

# Fuzzy Controller Application in the Electrical Stimulation Development for Accelerating Wound Healing

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**ABSTRACT** — Chronic wound healing remains a clinical challenge due to the limited capacity of conventional therapies to accelerate tissue regeneration. Electrical stimulation (ES) offers a promising therapeutic modality; however, open-loop ES cannot adaptively adjust the therapy duration. This study developed a closed-loop ES system incorporating a fuzzy controller to dynamically regulate stimulation duration based on wound progression. The method integrated an Atmega32-based ES platform, fuzzy controller algorithms, and preclinical testing on guinea pigs. The ES system operated at a frequency of 20 Hz, a pulse width of 250  $\mu$ s, and an output voltage of 50 V. The fuzzy controller adjusted stimulation duration within a range of 15–45 minutes according to the difference between the actual and target wound areas, achieving an estimation error of 0.3%. Preclinical evaluations compared the therapeutic effectiveness of closed-loop ES, open-loop ES, and no-ES conditions. Wound-area reduction over seven days in the closed-loop group reached 64–67%, higher than the open-loop (44–50%) and no-therapy (47%) groups. Closed-loop therapy also produced the highest tissue-density outcomes (75–100%), exceeding those of the open-loop (50%) and no-therapy (25–50%) groups. The fuzzy-controlled closed-loop ES accelerated tissue regeneration by approximately 1.5–2 times compared to open-loop and no-therapy conditions. Effectiveness rankings showed the closed-loop system achieving the highest scores (0.90 and 1.00), outperforming the open-loop (0.61) and no-therapy (0.51) groups. These findings indicate that fuzzy-controlled closed-loop ES provides superior wound-healing performance compared to conventional approaches, offering a more adaptive and precise therapeutic strategy with potential for broader medical application.

**KEYWORDS** — Electrical Stimulation, Fuzzy Logic, Wound Healing, Microcontroller.

## I. INTRODUCTION

Wound healing is a complex biological process involving hemostasis, inflammation, tissue proliferation, and tissue maturation or remodeling. Chronic wounds, such as diabetic ulcers, pressure ulcers, and vascular disorders, pose a significant global health challenge because they affect millions of individuals, reduce quality of life, increase morbidity, and impose substantial healthcare costs [1]. Standard care methods—including wound cleansing, antibiotic administration, and surgical intervention—are often insufficient for wounds that fail to heal normally, thereby motivating the development of innovative therapies to accelerate the healing process.

Electrical stimulation (ES) has emerged as a promising alternative therapy to accelerate wound healing by leveraging the body's bioelectrical mechanisms. The application of direct current (DC) has been shown to reduce pro-inflammatory cytokines, accelerate tissue regeneration, enhance perfusion, support cell migration, promote vascularization, and stimulate fibroblast proliferation [2]. ES also exhibits antibacterial effects that help prevent infection and accelerate chronic-wound healing by shortening the inflammatory phase, stimulating fibroplasia, increasing collagen deposition, and supporting orderly reepithelialization [2]–[4]. However, current ES implementations predominantly rely on open-loop systems, which are limited in their ability to adjust stimulation

duration and intensity in response to dynamic wound conditions. Such systems do not account for critical factors, including wound-area changes, tissue fatigue, or infection, leading to suboptimal therapeutic effectiveness.

Although ES has demonstrated substantial therapeutic benefits, its clinical application continues to face challenges due to variations in methodologies, treatment duration, and parameter settings that lack standardization. ES has the potential to accelerate chronic-wound healing and reduce treatment costs by approximately 15–16% compared with standard wound care. Several countries, including Australia, New Zealand, and the United States, have adopted ES as an adjunctive therapy [2], [5]. Nevertheless, further research is required to establish optimal treatment protocols and support broader clinical implementation.

The current research gap lies in the lack of ES systems capable of automatically adjusting stimulation duration and intensity based on wound progression. Addressing this limitation requires a closed-loop system that can optimize therapy through real-time feedback. The effectiveness of such a system must be supported by the selection of an appropriate control strategy that aligns with the biological characteristics of the wound-healing process.

Various control methods, including proportional–integral–derivative (PID) and on–off controller, have been widely applied in automated systems but exhibit limitations when

implemented in biological systems such as wound healing. PID controller performs optimally in systems that can be precisely modeled mathematically and that exhibit stable and linear parameters. In contrast, wound healing is a complex, dynamic, and nonlinear process influenced by multiple biological factors, including individual physiological responses, cellular activity, infection, and tissue fatigue, which are difficult to predict accurately [6]. On-off controller, being inherently discrete, is unable to provide smooth and proportional responses to changes in wound conditions. This approach tends to produce static therapy durations that fail to accommodate dynamic biological needs.

A fuzzy controller is therefore selected due to its advantages in handling uncertainty, nonlinearity, and complex biological dynamics without requiring a precise mathematical model. The fuzzy approach enables flexible, rule-based decision-making using linguistic variables, such as “if wound reduction is low, then apply a longer stimulation duration,” which are difficult to represent accurately using PID or on-off controllers. Fuzzy logic also allows real-time adaptive responses with smooth transitions that closely follow actual wound progression.

Fuzzy inference systems have been utilized to predict wound hydration levels through biomarker analysis based on body temperature and oxygen saturation detected by biosensors [7]. Similar approaches have also been applied to speed control under varying external torque using a fuzzy controller with adaptive parameters [8], demonstrating the suitability of fuzzy logic for handling biological uncertainty. Fuzzy logic exhibits dynamic characteristics that enable systems to adjust their responses based on continuously changing parameters [9]. This adaptive capability supports real-time decision-making in accordance with variations in wound conditions. When combined with measurement and feedback mechanisms, such systems have the potential to enhance therapeutic effectiveness.

Studies on wound-therapy systems, such as negative pressure wound therapy (NPWT), have shown that fuzzy logic controllers can maintain pressure more stably, improve healing effectiveness, and reduce the risk of tissue injury compared with conventional Boolean logic controllers [6]. Based on these findings, the application of a fuzzy controller in a closed-loop ES system in this study is considered the most relevant approach, as it aligns with the dynamic, individualized, and complex nature of the wound-healing process.

Despite significant advances in ES research, a gap remains in the literature regarding the practical implementation of closed-loop systems in wound care. Studies integrating fuzzy logic controllers with ES in clinical contexts are still limited, highlighting the need for stronger empirical evidence to support the effectiveness and applicability of this approach. To address this gap, this study develops a fuzzy-logic-based closed-loop ES system capable of adaptively adjusting stimulation duration according to wound-area reduction. Compared with open-loop systems or conventional controllers that employ fixed-duration stimulation without considering wound conditions, the proposed system is more responsive, as it processes biological feedback in real time. Consequently, therapy can be tailored more accurately, thereby reducing the risk of overstimulation or understimulation.

The novelty of this study lies in the integration of fuzzy logic with a closed-loop ES system based on real-time wound-area measurement, which, to the best of current knowledge, has not been previously reported in the literature. The proposed

system not only regulates stimulation adaptively but also adjusts therapy duration in accordance with the biological dynamics of wound healing, while validating its effectiveness through preclinical experiments demonstrating up to a twofold acceleration in healing. Accordingly, the contribution of this research extends beyond conventional fuzzy approaches by combining adaptive control, biological validation, and clinically relevant implications.

The proposed system is expected to enhance the effectiveness of ES therapy and significantly accelerate wound healing. This study contributes an adaptive and precise therapeutic solution for chronic wound management, enabling reduced healing time and minimized risks of therapeutic misapplication. The findings also open new opportunities for more effective chronic wound care, with the potential to improve treatment outcomes and patients' quality of life.

## II. METHODOLOGY

The methodology of this study is designed to develop and evaluate a fuzzy-logic-based closed-loop ES system through the integration of an electrical stimulator, a fuzzy controller mechanism, and wound-area measurement. The fuzzy approach is employed because it enables intuitive concepts to be represented in quantitative terms, allowing them to be utilized in an informative and systematic manner [10]. To validate system performance and compare it with conventional methods, preclinical testing was conducted using guinea pigs as experimental subjects.

Preclinical experiments were performed to compare the therapeutic effectiveness of open-loop ES, closed-loop ES, and no-ES conditions. The experimental animals were induced with stage-3 full-thickness wounds in accordance with ethical eligibility requirements. All procedures related to wound induction, therapy administration, and anatomical pathology testing—including assessments of tissue density and vascular growth—were conducted at dr. Ramelan Naval Hospital (RSAL dr. Ramelan), Surabaya, under the direct supervision of a board-certified anatomical pathologist from the same institution.

Data analysis was conducted to evaluate the effectiveness of the closed-loop ES system in accelerating wound healing by considering key parameters, namely wound-area reduction, connective tissue and blood vessel density, and stimulation duration. Wound-area reduction was calculated as the difference between the initial wound size and the final wound size at the end of the therapy period, while tissue density and blood vessel growth were assessed through microvascular analysis. Stimulation duration was dynamically regulated by the fuzzy controller based on daily wound progression. The evaluation was performed through intergroup statistical analysis and system performance assessment of the fuzzy controller, focusing on accuracy, adaptive capability, and effectiveness in preventing overstimulation and understimulation. Experimental data processing was carried out using Microsoft Excel for statistical analysis, including evaluations of the relationship between frequency and converter voltage, fuzzy controller output stimulation duration, target wound area for fuzzy control, as well as stimulation duration and wound-area reduction across each therapy group.

### A. CLOSED-LOOP ELECTRICAL SIMULATION SYSTEM DESIGN

The electrical stimulator in this study was designed to generate pulsed signals with adjustable parameters, namely an

amplitude range of 0–50 V, a frequency of 20 Hz, and a pulse width of 250  $\mu$ s, controlled by an Atmega32 microcontroller. The output current was limited to a maximum of 60  $\mu$ A to ensure safety and comfort during therapy [11].

Microcurrent therapy has been shown to be effective in disrupting bacterial cell membranes, reducing infection, accelerating pain control, and promoting wound healing [12]–[14]. Parameter selection was based on considerations of both efficacy and safety. A stimulation frequency of 20 Hz was selected to stimulate tissue regeneration without inducing muscle contraction, while a pulse width of 250  $\mu$ s fall within the physiological range and helps minimize pain. A maximum output voltage of 50 V is chosen to avoid the risk of involuntary muscle contraction. This parameter combination is expected to optimize the wound-healing process in a safe and effective manner.

Electrical stimulation can be applied to both chronic and acute wounds using various methods, with one of the most common approaches involving the placement of electrodes around the wound area [15]. The electrodes serve as the interface between the ES system and skin tissue, enabling electrical current to stimulate the healing process. The mechanism of electrical current conduction at the electrode–tissue interface depends on the nature of the conducting medium. In electrical circuits, current is conducted by electrons, whereas in biological tissue, current is conducted by ions. The wound-healing electrical stimulator consists of a boost converter module and a pulse generator circuit, as illustrated in Figure 1.

The desired function of the ES system is to increase the output voltage of the pulse generator; therefore, a step-up voltage converter, or boost converter, is selected [16], [17]. The boost converter is a dc–dc converter designed to increase input voltage. In this ES circuit, the boost converter employed an inductor (L) and a capacitor (C). During operation, the boost converter alternately charges the inductor and capacitor to incrementally increase the output voltage [18], [19].

The Atmega32 microcontroller provides sufficient specifications to regulate pulse signals and manage the fuzzy controller with precision. This 8-bit microcontroller is equipped with adequate memory, a clock speed of up to 16 MHz, and timer and serial communication features that support real-time control of electrical stimulation. In addition, the Atmega32 is easy to program, power-efficient, compatible with the developed circuitry, and supported by extensive technical documentation, making it highly suitable for portable systems and closed-loop electrical stimulation applications. In this system, the microcontroller serves as a digital control signal generator, producing basic trigger pulse signals with adjustable frequency and duty cycle. These pulse signals are low-voltage logic signals insufficient to directly stimulate wound tissue and were therefore further processed by the pulse generator. Systematically, the microcontroller acted as the control pulse signal generator, while the pulse generator was responsible for producing power-level pulse signals with amplitudes suitable for stimulation.

The pulse generator operates using two primary inputs, namely the voltage supplied by the boost converter as the energy source and the pulse signal generated by the microcontroller, which regulates pulse timing and frequency. The pulse generator consists of a linear radio-frequency (RF) amplifier and a high-pass filter (HPF). The pulse generator

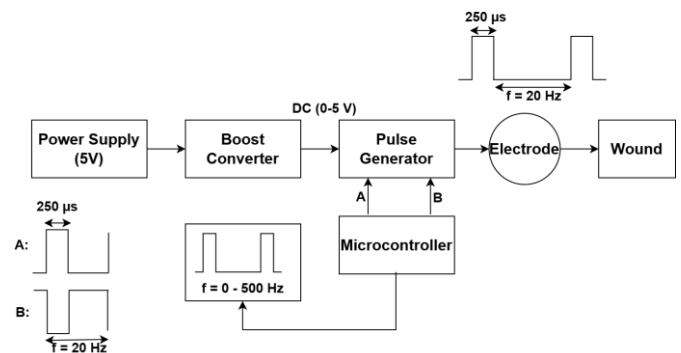


Figure 1. Diagram of electrical stimulation circuit.

amplifies the microcontroller signal through the linear RF amplifier and HPF, thereby producing filtered low-frequency pulses with very short durations, as reported in prior studies [20].

The microcontroller generates the control signal that triggers the operation of the pulse generator, whereas the pulse generator amplifies and shapes the electrical stimulation signal applied to the wound. Although these two components serve distinct functions, they are integrated into a single, cohesive system. This signal-processing stage yields pulse waveforms with higher amplitudes, ranging from 0 to 50 V, which are delivered to the electrodes to stimulate the wound-healing process. The output pulse waveform of the ES system is shown in Figure 2.

The ES system was equipped with a user interface comprising six push-button switches to facilitate user interaction. Each switch served a specific function, including increasing and decreasing the channel, increasing and decreasing the amplitude, as well as enter and reset operations. The presence of this interface allowed users to adjust ES parameters with greater flexibility and precision. Through the integration of these components, the developed ES system was able to deliver more adaptive and precise electrical stimulation, thereby enhancing therapeutic effectiveness in accelerating wound healing.

## B. PRECLINICAL TESTING

Preclinical testing was conducted on male guinea pigs (*Cavia porcellus*) aged five to six months with body weights ranging from 400 to 500 g. The experimental procedures were performed in several stages. First, a wound model was created on the dorsal area of each guinea pig, after which the wound was cleansed with saline solution and covered with a sterile dressing to prevent infection. Second, the therapeutic interventions were assigned according to predefined treatment groups.

Based on the type of therapy administered, the experimental animals were divided into four groups: a control group without ES therapy, an open-loop group receiving fixed stimulation (30 minutes on, 60 minutes off, for 12 hours per day), and two closed-loop groups receiving ES therapy with adaptively adjusted stimulation duration using a fuzzy controller based on daily wound-area reduction.

Variations in initial wound area among experimental animals 1–4 occurred because wound creation was performed manually in accordance with standard procedures. Such variability was difficult to avoid due to differences in anatomical characteristics and skin thickness among individual guinea pigs. To address this issue, the analysis was performed

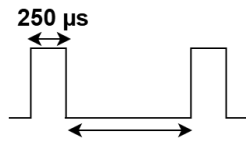


Figure 2. Electrical simulation signal waveform.

using the percentage of wound-area reduction relative to the initial wound size, allowing healing progress to be compared objectively. This percentage was also used as feedback input to the fuzzy controller to ensure that differences in initial wound size did not influence stimulation-duration control decisions.

Wound-healing analysis includes measurements of wound area and evaluation of tissue quality through assessments of connective tissue density and new blood vessel growth. The results indicated that, in addition to wound-area reduction, significant changes in tissue structure and the degree of angiogenesis also served as important indicators of therapeutic effectiveness. This observation is attributable to the role of biological factors, such as fibroblast activity and vascularization, which play a critical role in accelerating tissue regeneration [21]. During the wound-healing process, the formation and development of blood vessels are essential and occur predominantly during the proliferative phase, which begins on day four and continues through day twenty-one after wound formation [22].

### C. FUZZY CONTROLLER SYSTEM

The fuzzy controller system in this study was designed to adaptively regulate the duration of electrical stimulation based on wound progression. A fuzzy controller was selected because it is capable of handling uncertainty and biological dynamics without requiring a precise mathematical model. The design process included identification of input and output variables through the definition of membership functions, formulation of fuzzy rules, and selection of appropriate inference and defuzzification methods. This approach was intended to produce a flexible, precise, and responsive control mechanism capable of adapting to changes in wound conditions during therapy.

In the electrical stimulation regulation system for wound healing, the controlled stimulus parameters included stimulation duration and amplitude, while pulse width and frequency were maintained at constant values. The mechanism for updating stimulation duration is expressed in (1):

$$T[n] = T[n - 1] + \Delta T[n]. \quad (1)$$

The stimulation duration at the  $n$ th cycle, ( $T[n]$ ), was calculated based on the duration in the previous cycle, ( $T[n-1]$ ), and the adjustment generated by the fuzzy controller, ( $\Delta T[n]$ ). Accordingly,  $T[n]$  represented the current stimulation duration, which was adaptively updated in response to wound-condition progression. At each cycle, the fuzzy controller determined the value of  $\Delta T[n]$  to achieve the targeted wound-area reduction optimally. System accuracy was subsequently evaluated by comparing calculated values with fuzzy controller outputs to assess the effectiveness of therapy adjustment.

Fuzzy membership parameters are represented using triangular and trapezoidal functions, as defined in (2) and (3). The membership functions are expressed as follows:

$$Triangular(x; a, b, c) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ \frac{c-x}{c-b}, & b \leq x \leq c \\ 0, & c \leq x \end{cases} \quad (2)$$

$$Trapezoidal(x; a, b, c, d) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \frac{d-x}{d-b}, & c \leq x \leq d \\ 0, & d \leq x \end{cases} \quad (3)$$

The triangular membership function is defined by three parameters:  $a$  as the lower bound,  $b$  as the peak with maximum membership degree, and  $c$  as the upper bound. The trapezoidal membership function uses four parameters, where  $a$  is the lower bound,  $b$  and  $c$  define the range with full membership ( $\mu(x)=1$ ), and  $d$  represents the upper bound. The variable  $x$  denotes the input value mapped to a membership degree  $\mu(x)$  within the interval  $[0,1]$ .

The fuzzy controller employed two input variables, namely  $error[n-1]$  ( $e$ ) and  $delta\ error[n]$  ( $de$ ). The  $error[n-1]$  variable was defined as the difference between the targeted wound-area reduction and the actual reduction in the  $(n-1)$ th cycle. The  $delta\ error[n]$  variable represented the change in error value, calculated as the difference between  $error[n]$  and  $error[n-1]$ . The fuzzy input membership functions for wound-area reduction error ( $e$ ) and delta difference ( $de$ ) are shown in Figure 3(a) and Figure 3(b), respectively. The fuzzy membership parameter values were determined based on experimental results from open-loop electrical stimulation trials. The fuzzy output membership function was defined as a singleton, as illustrated in Figure 4.

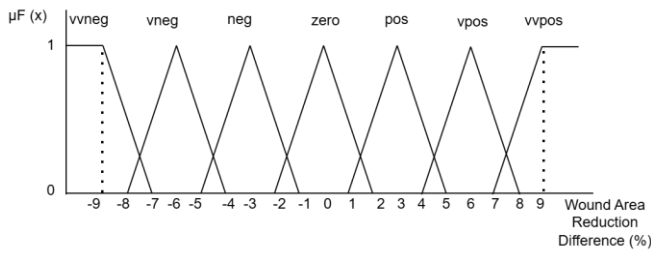
The fuzzification process converted numerical input values into fuzzy membership degrees for processing by the system. These inputs were then evaluated using 21 fuzzy rules (e.g., if  $e = \text{“neg”}$  and  $de = \text{“B”}$ , then duration = “pdk”), as shown in Table 1.

Following fuzzification, the inference stage applied the fuzzy rules to determine an appropriate system response to the wound condition. The inference process produced a fuzzy output, namely  $\Delta T[n]$ , in the form of linguistic variables. After inference and rule evaluation, defuzzification was performed to obtain a crisp output value. The defuzzification method used was the weighted average, as expressed in (4):

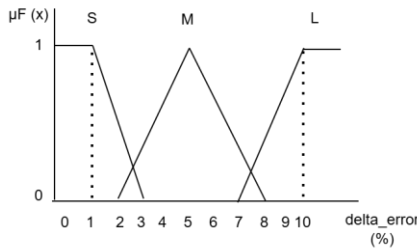
$$Final\ output = \frac{\sum_{i=1}^7 \mu_i z_i}{\sum_{i=1}^7 \mu_i} \quad (4)$$

In (4),  $\mu_i$  represents the input membership degree, which determines the degree to which a given input belongs to the relevant fuzzy set, while  $z_i$  denotes the output value obtained from the fuzzy inference process. This value represents the system output after fuzzification, rule evaluation, and defuzzification. The resulting output was then used to adaptively adjust the duration of electrical stimulation.

The fuzzy controller in the closed-loop system adjusted the duration of electrical stimulation to remain within an optimal range, thereby accelerating wound healing without inhibiting cellular regeneration or inducing tissue fatigue due to overstimulation. The block diagram of the fuzzy control system used to regulate electrical stimulation during the wound-healing process is shown in Figure 5.



(a)



(b)

Figure 3. Input membership function, (a) fuzzy (e) and fuzzy (de)

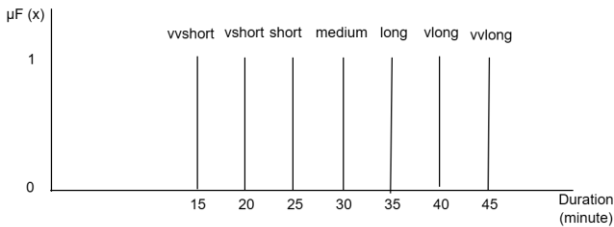


Figure 4. Fuzzy output membership function.

TABLE I  
FUZZY RULES

e \ de	K	M	B
ssneg	sspdk	sspdk	sspdk
sneg	spdk	spdk	spdk
neg	spdk	pdk	pdk
nol	sdg	sdg	sdg
pos	lama	lama	slama
spos	slama	slama	slama
sspos	sslama	sslama	sslama

The effectiveness of stimulation-duration adjustment was evaluated through a wound-area feedback mechanism using a digital image-based measurement method with color detection, allowing healing progress to be monitored objectively. Wound area was calculated in pixel units and analyzed by comparing values obtained on each observation day with those from the previous day to determine the percentage of reduction. Image data were acquired from wound photographs captured periodically using a camera and were subsequently used as input to the fuzzy controller to adaptively adjust stimulation duration.

The percentage of wound-area reduction was converted into an error value and compared with the targeted reduction. Based on this error, the system adjusted stimulation duration: the duration was extended when a large negative error occurred and reduced when wound reduction approached or exceeded the target. These adjustments were performed periodically to ensure that therapy duration consistently aligned with the current biological condition of the wound.

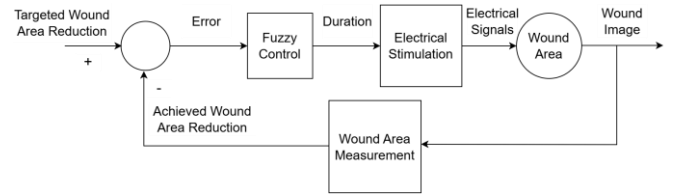


Figure 5. Fuzzy controller of the electrical stimulator.

III. RESULTS AND DISCUSSION

This study has successfully developed a fuzzy logic-based closed-loop electrical stimulation system and evaluated its effectiveness in accelerating wound healing in guinea pig models. The system is able to automatically adjust the duration of electrical stimulation based on wound progression, thereby improving therapeutic efficiency and promoting faster tissue regeneration. This adaptive approach demonstrates strong potential as a more optimal solution compared with conventional stimulation methods.

A. PERFORMANCE OF THE ELECTRICAL SIMULATOR CIRCUIT

Bioelectrical-based technologies play an important role in the early detection and management of diabetic foot ulcers, particularly through innovative therapies such as electrical stimulation, which has been shown to accelerate tissue regeneration and enhance blood circulation in wound areas [23]. For the therapy to be effective, the electrical stimulation system must generate signals that conform to the designed parameters. Therefore, performance testing was conducted to verify frequency, amplitude, and pulse width, ensuring that the delivered stimulation was safe, effective, and supportive of the wound-healing process.

1) MICROCONTROLLER OUTPUT PULSE SIGNAL

Measurement results showed that the pulse signal frequency generated by the microcontroller was 20 Hz, with an error rate of 2.5%. This value remains within the acceptable tolerance range for wound therapy applications [24]. In addition, the designed pulse width of 250 μs exhibited an average error of 20.8%, and the pulse width increased to 314 μs when connected to biological tissue. Despite this increase, the value is still considered safe for wound-healing applications, as non-painful pulse widths span a wide range, reaching up to 500 μs [24]. These results indicate that the developed electrical stimulation circuit remains suitable for effective application in electrical stimulation-based wound therapy.

2) AMPLIFIER CONVERTER

Testing of the amplifier converter was performed to measure the output voltage under various input frequencies in order to evaluate its performance, as shown in Figure 6. The amplifier converter received a pulse signal as input and produced a DC voltage output suitable for driving the electrical stimulation electrodes.

The maximum output voltage generated by the amplifier converter reached 50 V, which is consistent with the designed specifications. This result indicates that the amplifier converter operates properly in providing a stable voltage to support the electrical stimulation system.

The test results are modeled in (5), which shows that the output voltage increases linearly with increasing input frequency.

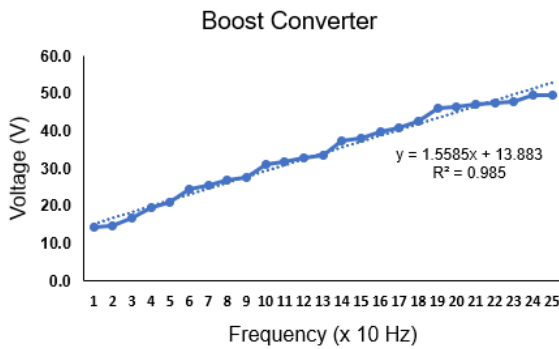


Figure 6. Relationship between frequency and voltage of the amplifier converter.

$$Y = 13.83 + 1.56 X. \tag{5}$$

Here,  $Y$  represents the output voltage, while  $X$  denotes the input frequency. The constant 13.83 indicates the output voltage at zero frequency, whereas the coefficient 1.56 represents the rate of increase in output voltage with respect to the input frequency, confirming a positive linear relationship between the two variables.

### 3) PULSE GENERATOR

Final testing of the stimulator was conducted at the output of the pulse generator, both under no-load and loaded conditions, to evaluate the influence of biological tissue on the stimulation signal parameters. The tested parameters included voltage amplitude, current, signal waveform, frequency, and pulse width, ensuring that the system operates in accordance with the design specifications. The results showed that the output voltage amplitude of the pulse generator varied from 15.4 V to 50.8 V, depending on the input frequency. This variation indicates that the pulse generator is capable of adjusting its output voltage to meet the requirements of electrical stimulation therapy.

The output voltages of both the amplifier converter and the pulse generator satisfy the design specifications, demonstrating the ability to adapt the stimulation amplitude according to therapeutic needs. Subsequently, current measurements were performed at an amplitude of 25 V across various resistance values, including simulations of conditions when electrodes are attached to skin tissue. The purpose of these measurements was to determine the maximum current generated by the electrical stimulation circuit. The results showed that at a resistance of 1  $\Omega$ , the maximum current produced was 52  $\mu\text{A}$  with a pulse width of 323  $\mu\text{s}$ . Meanwhile, when applied to skin tissue with a resistance of approximately 400 k $\Omega$ , the measured current was 0.58  $\mu\text{A}$ . The 1  $\Omega$  resistor was selected as the reference value for current measurement because it provides minimal resistance, allowing direct determination of the maximum circuit current without the influence of external resistance. In addition, the maximum electrical charge generated at this resistance reached 168  $\mu\text{C}$ , which remains within the safe range for electrical stimulation therapy. According to electrical therapy standards, the charge delivered per pulse must remain within the microcoulomb ( $\mu\text{C}$ ) range to ensure both safety and therapeutic effectiveness [25].

### 4) STIMULATION DURATION

The stimulation duration generated by the system exhibited a maximum error of 2.5% due to rounding in microcontroller calculations; however, this error remains within safe limits and

does not affect therapeutic effectiveness. Overall, the electrical stimulator circuit demonstrates reliable performance and meets the initial design specifications. The system is capable of generating electrical stimulation signals with accurate parameters and can be dynamically adjusted based on feedback from wound progression, thereby ensuring both effectiveness and safety in practical applications.

### B. EFFECTIVENESS OF THE FUZZY CONTROLLER IN ADJUSTING STIMULATION DURATION

The fuzzy logic controller was developed through five main stages: selection of control inputs, definition of fuzzy membership functions, formulation of fuzzy rules, selection of the fuzzy inference method, and implementation of the defuzzification process. The fuzzy controller adaptively adjusted the duration of electrical stimulation based on the error between the actual reduction in wound area and the target reduction. The system used wound area measurements as feedback to determine the error value, which was then processed as fuzzy input to regulate stimulation duration. When the wound reduction was smaller than the target, the stimulation duration was extended; conversely, when the reduction exceeded the target, the duration was reduced to prevent tissue fatigue. The generated electrical stimulus was applied to the wound to optimally promote tissue regeneration without adverse effects. This approach is effective because the fuzzy controller is capable of handling the complex and nonlinear dynamics of biological systems.

Defuzzification using the weighted average method shows that under conditions of  $e = +4,5$  and  $de = 3$ , the stimulation duration increases to 41.2 minutes to prevent understimulation, whereas under conditions of  $e = -4,5$  and  $de = 3$ , the duration decreases to 23.8 minutes to prevent overstimulation. These results confirm that the fuzzy controller adaptively adjusts stimulation duration based on the achieved wound area reduction, making it more effective than an open-loop system with a fixed stimulation duration.

The application of fuzzy logic is shown to be effective in adaptively regulating the duration of electrical stimulation therapy according to wound progression. By processing the difference between the target and the actual outcome, the system determines the optimal stimulation duration while managing uncertainty [26]. The results presented in Figure 7 indicate that greater wound area reduction corresponds to shorter stimulation durations.

The fuzzy system adjusted the electrical stimulation duration within a range of 15–45 minutes based on wound area reduction. The duration was extended when the achieved reduction was below the target, maintained at 30 minutes when it met the target, and reduced when it exceeded the target to prevent overstimulation.

The fuzzy controller is able to adjust electrical stimulation duration in real time with high accuracy (error of 0.3%), thereby improving both the efficiency and effectiveness of wound healing therapy. This level of accuracy confirms that the fuzzy controller provides an adaptive and precise solution for wound healing applications. The control parameters are determined based on preclinical testing of the open-loop system, which follows an exponential wound area reduction model with delay, and are designed based on qualitative knowledge of the healing process formulated into fuzzy rules and membership functions.

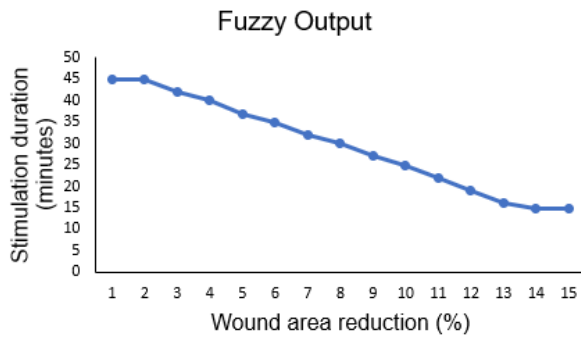


Figure 7. Duration of fuzzy electrical stimulation output.

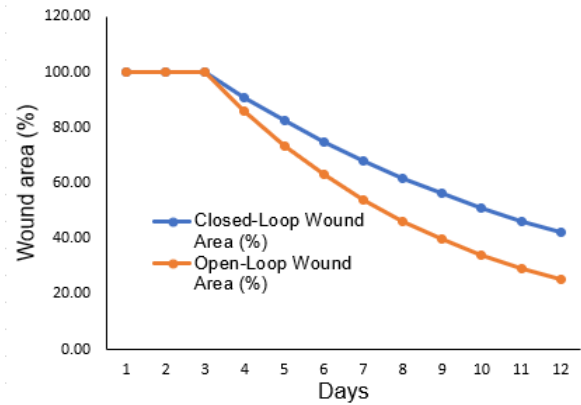


Figure 8. Target wound area for fuzzy control.

**C. EFFECTIVENESS OF FUZZY CONTROLLER IN ELECTRICAL STIMULATION THERAPY FOR WOUND HEALING**

A quantitative approach was employed to determine the wound healing rate and the optimal stimulation duration, using a normalization value of  $\theta = 0,09/\text{day}$  and a delay time of 3 days as the basis for the target daily wound area reduction in the closed-loop ES system. Equation (6) is used to describe the wound healing dynamics over time [27]. The corresponding design target for a 12-day period is illustrated in Figure 8.

$$S(t) = \begin{cases} S_{DEX}, & 0 \leq t \leq T_{DEX} \\ S_{DEX} \cdot e^{-\theta_{DEX}(t-T_{DEX})}, & t > T_{DEX} \end{cases} \quad (6)$$

Equation (6) indicates that  $S(t)$  represents the estimated wound area (%) at time  $t$ , while  $S_{DEX}$  denotes the initial wound area (%). The parameter  $\theta_{DEX}$  represents the healing rate (% per day), and  $T_{DEX}$  denotes the healing delay time (days).

The closed-loop system was designed to accelerate wound healing by up to 1.5 times compared with the open-loop system while still considering the risk of tissue fatigue. During the first three days of the healing target design, both therapy systems exhibited similar healing patterns, as this period corresponds to the early phase of tissue regeneration. On day 12, the closed-loop system reduced the wound area to approximately 25%, whereas the open-loop system remained at around 42%. The acceleration factor of 1.5 was selected based on prior studies, which report that electrical stimulation therapy increases wound healing rates by approximately 1.3 to 2 times, depending on wound type and stimulation parameters [27]–[29].

In the open-loop therapy, the electrical stimulation duration was fixed at 30 minutes on and 60 minutes off, whereas in the closed-loop therapy, the duration was adaptively adjusted between 15 and 45 minutes based on wound progression. The control group did not receive electrical stimulation. Days 6 or 7 were designated as intermittent rest days to prevent adverse effects of continuous stimulation, such as temperature elevation and tissue fatigue.

The experimental treatment protocol was structured to enable comparison among therapy methods, with Table II summarizing the treatment applied to each animal. The initial wound area was measured as a reference for effectiveness, and animal 1 served as the control group, receiving standard wound care without electrical stimulation. Each treatment condition was designed to allow objective evaluation of the contribution of electrical stimulation to the wound healing process.

Therapy effectiveness was evaluated by measuring wound area reduction for each animal throughout the study, comparing

TABLE II  
EXPERIMENTAL ANIMAL THERAPY ACTIONS

Animal	Area of Initial Wound (mm <sup>2</sup> )	Action
1	182	No therapy
2	500	Open-loop therapy
3	500	Closed-loop therapy
4	375	Closed-loop therapy

closed-loop therapy, open-loop therapy, and no stimulation. The results demonstrate the adaptive capability of the closed-loop system in adjusting therapy duration, as shown in Figure 9 until Figure 12 and Table III.

Variations in stimulation duration among the experimental animals illustrate how the ES system adjusted therapy duration through the fuzzy controller. The graphs in Figure 13 until Figure 16 depict the relationship between the target wound area reduction, the achieved reduction, and the applied stimulation duration during therapy.

For animal 1, which did not receive ES therapy, the achieved wound area reduction was consistently lower than the target, as shown in Figure 13. For animal 2 under open-loop therapy (Figure 14), the electrical stimulation duration remained constant at approximately 30 minutes per session. Wound area reduction became apparent on day 3 and approached the target on days 4 and 5, indicating the effectiveness of the therapy. However, on days 7 and 8, the achieved wound reduction again fell below the target. Overall, open-loop therapy exhibited a gradual trend of wound area reduction over time.

Figure 15 and Figure 16 show that the stimulation duration for animals 3 and 4 was adaptively regulated by the fuzzy controller based on the difference between the achieved wound area reduction and the target. Although animal 3 had a larger initial wound area, both animals exhibited significant improvement from day 3 to day 6, with a peak on day 4 that exceeded the target, prompting a reduction in stimulation duration to avoid overstimulation. On day 5, the healing rate decreased, and the stimulation duration was maintained at a lower level to preserve healing stability. On days 7 and 8, the duration was increased again in response to a slowdown in wound reduction. On day 8, animal 4 reached the target, whereas animal 3 remained slightly below the target, which may be influenced by its larger initial wound size. These findings demonstrate the effectiveness of the fuzzy controller in dynamically adjusting stimulation duration according to the wound healing phase.

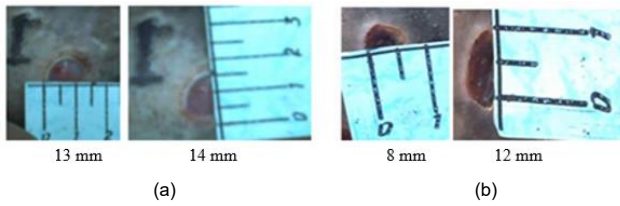


Figure 9. Wound area of animal 1, (a) day 0 = 182 mm<sup>2</sup> and (b) day 7 = 96 mm<sup>2</sup>.

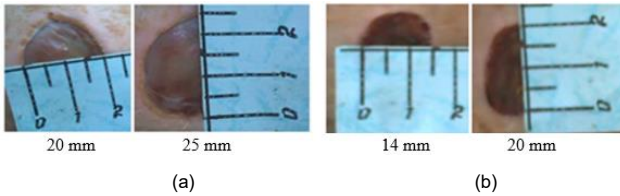


Figure 10. Wound area of animal 2, (a) day 0 = 500 mm<sup>2</sup> and (b) day 7 = 280 mm<sup>2</sup>.

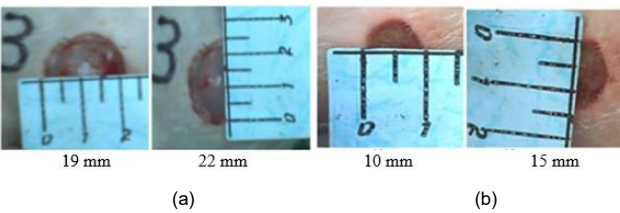


Figure 11. Wound area of animal 3, (a) day 0 = 418 mm<sup>2</sup> and (b) day 7 = 150 mm<sup>2</sup>.

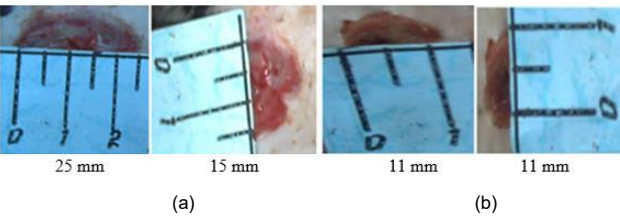


Figure 12. Wound area of animal 4, (a) day 0 = 375 mm<sup>2</sup> and (b) day 7 = 121 mm<sup>2</sup>.

TABLE III  
REDUCTION OF WOUND AREA IN EXPERIMENTAL ANIMALS

Animal	Initial Wound Area (mm <sup>2</sup> )	Wound Area in the 7th Day (mm <sup>2</sup> )	Wound Area Reduction (%)
1 (Without therapy)	182	96	47
2 (Open-loop therapy)	500	280	44
3 (Closed-loop therapy)	418	150	64
4 (Closed-loop therapy)	375	121	67

The fuzzy controller played a critical role in determining the optimal electrical stimulation duration in real time based on the difference between the target and achieved wound area reduction. This adaptive adjustment prevented overstimulation, which poses a risk of tissue fatigue, and understimulation, which may delay healing. The closed-loop system ensured that therapy was delivered at an appropriate dosage and tailored to the condition of each experimental animal. Variations in healing time were also influenced by biological factors, including initial wound size, tissue response, and individual physiological conditions.

Preclinical test results demonstrate that closed-loop therapy produce the most significant wound area reduction, reaching approximately 64–67% within seven days. This outcome is attributed to the ability of the fuzzy controller to dynamically adjust stimulation duration in accordance with wound progression, thereby providing a more precise and effective

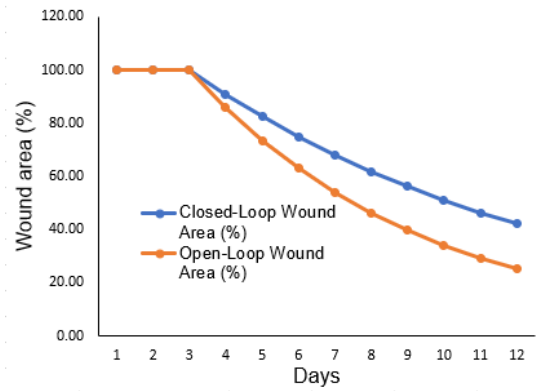


Figure 13. Duration and reduction of wound area without ES therapy.

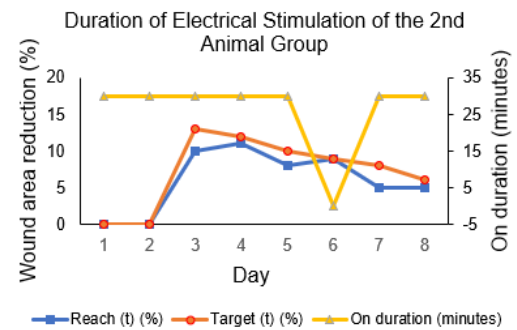


Figure 14. Duration and reduction of wound area with open-loop therapy.

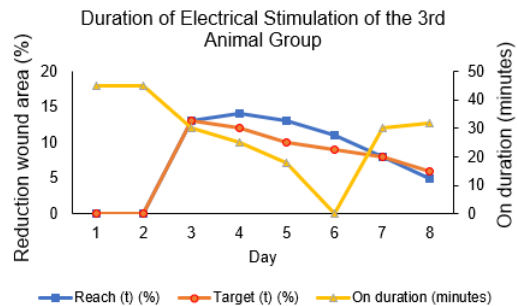


Figure 15. Duration and reduction of wound area with closed-loop therapy (animal 3).

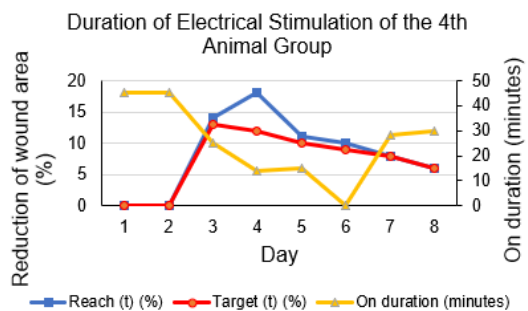


Figure 16. Duration and reduction of wound area with closed-loop therapy (animal 4).

therapeutic response. In contrast, open-loop therapy employing a fixed stimulation duration (30 minutes on–60 minutes off) achieved only a 44% reduction in wound area, which was even lower than that observed in the control group (47%). This result may be explained by the smaller initial wound size in the control group and the inability of the open-loop system to adapt therapy to individual needs. Nonadaptive stimulation durations may lead to ineffective or biologically mismatched stimulation.

TABLE IV  
CALCULATION OF THERAPY EFFECTIVENESS SCORE

Animal	Score			
	Wound Area Reduction	Connective Tissue Density	New Blood Vessels	Total Score
1 (Without therapy)	0.70	0.25	0.58	0.51
2 (Open-loop therapy)	0.66	0.50	0.69	0.61
3 (Closed-loop therapy)	0.96	0.75	1.00	0.90
4 (Closed-loop therapy)	1.00	1.00	1.00	1.00

The superiority of the fuzzy-controller-based closed-loop system was further supported through comparison with previous studies. Several earlier investigations report that electrical stimulation therapy for chronic wounds typically achieves an average wound area reduction of about 22% over four weeks, including in patients with diabetic foot ulcers using home-based ES systems [28], [30]. In contrast, the system developed in this study achieved a wound area reduction of 64–67% within seven days, indicating a substantially higher healing acceleration. This advantage arises from the capability of the fuzzy-based closed-loop system to adjust stimulation duration in real time according to actual wound progression, unlike open-loop systems that apply fixed stimulation durations without adaptive responses to biological wound dynamics [31], [32]. Through this adaptive approach, the system not only significantly accelerated wound area reduction but also reduced the risk of overstimulation and understimulation, resulting in a more efficient, responsive, and quantifiable healing process based on daily wound area reduction percentages.

The success criteria in this study comprises three primary aspects: (a) the rate of daily wound area reduction, where the developed system exhibited faster healing than both open-loop and untreated systems; (b) the adaptive capability of the fuzzy-based closed-loop system to adjust stimulation duration in real time according to current wound conditions, a feature absent in open-loop systems; and (c) reduced risk of overstimulation, enabling the adaptive system to minimize excessive or insufficient therapy durations that commonly occur in open-loop systems.

Evaluation of wound healing outcomes across therapy groups was not limited to wound area reduction but also considered significant differences in tissue quality and regeneration level as key indicators of electrical stimulation therapy effectiveness. The closed-loop group exhibited the best healing outcomes, with the highest connective tissue density (75–100%) and an average of 9.6 newly formed blood vessels. The open-loop group showed a connective tissue density of approximately 50% with an average of 6.6 new blood vessels, while the control group demonstrated the lowest density (25–50%) with an average of 5.6 new blood vessels. Wound diameter and fibroblast analysis were used as primary healing indicators, which are influenced not only by initial wound size but also by fibroblast activity, connective tissue density, and angiogenesis.

The healing indicators used for score calculation included wound area reduction, connective tissue density, and new blood vessel growth, each assigned equal weighting. This assessment was required to evaluate therapy effectiveness objectively and in a standardized manner, allowing fair and quantifiable comparison of multiple indicators across groups. The indicator score calculation is presented in (7) and Table IV.

$$Score_i = \frac{X_i}{X_{i_{max}}} \quad (7)$$

Equation (7) indicates that  $Score_i$  represents the score of the  $i$ th indicator, calculated as the ratio between the indicator value of the observed group ( $X_i$ ) and the maximum indicator value ( $X_{i_{max}}$ ) across all groups. This formulation provides a relative performance measure for each indicator.

The results demonstrate that closed-loop therapy is significantly more effective than both the control and open-

loop groups in reducing wound area, increasing connective tissue density, and accelerating new blood vessel formation, as confirmed by the composite scoring based on multiple wound healing indicators.

Overall, preclinical evaluation shows that fuzzy-based closed-loop electrical stimulation is more effective than open-loop stimulation and no therapy, achieving faster healing and improved tissue density within a shorter time frame. These findings highlight the potential for developing more adaptive and precise wound therapy systems, with promising implications for improving treatment outcomes and patient's life quality.

#### IV. CONCLUSION

The electrical stimulator system has successfully generated pulse signals with the designed parameters, including amplitude (0–50 V), frequency (20 Hz), and pulse width (250  $\mu$ s). The boost converter increases the input voltage linearly, with a maximum output voltage of 50 V. The generated current does not exceed 60  $\mu$ A, ensuring safety and comfort during therapy.

The fuzzy controller successfully adjusts the stimulation duration dynamically (15–45 minutes) according to wound progression, thereby preventing overstimulation and understimulation and improving therapeutic effectiveness. The average error between the fuzzy controller computation and the actual output is 0.3%, indicating high control accuracy. The system also dynamically regulates stimulation duration to prevent tissue fatigue, resulting in a faster and more effective wound healing process.

The closed-loop group achieves the highest score (0.90–1.00), indicating optimal wound healing effectiveness. The open-loop group obtains a moderate score (0.61), which is better than the control group but less effective than the closed-loop system. Meanwhile, the control group records the lowest score (0.51), reflecting the least effective healing outcome. These results demonstrate that closed-loop therapy is the most effective method for wound healing based on the three evaluated indicators.

Overall, this study provides a significant contribution to the development of adaptive, flexible, and more effective closed-loop electrical stimulation therapy systems for chronic wound healing, while also opening opportunities for further development of fuzzy-controller-based therapies in broader medical applications.

#### CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest associated with this study.

## AUTHORS' CONTRIBUTIONS

Conceptualization, Rahmawati and Achmad Arifin; methodology, Rahmawati and Gunawan; software, Rahmawati and Achmad Arifin; validation, Rahmawati, Achmad Arifin, and Duti Sriwati Aziz; formal analysis, Rahmawati; investigation, Duti Sriwati Aziz and Gunawan; resources, Rahmawati, Gunawan, Siti Amra, and Raisah Hayati; data curation, Rahmawati, Achmad Arifin, and Raisah Hayati; writing—original draft preparation, Rahmawati, Siti Amra, and Raisah Hayati; writing—review and editing, Rahmawati; visualization, Rahmawati.

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