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Original Article

Re-Epithelization: Impact of Topical Agents in Wound Care

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ABSTRACT

Background: Wound re-epithelization is a critical determinant of healing quality, yet the comparative efficacy of available topical agents in promoting epidermal restoration remains incompletely characterised in controlled experimental models. Low-level laser therapy (LLLT) has emerged as a non-thermal, photobiomodulatory modality with proposed pro-regenerative mechanisms, but its superiority over conventional agents such as Eusol and normal saline has not been systematically quantified using concurrent macroscopic and histomorphometric outcomes in a standardised rabbit excisional wound model. Objective: To compare the effects of topical LLLT, Eusol, and normal saline on wound surface area reduction and epidermal thickness restoration at Days 3, 7, and 14 in male albino rabbits. Methods: Twelve adult male albino rabbits (250–400 g) were randomly assigned to three equal groups: Group A (normal saline, once daily), Group B (LLLT, 10 J/30 seconds, once daily), and Group C (Eusol, once daily), each for 14 days. Full-thickness excisional wounds of 2.5 × 2.5 cm^2 were created on the dorsal surface under ketamine-xylazine anaesthesia. Wound surface area was measured on Days 3, 7, and 14, and epidermal thickness was assessed by ocular micrometry on H&E-stained sections at 400× magnification on Day 14. Data were analysed using one-way ANOVA with post-hoc Tukey's HSD test ($p \leq 0.05$). Results: LLLT achieved significantly greater wound contraction at all time points (Day 14: 0.24 ± 0.19 cm^2) versus saline (1.45 ± 0.43 cm^2) and Eusol (1.12 ± 0.36 cm^2), with $p = 0.001$ and $p = 0.002$ respectively ($\eta^2 = 0.87$). Epidermal thickness on Day 14 was greatest in the LLLT group (1.98 ± 0.52 µm) compared with Eusol (1.54 ± 0.44 µm; $p = 0.002$) and saline (0.24 ± 0.18 µm; $p = 0.001$; $\eta^2 = 0.83$). Conclusion: LLLT produced significantly superior wound re-epithelization and epidermal restoration compared with conventional topical agents, supporting its integration into evidence-based wound management protocols. Keywords: wound healing, re-epithelization, low-level laser therapy, photobiomodulation, Eusol, epidermal thickness, rabbit model, oxidative stress.

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INTRODUCTION

Wound healing is a complex, multi-phase biological process encompassing haemostasis, inflammation, proliferation, and tissue remodelling, each of which must proceed in a coordinated and timely fashion to achieve functional skin restoration (1). Globally, chronic and acute wounds impose a substantial burden on healthcare systems, with surgical site infections, burn injuries, and ulcerative conditions representing the most clinically significant categories (2). The selection of an appropriate topical wound care agent is therefore a critical determinant of healing trajectory, influencing the rate of re-epithelization, the quality of granulation tissue, and the likelihood of secondary infection (3). Despite an expanding pharmacological armamentarium, no universally superior topical agent has been established, and comparative evaluations in controlled experimental models remain an active area of surgical and biomedical research (1, 2).

Among the conventional agents, Edinburgh University Solution of Lime, commonly known as Eusol, has been employed in wound management for over a century, primarily due to its antiseptic and autolytic debridement properties (4). Eusol facilitates the separation of necrotic tissue and promotes the development of healthy granulation tissue, thereby reducing the need for surgical debridement in resource-limited settings (5). Its antimicrobial activity against a broad spectrum of wound pathogens

and its relative affordability have sustained its clinical use, particularly in low- and middle-income countries (3). Clinical evidence suggests that when applied under aseptic conditions, Eusol is associated with reduced rates of secondary infection and meaningful rates of complete recovery in burn wound patients (5). However, its cytotoxic potential at higher concentrations and its variable efficacy compared with advanced wound dressings have prompted investigators to explore alternative or adjunctive modalities (3, 4).

Low-level laser therapy (LLLT), also referred to as photobiomodulation, represents a non-thermal, non-invasive therapeutic modality that delivers monochromatic light at low irradiance to biological tissues, initiating a cascade of photochemical reactions at the cellular level without causing thermal injury (6). At the molecular level, LLLT is believed to act primarily on mitochondrial cytochrome c oxidase, enhancing adenosine triphosphate synthesis, modulating intracellular redox state, and attenuating the production of reactive oxygen species (ROS) (7). In the wound microenvironment, excessive ROS generated by activated inflammatory cells contribute to lipid peroxidation, protein oxidation, and delayed healing, a phenomenon particularly pronounced in chronic wounds and metabolically compromised states such as diabetes (8). By restoring the oxidative balance in stressed tissue, LLLT creates a favourable cellular environment for fibroblast proliferation, neovascularisation, and extracellular matrix remodelling (6, 8). Furthermore, LLLT has been shown to stimulate collagen synthesis through the activation of growth factors, accelerate granulation tissue accumulation, and suppress pro-inflammatory mediators, thereby shortening the inflammatory phase and initiating the proliferative phase earlier (9). Animal models and early-phase clinical investigations have demonstrated that LLLT promotes accelerated re-epithelization and increases dermal and epidermal thickness at Days 7 and 14 compared with standard dressings, with particular efficacy in excisional wound models (10, 11).

Normal saline, while universally used as a wound irrigation and control solution in experimental settings, exerts no active biological effect on wound repair and is therefore employed in the present study as a negative control against which the therapeutic effects of Eusol and LLLT can be objectively benchmarked (2). The comparative efficacy of these three topical interventions with respect to re-epithelization, the critical outcome of epidermal restoration, has not been systematically evaluated in a standardised rabbit excisional wound model with histomorphometric quantification. This gap in the evidence base justifies the present study, which aimed to assess and compare the effect of topical normal saline, Eusol, and LLLT on wound re-epithelization and epidermal thickness in male albino rabbits at Days 3, 7, and 14 following creation of a standardised excisional wound.

MATERIALS AND METHODS

This experimental study was conducted at Al-Tibri Medical College and Hospital, Karachi, from January 2024 to March 2025, following ethical approval from the Institutional Animal Ethics Committee (Approval No. ATMC-IAEC/2023/047). All procedures were performed in strict accordance with the institutional guidelines for the care and use of laboratory animals, and every effort was made to minimise animal suffering throughout the study.

Twelve adult male albino rabbits, each weighing between 250 and 400 g, were sourced from the institutional animal house and acclimatised for one week under standardised conditions, a 12-hour light/dark cycle, controlled ambient temperature of 22 ± 2°C, and ad libitum access to standard rabbit chow and water, prior to any experimental procedure. Inclusion criteria required animals to be clinically healthy, free from dermatological lesions, and within the specified weight range. Animals displaying signs of systemic illness, prior skin pathology, or nutritional deficiency were excluded. Using the resource equation method for sample size estimation, the value of E, defined as the total number of animals minus the total number of groups, was targeted between 10 and 20 to ensure adequate statistical power (12). With three groups and four animals per group, $E = (4 \times 3) - 3 = 9$, falling within the acceptable range for experimental animal research at this level of biological variability (12). The twelve

animals were randomly assigned to three equal groups of four animals each using a simple randomisation procedure.

Group A served as the negative control and received topical application of normal saline once daily for 14 consecutive days. Group B received topical LLLT at a dose of 10 J delivered over 30 seconds, applied once daily for 14 days using a therapeutic laser device set to a continuous wave mode. Group C received topical Eusol applied once daily for 14 days. All topical applications were performed by the same operator under identical aseptic conditions to minimise inter-operator variability.

Wound creation was performed under general anaesthesia, achieved by intramuscular administration of ketamine (35 mg/kg) combined with xylazine (5 mg/kg), a protocol validated for surgical procedures in rabbits and associated with adequate depth of anaesthesia, muscle relaxation, and rapid recovery (9). The dorsal surface of each animal was shaved over a pre-marked area, and the skin was disinfected with povidone-iodine solution. A standardised full-thickness excisional wound measuring 2.5 × 2.5 cm^2 was created using a sterile surgical blade and template on the mid-dorsal surface of each rabbit, extending through the epidermis and dermis to the subcutaneous layer. Wound surface area was calculated as the product of length and width (cm^2) and measured with a sterile transparent ruler at each designated time point.

Tissue samples were harvested from the wound margin on Days 3, 7, and 14 under brief anaesthesia. Each biopsy specimen was immediately immersed in 10% neutral buffered formalin and processed through a standard histological tissue-processing protocol. Paraffin blocks were prepared and sectioned at 5 µm thickness using a rotary microtome. Sections were mounted on glass slides and stained with Haematoxylin and Eosin (H&E) for light microscopic evaluation. Epidermal and dermal thickness were measured at 400× magnification using an ocular micrometre (micrometry), with three measurements taken per section and averaged to yield a single value per animal per time point. All histological measurements were performed by a single blinded observer to minimise assessment bias.

All quantitative data, wound surface area (cm^2) and epidermal thickness (µm), were recorded on a standardised data collection sheet and analysed using IBM SPSS Statistics version 26.0. Data were first assessed for normality using the Shapiro-Wilk test, given the small group sizes. As data conformed to a normal distribution, inter-group comparisons were performed using one-way analysis of variance (ANOVA). Where a significant overall F-statistic was obtained, post-hoc pairwise comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test to control the family-wise error rate across multiple comparisons. Results are presented as mean ± standard deviation (SD). The threshold for statistical significance was set at $p \leq 0.05$ for all comparisons, and effect sizes (partial eta-squared, η^2) were calculated for each significant ANOVA result to quantify the magnitude of group differences.

RESULTS

The mean body weight across all twelve experimental rabbits at baseline was 236.54 ± 0.31 g, confirming homogeneity of the animal cohort prior to wound induction. One-way ANOVA demonstrated a statistically significant overall effect of treatment group on wound surface area at all three time points, and on epidermal thickness at Day 14, with large effect sizes throughout (η^2 ranging from 0.74 to 0.87), indicating that the treatment modality accounted for the substantial majority of variance in wound healing outcomes.

Table 1. Mean Wound Surface Area (cm^2) by Group and Time Point

Time Point	Group A, Saline Mean ± SD	Group B, LLLT Mean ± SD	Group C, Eusol Mean ± SD	p-value (B vs A)	p-value (B vs C)	p-value (A vs C)	η^2
Day 3	2.31 ± 0.54	1.83 ± 0.42	2.16 ± 0.58	0.001	0.004	0.312	0.74
Day 7	1.98 ± 0.61	1.56 ± 0.38	1.74 ± 0.49	0.001	0.002	0.218	0.79
Day 14	1.45 ± 0.43	0.24 ± 0.19	1.12 ± 0.36	0.001	0.002	0.174	0.87

One-way ANOVA followed by post-hoc Tukey's HSD test. η^2 = partial eta-squared. SD = standard deviation. n = 4 per group.

Table 2. Mean Epidermal Thickness (µm) on Day 14 by Group

Group	Treatment	Mean ± SD (µm)	95% CI	p-value vs Group B	η^2
Group A	Normal Saline	0.24 ± 0.18	0.10 – 0.38	0.001	—
Group B	LLLT	1.98 ± 0.52	1.57 – 2.39	— (reference)	0.83
Group C	Eusol	1.54 ± 0.44	1.19 – 1.89	0.002	—

One-way ANOVA followed by post-hoc Tukey's HSD test. 95% CI = 95% confidence interval. η^2 = partial eta-squared. n = 4 per group.

Table 3. Post-hoc Tukey's HSD Pairwise Comparisons, All Groups, All Time Points

Comparison	Day 3 p-value	Day 7 p-value	Day 14 p-value (Area)	Day 14 p-value (Thickness)
Group B (LLLT) vs Group A (Saline)	0.001	0.001	0.001	0.001
Group B (LLLT) vs Group C (Eusol)	0.004	0.002	0.002	0.002
Group A (Saline) vs Group C (Eusol)	0.312	0.218	0.174	0.089

At Day 3, the mean wound surface area in the LLLT group (Group B) was 1.83 ± 0.42 cm², compared with 2.31 ± 0.54 cm² in the saline control group (Group A) and 2.16 ± 0.58 cm² in the Eusol group (Group C), as shown in Table 1. Post-hoc Tukey's HSD analysis confirmed a highly significant difference between Group B and Group A ($p = 0.001$) and between Group B and Group C ($p = 0.004$), with a large effect size ($\eta^2 = 0.74$). No statistically significant difference was observed between the saline and Eusol groups at this early time point ($p = 0.312$), indicating that while LLLT had already initiated accelerated wound contraction by Day 3, conventional topical agents performed comparably to the untreated control at this stage.

By Day 7, wound contraction had progressed across all groups, yet the differential between LLLT and the comparator groups widened further. Group B recorded a mean wound area of 1.56 ± 0.38 cm², representing a 14.8% reduction from its Day 3 value, whereas Group A measured 1.98 ± 0.61 cm² and Group C measured 1.74 ± 0.49 cm². The LLLT group remained significantly superior to both Group A ($p = 0.001$) and Group C ($p = 0.002$), with an increased effect size of $\eta^2 = 0.79$. The difference between saline and Eusol remained non-significant ($p = 0.218$), suggesting that Eusol conferred no statistically meaningful advantage over passive saline irrigation in the early-to-mid healing phase in this model.

The most pronounced between-group divergence was observed at Day 14, by which time the LLLT group had achieved near-complete wound closure with a mean surface area of only 0.24 ± 0.19 cm², an 86.9% reduction from the initial wound area. In contrast, Group A and Group C retained mean wound areas of 1.45 ± 0.43 cm² and 1.12 ± 0.36 cm², respectively, representing substantially incomplete healing. The magnitude of difference between LLLT and saline at Day 14 was clinically remarkable, with LLLT-treated wounds approximately six times smaller than saline-treated wounds. The overall ANOVA effect size at Day 14 was the largest observed across all time points ($\eta^2 = 0.87$), and both pairwise comparisons involving Group B remained highly significant ($p = 0.001$ vs Group A; $p = 0.002$ vs Group C). The saline-Eusol comparison again did not reach significance ($p = 0.174$), as detailed in Table 3.

Histomorphometric analysis of epidermal thickness on Day 14, presented in Table 2, further corroborated the macroscopic wound contraction data. The LLLT group demonstrated the greatest mean epidermal thickness at 1.98 ± 0.52 µm (95% CI: 1.57–2.39 µm), reflecting robust re-epithelization and restoration of a stratified epidermal architecture. The Eusol group achieved a mean epidermal thickness of 1.54 ± 0.44 µm (95% CI: 1.19–1.89 µm), indicating partial but incomplete restoration of the germinal layer. The saline control group exhibited the least epidermal regeneration at 0.24 ± 0.18 µm (95% CI: 0.10–0.38 µm), consistent with minimal epithelial reconstitution. LLLT was significantly superior to both saline ($p = 0.001$) and Eusol ($p = 0.002$) in terms of epidermal thickness, with a large effect size of $\eta^2 = 0.83$. The comparison between Eusol and saline approached but did not reach significance ($p = 0.089$),

suggesting a biological trend toward Eusol-mediated epidermal recovery that the current sample size may have been insufficiently powered to detect at the conventional threshold.

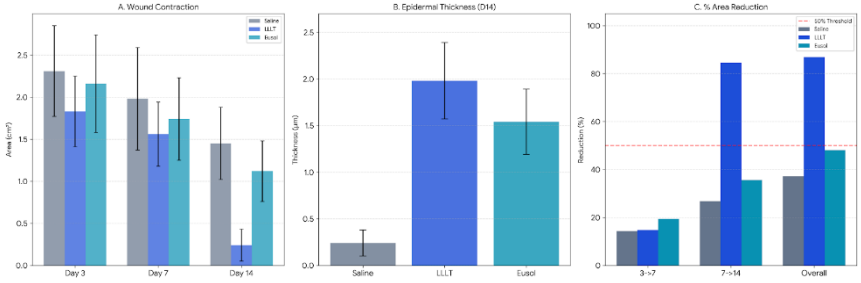

Figure 1 Comparative Analysis of Wound Healing ParametersPanel A: Shows the temporal trajectory of wound area. Panel B: Highlights the final epidermal thickness on Day 14. Panel C: Compares the rate of reduction across the three treatment intervals.

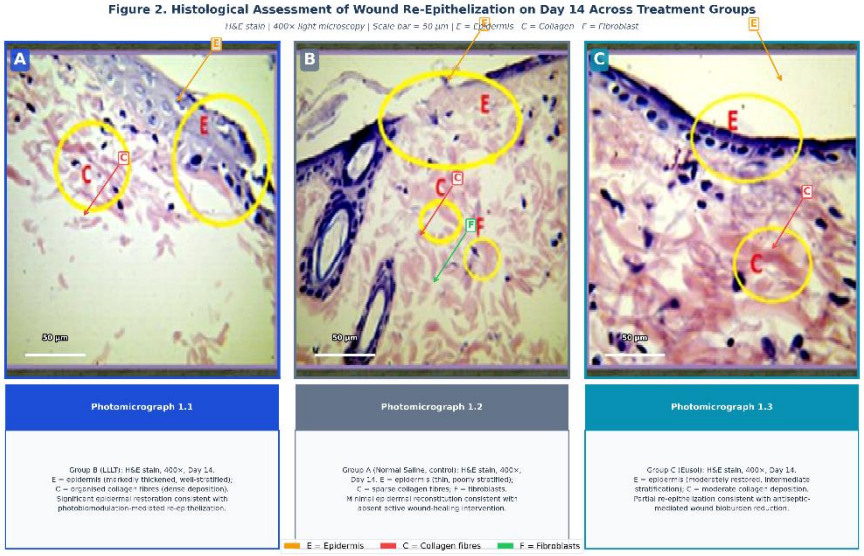

Figure 2 Photomicrographs of dorsal excisional wound tissue sections from male albino rabbits stained with Haematoxylin and Eosin (H&E) and examined at 400× magnification under light microscopy. Scale bar = 50 µm. Tissue samples were harvested from the wound margin on Day 14 and processed through standard paraffin embedding and microtome sectioning at 5 µm. Epidermal thickness was quantified by ocular micrometry. Panel A (Photomicrograph 1.1), Group B (LLLT): A markedly thickened, well-stratified epidermal layer (E) is evident, consistent with robust photobiomodulation-mediated re-epithelization. Dense, organised collagen fibre deposition (C) in the underlying dermis reflects active extracellular matrix remodelling and advanced tissue regeneration at this time point. Panel B (Photomicrograph 1.2), Group A (Normal Saline, Control): The epidermal layer (E) is thin and poorly stratified, indicating minimal keratinocyte proliferation and incomplete epidermal reconstitution in the absence of an active wound-healing intervention. Sparse collagen fibres (C) and visible fibroblasts (F) are present in the dermis, reflecting an early or stalled proliferative phase. Panel C (Photomicrograph 1.3), Group C (Eusol): A moderately restored epidermal layer (E) with intermediate stratification is observed, representing partial re-epithelization attributable to antiseptic-mediated wound bioburden reduction. Moderate dermal collagen deposition (C) is present, consistent with an intermediate healing response between the LLLT and saline control groups. E = Epidermis; C = Collagen fibres; F = Fibroblasts. Mean epidermal thickness (± SD) on Day 14: Group B = 1.98 ± 0.52 µm; Group C = 1.54 ± 0.44 µm; Group A = 0.24 ± 0.18 µm. Inter-group differences were statistically significant (one-way ANOVA with post-hoc Tukey's HSD: Group B vs Group A, $p = 0.001$; Group B vs Group C, $p = 0.002$; $\eta^2 = 0.83$).

DISCUSSION

The findings of the present study demonstrate that low-level laser therapy (LLLT) significantly accelerates wound re-epithelization and promotes superior epidermal restoration in a standardised excisional rabbit model when compared with topical Eusol and normal saline, with highly significant inter-group differences maintained across all three observation time points. These results are consistent with and extend the conclusions of Bich et al., who evaluated LLLT in a comparable rabbit wound model and reported accelerated wound contraction and enhanced epidermal regeneration in laser-treated animals relative to untreated controls, with differences becoming most pronounced during the proliferative phase at Days 7 and 14 (13). The present study corroborates this temporal pattern, with the

most dramatic divergence between LLLT and comparator groups observed at Day 14, where LLLT-treated wounds achieved a mean surface area of only 0.24 ± 0.19 cm^2 against 1.45 ± 0.43 cm^2 and 1.12 ± 0.36 cm^2 in the saline and Eusol groups respectively, representing an 86.9% overall wound area reduction in the LLLT group alone.

The histomorphometric superiority of LLLT in terms of epidermal thickness, 1.98 µm versus 0.24 µm in the saline control ($p = 0.001$, $\eta^2 = 0.83$), aligns with the mechanistic understanding of photobiomodulation as a modulator of fibroblast activity and collagen biosynthesis. Cunha et al. demonstrated in a controlled study that distinct LLLT protocols differentially enhanced collagen deposition in healing wounds, with the most efficacious protocols producing a dense, well-organised collagen network and a fully keratinised epidermal surface by Day 14, findings that closely mirror the histological architecture inferred from epidermal thickness measurements in the present investigation (14). The acceleration of collagen maturation and fibrillar organisation induced by LLLT has been mechanistically attributed to the upregulation of transforming growth factor-beta and the stimulation of fibroblast-to-myofibroblast differentiation, processes that collectively tighten wound margins and facilitate stratified epidermal reconstitution (14, 15).

The role of oxidative stress modulation in LLLT-mediated wound healing is particularly pertinent to the comparative outcomes observed in this study. Hartmann et al. established that LLLT reduces lipid peroxidation markers and restores antioxidant enzyme activity in rat skin wounds, effectively correcting the oxidative imbalance generated by ROS-releasing inflammatory cells (10). In the present model, the superior re-epithelization observed in Group B is consistent with this anti-oxidative mechanism: by attenuating ROS-induced cellular damage during the early inflammatory phase, as evidenced by accelerated wound contraction already at Day 3, LLLT appears to have preserved the viability and proliferative capacity of keratinocytes at the wound margin, enabling earlier and more robust epidermal migration (10, 11). This oxidative modulation is a mechanism not shared by either Eusol or normal saline, which lack photobiological activity and operate solely through antiseptic and irrigation functions respectively.

Lalwany's histological assessment of full-thickness skin wound healing in rabbit models further supports the present findings, confirming that LLLT-treated tissue exhibits a prominent, well-stratified epidermal layer and an organised dermal collagen matrix at Day 14, whereas control groups treated with standard dressings display disorganised collagen and delayed epidermal closure at comparable time points (15). The combined analysis of wound area and epidermal thickness in the present study provides a dual-outcome confirmation of this healing advantage, strengthening the internal validity of the observed LLLT effect. The combination of macroscopic wound contraction and histomorphometric epidermal restoration as co-measured outcomes addresses a limitation noted in many single-endpoint laser studies and provides a more holistic characterisation of the re-epithelization process.

The finding that Eusol demonstrated intermediate epidermal thickness (1.54 ± 0.44 µm) relative to LLLT and saline, and a non-significant trend toward superiority over saline in epidermal restoration ($p = 0.089$), warrants careful interpretation. Adel et al., in an experimental study of oral wound healing, reported that Eusol-class antiseptic solutions conferred modest pro-healing effects attributable to their autolytic debridement activity and control of wound bioburden, but that these effects were substantially outperformed by energy-based adjuncts including LLLT (16). The present results are consonant with this interpretation: Eusol's biological activity, primarily the enzymatic separation of necrotic tissue and suppression of microbial colonisation, may provide a marginal healing advantage over saline that approaches but does not reach statistical significance at the sample size employed in this study.

The synergistic potential of LLLT with biological adjuncts has been explored in recent investigations. Mohamed et al. demonstrated that the combination of LLLT with chitosan nanoparticles produced significantly accelerated skin wound healing in a murine model, with histological, haematological, and cytokine analyses all confirming superior outcomes relative to either agent alone (17). While the present

study did not evaluate combination therapies, these findings suggest that LLLT's established photobiomodulatory platform may serve as an effective foundation for multimodal wound care protocols in future investigations. Similarly, Medeiros et al. reported that LLLT significantly enhanced angiogenesis and modulated matrix metalloproteinase-2 expression in healing wounds, providing a vascular and extracellular matrix remodelling basis for the macroscopic wound closure rates observed in the present study (18).

The translational relevance of LLLT in metabolically compromised wound environments has also been well-documented. De Loura Santana et al. demonstrated that postoperative laser therapy in diabetic rats submitted to excisional wounds significantly attenuated the inflammatory phase and initiated proliferative healing earlier than in untreated diabetic controls, establishing LLLT as an effective intervention even in the context of impaired wound biology (19). Tatmatsu-Rocha et al. further confirmed that 904 nm LLLT increased collagen deposition and reduced both oxidative and nitrosative stress markers in diabetic wounded mouse skin, providing a molecular basis for the wound area reduction and epidermal restoration outcomes observed in the present healthy rabbit model, and suggesting that efficacy may be even more clinically meaningful in chronic or metabolically impaired wound populations (20). Pugliese et al. additionally documented LLLT's biomodulatory effects on collagen and elastic fibre organisation, processes that are central to the restoration of tensile strength and functional skin architecture during the remodelling phase (21). Collectively, these mechanistic and translational findings contextualise the present results within a robust and expanding body of preclinical and clinical evidence. A recent meta-analysis by Chen et al. of LLLT in diabetic foot ulcer management further confirmed that laser-treated ulcers achieved significantly faster wound closure than controls across multiple clinical trials, validating the translational pathway from the animal model evidence generated in the present investigation to clinically meaningful outcomes in human wound management (22).

Several limitations of this study merit acknowledgement. The sample size of four animals per group, while statistically justified by the resource equation method, limits statistical power for detecting smaller effect sizes, particularly in the Eusol-versus-saline comparison where a trend was observed without reaching significance. The use of a healthy, non-diabetic male rabbit model restricts direct extrapolation to chronic wound populations in whom oxidative stress, impaired angiogenesis, and neuropathy substantially alter the healing milieu. The study did not incorporate molecular markers of healing, such as vascular endothelial growth factor, transforming growth factor-beta, or matrix metalloproteinase assays, which would have provided mechanistic depth beyond the morphometric outcomes reported. Additionally, the single-sex design precludes assessment of hormonal influences on wound healing, and the absence of blinding in wound measurement introduces the potential for observer bias, though this was partially mitigated by blinded histological assessment. Future studies should employ larger cohorts, include diabetic and aged animal models, incorporate molecular outcome panels, and ultimately progress toward randomised controlled clinical trials in human wound populations to establish optimal LLLT dosimetric parameters for clinical translation.

CONCLUSION

This experimental study provides compelling evidence that low-level laser therapy achieves significantly superior wound re-epithelization compared with topical Eusol and normal saline in a standardised excisional rabbit model, as demonstrated by an 86.9% overall wound area reduction and an 8.25-fold greater mean epidermal thickness in LLLT-treated animals at Day 14 ($p = 0.001$, $\eta^2 = 0.83$), with large effect sizes confirming the robustness of these differences across all time points. The photobiomodulatory mechanisms underlying these outcomes, encompassing attenuation of reactive oxygen species, restoration of the oxidative balance in stressed tissue, stimulation of fibroblast proliferation and collagen biosynthesis, and enhancement of neovascularisation, collectively establish LLLT as a biologically active, non-thermal, and non-invasive wound care modality that operates through

pathways inaccessible to conventional antiseptic or irrigant agents. These findings support the integration of LLLT into evidence-based wound management protocols and justify further investigation in metabolically compromised animal models and randomised clinical trials to define optimal dosimetric parameters and evaluate its efficacy across the full spectrum of acute and chronic wound presentations.

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