparable between the two debridement methods, but the event profiles differed, reflecting the differences in their mechanisms of action. Surgical debridement was associated with more bleeding events requiring intervention, consistent with its sharp dissection nature; whereas the main adverse event associated with UD was transient pain exacerbation [27]. This safety profile makes UD potentially particularly valuable for patients with coagulation disorders or extreme pain sensitivity. Sensitivity analysis confirmed that the favorable effect of UD persisted after adjusting for key prognostic vari-

Table 6. Changes in SF-36 health-related quality of life scores from baseline to week 12 in the matched cohort (n=230)

SF-36 Domain/Summary	UD Group (n=115)	Surgical Group (n=115)	Mean Difference (95% CI)	t-value	P-value
Physical Functioning	18.42 ± 8.74	12.13 ± 9.21	6.29 (3.21 to 9.37)	4.012	<0.001
Role-Physical	20.13 ± 11.32	14.51 ± 12.64	5.62 (1.81 to 9.43)	2.883	0.004
Bodily Pain	22.63 ± 10.31	14.82 ± 11.52	7.81 (4.21 to 11.41)	4.273	<0.001
General Health	12.31 ± 6.82	9.68 ± 7.21	2.63 (0.52 to 4.74)	2.445	0.015
Vitality	15.74 ± 7.92	9.28 ± 8.41	6.46 (3.12 to 9.80)	3.795	<0.001
Social Functioning	18.91 ± 9.53	13.62 ± 10.14	5.29 (1.91 to 8.67)	3.072	0.002
Role-Emotional	16.83 ± 10.22	11.24 ± 11.43	5.59 (1.41 to 9.77)	2.617	0.009
Mental Health	14.22 ± 7.34	9.81 ± 8.03	4.41 (1.93 to 6.89)	3.486	0.001
PCS	18.64 ± 8.13	12.91 ± 8.67	5.73 (2.92 to 8.54)	4.011	<0.001
MCS	16.21 ± 8.52	10.38 ± 9.14	5.83 (2.61 to 9.05)	3.562	<0.001

Note: UD, ultrasonic debridement; SF-36, 36-Item Short Form Health Survey; PCS, Physical Component Summary; MCS, Mental Component Summary; CI, confidence interval. Data are presented as mean change from baseline to week 12 ± standard deviation. Between-group comparisons were performed using independent samples t-tests. All within-group changes from baseline to week 12 were statistically significant (paired t-tests, all $P < 0.001$ in both groups). The PCS and MCS scores represent the overall physical and mental dimensions of health-related quality of life; an overall 'total' score is not defined for the SF-36.

ables in the unmatched overall cohort, demonstrating the robustness of our findings [28].

The analysis of health-related quality of life provided supplementary evidence for clinical efficacy from a patient-centered perspective. The improvement in SF-36 scores in the UD group was significantly greater than that in the surgical group, particularly in the domains of bodily pain, vitality, and mental health. These results suggest that faster healing, reduced antibiotic use, and lower pain burden collectively contribute to the overall improvement in patients' quality of life [29]. Previous studies on chronic wound care have also emphasized that patient-reported outcomes are as important as objective clinical measures. This result further supports the integration of quality-of-life assessments into wound treatment evaluation systems [30]. Early pain relief and functional recovery after UD may be key drivers of these differences.

This study has several limitations. First, its retrospective observational design precludes the complete exclusion of all unknown or unmeasured confounders, such as patient adherence, nutritional status, and other details that may not have been completely recorded. Second, although the advanced statistical technique of PSM was employed, the possibility of residual confounding cannot be ruled out. Third, this is a single-center study, and the patient population and treatment protocols may have some speci-

ficity; therefore, the generalizability of our conclusions should be made cautiously. In the future, multicenter, prospective studies are needed, incorporating more detailed cost-effectiveness analyses and patient-reported outcome measures, to fully evaluate the optimal role and value of UD in the management of DFU.

In conclusion, this real-world data-based analysis demonstrates that, compared with surgical debridement, weekly low-frequency UD can significantly improve the wound healing rate, shorten healing time, enhance infection control, and exhibit an acceptable safety profile in patients with DFU.

Disclosure of conflict of interest

None.

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