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PORTABLE NEUROMUSCULAR TRANSMISSION MONITOR MODELING FOR POST-ANESTHESIA PATIENT CONSCIOUSNESS MONITORING BASED ON MICROCONTROLLERS

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ABSTRACT In the medical field, particularly in anesthesia procedures, neuromuscular transmission monitoring plays a crucial role in ensuring patients have fully recovered before being moved from the recovery room. One device used for neuromuscular transmission monitoring is the Neuromuscular Transmission Monitor (NMT). The NMT device operates by using an accelerometer sensor to detect muscle movements generated by low-current electrical stimulation (20 mA and 30 mA) through electrodes on the ulnar nerve. This model uses the train-of-four (TOF) method to assess neuromuscular blockade. The data is processed by an ESP32 microcontroller and displayed in real time as a percentage on a TFT LCD. To enhance efficiency, the monitoring data is automatically saved to a Google spreadsheet. The device model and prototype were successfully created and tested with 10 respondents at 20 mA and 30 mA, demonstrating that the device operates well and produces a square-pulse waveform. Current intensity testing showed an error value of 0.7 and an error percentage of 1.4% with an accuracy of 98.6%.

INDEX TERMS neuromuscular transmission, NMT, neuromuscular blockade, TOF method

I. INTRODUCTION

Anesthesia is a standard medical procedure used in surgical procedures to eliminate pain and render the patient unconscious during surgery. General anesthesia is administered by inhalation or injection. It involves the use of drugs that affect consciousness and the central nervous system, as well as affecting the body's respiratory and circulatory systems. Therefore, during the anesthesia procedure, the patient will be monitored by the medical team to ensure patient safety and security [1]. The use of anesthetic drugs, particularly neuromuscular blocking agents (N.M.B.A., can pose a risk of residual muscle weakness post-surgery if monitoring is not performed correctly. Therefore, neuromuscular transmission monitoring is crucial to ensure patients have fully recovered before being transferred from the recovery room [2].

The most commonly used method for monitoring neuromuscular function is the Train of Four (TOF) technique, which involves administering four consecutive electrical stimuli to the ulnar nerve at 2 Hz, followed by analysis of the muscle contraction response [3]. The train-of-four (TOF) is an examination method used to assess how well the connection between nerves and muscles is functioning, especially when a person is given muscle-relaxant drugs for surgery. TOF delivers four small electrical stimuli to the ulnar nerve in the hand at 2 Hz, each lasting 0.5 seconds. Each impulse (stimulation) will cause the thumb muscle to contract, producing the following twitches: T1 (first twitch), T2 (second twitch), T3 (third twitch), and T4 (fourth twitch).

If there is no influence of neuromuscular blockade (muscle relaxants), then all four twitches will be equally strong. However, if the muscle relaxant is still active, the T4 twitch will appear weaker than the T1 twitch or may even be absent.

The TOF ratio is used to determine the extent of neuromuscular blockade (muscle relaxants) on muscle strength, whether the muscle is still affected by the drug or has returned to normal. Based on the clinical standards advisory group (C.S.A.G.," for values, percentage recovery of neuromuscular nerve junctions in the range of 90% - 100% indicates that the muscle nerve junction has recovered well and is normal, especially in conscious individuals without anesthesia. Conversely, percentage values below 90% can be interpreted as abnormal [11]. The following is the TOF ratio formula:

$$TOF\ Ratio = \frac{T4}{T1} \text{ x } 100\ \% \qquad (1)$$

TOF-Scan is a medical device that monitors neuromuscular transmission, particularly during anesthesia and muscle relaxants, prior to surgery. This device uses the train-of-four (TOF) technique, which delivers four consecutive low-level electrical stimuli to the ulnar nerve in the hand. After stimulation is administered, TOF-Scan measures how strongly the muscle contracts. If the muscle responds well, it means that the effects of the muscle relaxant are beginning to wear off. However, if the muscle is weak or not moving, it means the drug is still working. The results of this stimulation are displayed on the TOF-Scan screen as numbers. Monitoring neuromuscular transmission helps doctors determine when the patient's muscles have recovered. This is important to avoid post-anesthesia problems, such as difficulty breathing or temporary paralysis. If the TOF ratio is more than 90%, this indicates that the connection between the patient's nerves and muscles has returned to normal. In other words, the effects of the anesthetic that prevented the muscles from moving have completely worn off. This value is important because if the TOF is less than 90%, the patient may experience muscle weakness and difficulty breathing [12].

The TOF ratio (T4/T1) is used as an indicator of neuromuscular blockade recovery, with a value ≥90% indicating normal neuromuscular function [4]. Previous studies have shown that low electrical currents (20-30 mA) are safe to use on conscious individuals without anesthesia and can elicit measurable muscle responses [5].

The TOF-Scan device, based on the acceleromyograph "A.M.G.," is one of the technologies used to detect muscle contraction objectively; however, commercial devices are generally expensive and complex, limiting their use [6]. With this background, this study aims to develop a portable neuromuscular transmission monitor model for post-anesthesia patient consciousness monitoring using microcontrollers.

II. RESEARCH METHODS

A. RESEARCH DESIGN

This study uses an experimental method with a modeling approach and tests a portable neuromuscular transmission monitor prototype powered by an ESP32 microcontroller. The device is designed to detect muscle contractions induced by electrical stimulation using the train-of-four method at current intensities of 20 mA and 30 mA.

The research flowchart in Fig. 1 outlines the sequential steps of the research. If any step does not meet expectations, the process is repeated until the desired results are achieved.

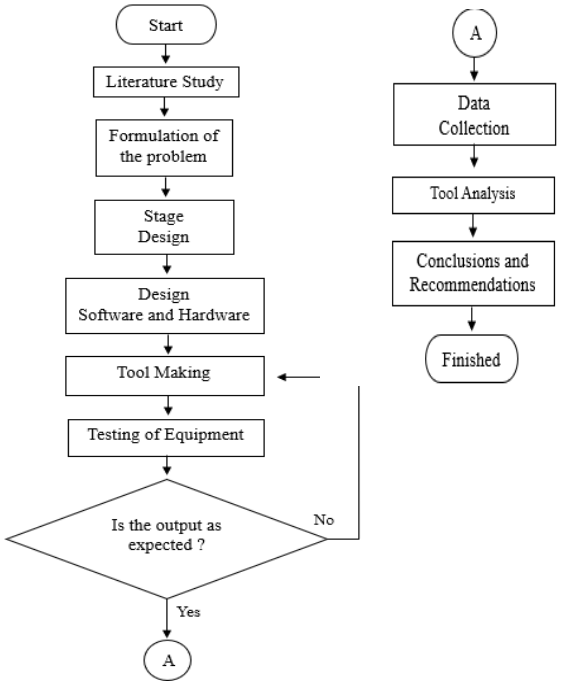

FIGURE 1. Research flowchart.

B. DESIGN PLANNING OF THE DEVICE

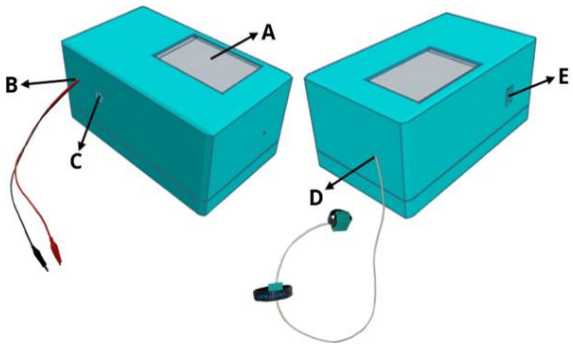

FIGURE 2. Design planning of the device, showing main components: (A) Display screen, (B) Positive and negative output cable ports, (C) Adapter port, (D) Cable from the device to the patient, and (E) On/off button to turn the device on.

Fig. 2 shows a 3-dimensional design of the tool. The following is an explanation of the letters in the figure:

A. 2.8-inch TFT LCD to display the electrical impulse setting process and neuromuscular blockade measurement data.
B. Cables from the device to the patient, consisting of positive and negative cables used in conjunction with stimulation electrodes.
C. Adapter port for direct power supply from an electrical outlet.
D. A cable from the device to the patient, including a sensor to be placed on the patient's thumb.
E. An on/off button to turn the device on when in use and off when not in use.

C. DEVICE SPECIFICATIONS

The portable neuromuscular transmission monitor model has the following specifications:

1) Display: 2.8-inch TFT LCD
2) Microcontroller: ESP32
3) Sensor: MPU-6050 accelerometer
4) Impulse range: 20 mA and 30 mA
5) Battery supply: ± 12 volts
6) Device dimensions: 17cm x 10cm x 7.5cm

D. GOOGLE SPREADSHEET INTERFACE DESIGN

The NMT system in this research uses Google Spreadsheet to display measurement results and other information, including date, time, age, name, measurement results, normal/abnormal status, and the current status used on the patient. The Google spreadsheet interface display is shown in Fig. 3.

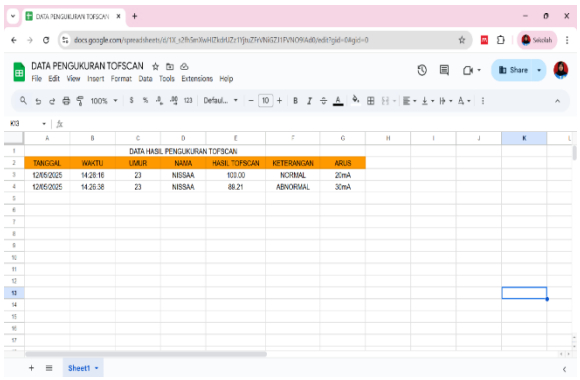

FIGURE 3. Google spreadsheet interface displaying data measured by the NMT device.

Users and doctors can access the measurement results in the Google spreadsheet if further patient diagnosis is required.

E. SYSTEM BLOCK DIAGRAM

The block diagram shown in Fig. 4 provides a general overview of the entire neuromuscular transmission monitor. The following are the functions of each component:

1) 12V DC supply: powers the entire device system.
2) Step-down driver: reduces the 12V supply to 5V for the ESP32 and other components.
3) Relay 2: an electronic switch controlled by the microcontroller that connects/disconnects the 5V power supply to the ESP32.
4) 5V supply: the step-down driver's output powers the ESP32 and other components.
5) ESP32 microcontroller: issues commands to the components to turn on, send, and process data.
6) Relay 1: connects or disconnects the current to the stimulator electrodes.
7) 2.8-inch TFT LCD: a visual interface for users and displays real-time measurement data.
8) Buzzer: emits a sound when the impulse is applied to the patient.
9) MPU-6050 accelerometer sensor: detects and measures movements of the nerves in the hand.
10) Step-up driver: increases the voltage from 12V to a higher voltage as required by the muscle stimulator. The step-up voltage used for muscle stimulation is 50V.
11) MOSFET: separates the signal path from the load, preventing load-related interference, such as voltage spikes or reverse current.
12) Stimulator electrode: transmits electrical signals to human muscles to provide stimulation.
13) Google spreadsheet: stores the results of the experiment.

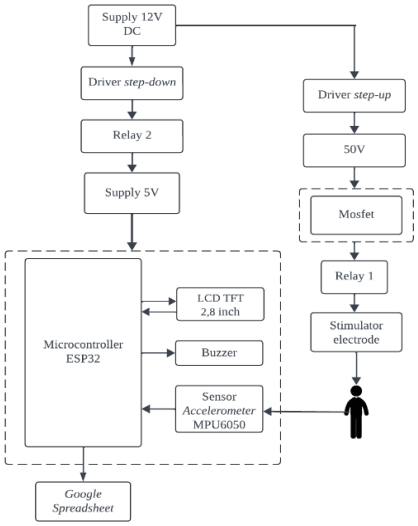

FIGURE 4. Block diagram system hardware.

F. FLOWCHART PLANNING

The flowchart of the NMT device operation system includes the initialization process, patient data input, sensor data reading and processing, patient diagnosis analysis, and data storage in Google spreadsheets.

Based on the flowchart in Fig. 5, when the battery supply powers all components and the on button is pressed, the device turns on and initializes the LCD. Next, the user must connect the wifi to the NMT device. If the wifi is connected, the device can be used by the user. Users can click "start" to access the patient data menu, such as the patient's name and age. After the patient data has been entered, attach the stimulator electrodes to the patient's hand. The process continues to the next step, where the user is prompted to set the electrical impulse to be administered to the patient, either 20 mA or 30 mA. Next, click the "start" button on the LCD screen to initiate the electrical impulse and

begin stimulation. When the impulse begins, a buzzer sounds to indicate it has started. After that, the patient's measurement results will appear on the LCD screen. The user can select on the LCD screen whether to save the data to a Google spreadsheet. If the user clicks "save data," the measurement data will automatically be saved to a Google spreadsheet. However, if the user does not wish to save the measurement data, they can click "finish," and the LCD will return to the NMT device's initial screen.

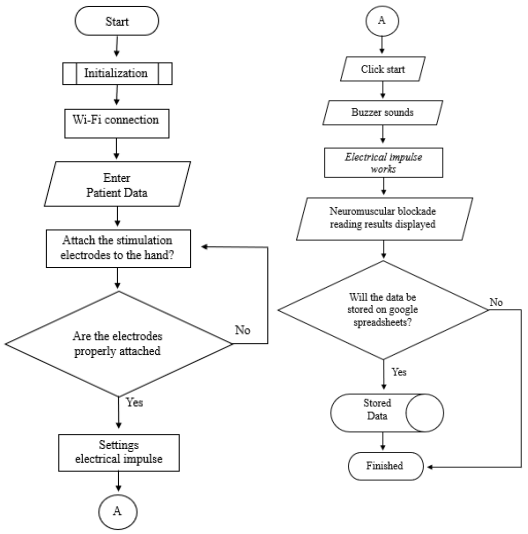

FIGURE 5. **The flowchart of the NMT device operation system.**

G. ELECTRONIC CIRCUIT DESIGN

The system hardware includes an ESP32 microcontroller, a driver, a relay, and a stimulator controller, all connected to supporting components. Fig. 6 shows the entire circuit of the NMT device components. This circuit is a microcontroller circuit that functions as the controller for the NMT device system. This circuit consists of a power supply, a stimulator, an LCD, and a buzzer.

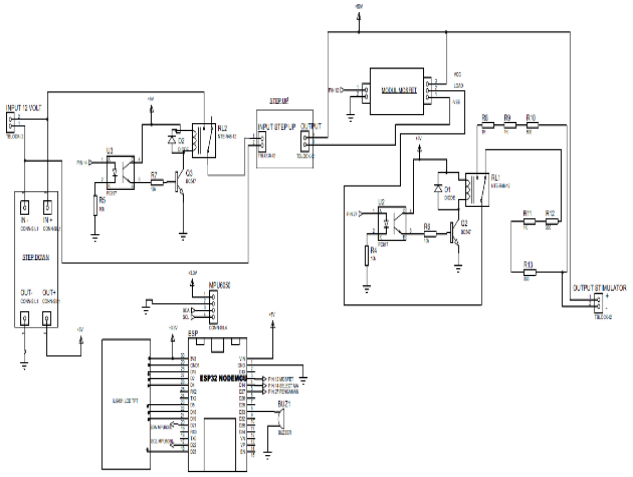

FIGURE 6. **Schematic diagram of the NMT device**

III. RESULTS AND DISCUSSION

A. PHYSICAL FORM OF THE DEVICE

The physical form of the NMT device is shown in Fig. 7, which consists of positive and negative cables attached to electrodes on the patient's wrist. Then, there is a white cable, which is an MPU-6050 accelerometer sensor attached to the patient's thumb.

FIGURE 7. **Front view of the NMT device**

At the top of the NMT device, there is a TFT LCD screen that serves as the user interface. To the left of the screen, a barcode can be scanned to view the NMT device's operating standards. On the front, there is a red positive cable and a black negative cable that will be connected to the electrodes attached to the patient's hand. On the right side, a white cable will be attached to the patient's thumb to measure finger muscle contraction. There is also an adapter port and an on/off button.

B. STANDARD OPERATING PROCEDURE (SOP)

Here are some things to keep in mind when setting up and operating the NMT device:

1) Place the device on a flat surface.
2) The device should be placed close to the patient undergoing neuromuscular blockade measurement.
3) The patient should be in a sitting or lying position.

The following are the standard operating procedures for the NMT device:

1) Connect the device's power cable to the mains or power supply. If the device has a battery, it is best not to use the mains power supply.
2) Press the device's on/off button. Press and hold to turn the device on and off.
3) The LCD will initialize. Wait until the LCD screen appears.
4) Then connect the NMT device to the internet on your smartphone using the wifi name Delfia and password teknisi321.

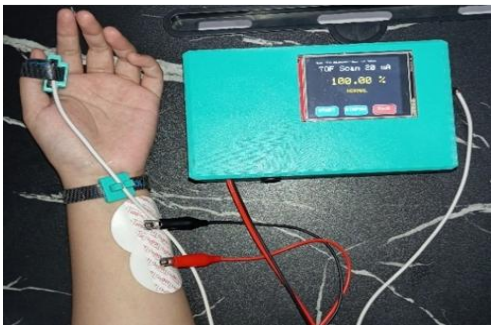

FIGURE 8. Place the electrodes and stimulation cables on the wrist.

5) Once the NMT device is connected to the internet, click Start to enter the patient's data. Users can enter the patient's name and age.
6) Next, attach two stimulation electrodes to the patient's lower wrist, spaced 2-3 cm apart. Then connect the device's cables: one cable with the accelerometer sensor is placed on the patient's thumb. The other two cables are connected to the stimulation electrodes, with the red cable on the left and the black cable on the right, as shown in Figure 10. If the cables are misconnected, the measurement results will be affected, so the user must ensure they are correctly connected.
7) After that, the user can select the lower electrical current to administer to the patient from the options of 20 mA or 30 mA. After selecting the low electrical current to administer to the patient, the LCD will display the patient's name, age, and the selected low electrical current. If the user wishes to change the low current, they can click the back button on the screen. However, if the settings are correct, the user can directly click Start, and the system will administer the electrical impulse to the patient. When the impulse is active, a buzzer will sound to indicate that current is being delivered to the patient.
8) After the electrical impulse is applied to the patient, the system will record the neuromuscular blockade measurement results. The measurement results will appear on the LCD screen. If the user wishes to save the data, it can be saved to a Google spreadsheet by clicking "save," and the data will be automatically saved. However, if the user does not wish to save the measurement data, they can click "back" to return to the initial NMT device display.
9) The neuromuscular blockade measurement process is complete. Remove the device cables from the patient and the attached stimulation electrodes. Press the "back" button on the device to return to the main menu, then turn off the device by pressing the "off" button.

C. CURRENT INTENSITY TESTING

According to Ohm's law, the current magnitude is determined by the voltage and resistance; if the resistance is high, the required voltage will also increase. In some conditions, this voltage can reach 50 volts or more, depending on the condition of the patient's skin. Nevertheless, the current delivered remains low and safe, ranging between 20 and 30 mA. This device uses a constant-current system, where the current is maintained constant while the voltage automatically adjusts to keep it constant. With this principle, muscle stimulation can be performed stably, safely, and effectively [13].

This aligns with the findings of a study by Reka Nemes, MD, Gyorgy, et al., which showed that conscious individuals well tolerate the current range of 20-30 mA during neuromuscular monitoring. The study by Reka Nemes, MD, Gyorgy, et al., titled "Pain Scores of Awake Volunteers During Neuromuscular Monitoring." The study noted that a current of 20–30 mA is an acceptable and safe intensity for use on conscious individuals [14]. However, in the device model used in this study, only two test points were used: the minimum (20 mA) and the maximum (30 mA). The current intensity testing was conducted using an avometer, and the results are presented in Table I.

TABLE I
TESTING OF CURRENT INTENSITY AT 20 MA AND 30 MA

Current Setting (mA)	Voltage Measurement Results (V)	Current Output Calculation
20 mA		I = V/R I = 49,3 / 2.500 I = 0,01972 A I = 19,72 mA
30 mA		I = V/R I = 49,3 / 1.660 I = 0,0297 A I = 29,70 mA

The results of the current intensity test are shown in Table I. To generate a current of 20 mA, a resistance of 2,500 Ω is required, while to generate a current of 30 mA, a resistance of 1,660 Ω is required. These values were obtained under a measured voltage of 49.3 volts using an avometer.

The following are the calculations from the current intensity test that has been conducted, namely the error value formula, error percentage, and accuracy value:

$$\text{Error Value} = \text{Voltage Value} - \text{Setting Value}$$
$$= 0{,}7$$
$$\text{Error Percentage} = \frac{\text{Voltage Value} - \text{Setting Value}}{\text{Setting Value}} \times 100\ \%$$
$$= \frac{50-49{,}3}{50} \times 100\ \%$$
$$= \frac{0{,}7}{50}$$
$$= 1{,}4\ \%$$
$$\text{Accuracy Value} = 100\ \% - \text{Error Percentage}$$
$$= 100\ \% - 1{,}4\ \%$$
$$= 98{,}6\ \%$$

D. OSCILLOSCOPE SIGNAL SHAPE TESTING

FIGURE 9. Pulse signal display on an oscilloscope with an amplitude of 52.8 V, frequency of 1.94 Hz, duty cycle of 41.39%, and period of 515 ms.

FIGURE 10. The results of measuring the pulse signal on an oscilloscope show an amplitude of 49.6 V, a frequency of 1.96 Hz, a duty cycle of 41.31%, and a period of 509.6 ms.

In the results of signal shape testing using a digital oscilloscope, a square wave signal shape was obtained with several important parameters displayed on the oscilloscope screen, namely:

1) Signal amplitude voltage (Vamp): indicates the voltage difference between the high and low conditions of the signal. At a current of 20 mA, the signal oscillates between two voltage values, ranging from 0 to 52.8 volts. Meanwhile, at a current of 30 mA, the signal oscillates between two voltage values, ranging from 0 volts to 49.6 volts. The Vamp test results on the oscilloscope screen are close to the device's 50-volt voltage setting.
2) Frequency: indicates how often the signal repeats in one second. At a current intensity of 20 mA, the frequency is 1.942 Hz; at 30 mA, it is 1.962 Hz. The frequency test results on the oscilloscope screen at current intensities of 20 mA and 30 mA are close to the problem limit of 2 Hz, indicating that the device operates within the expected frequency range.
3) Duty cycle: indicates the percentage of time the signal is in the high state during a complete cycle. At current intensities of 20 mA and 30 mA, approximately 41% of the time the signal is on and the remaining 59% of the time the signal is off during one cycle.
4) High voltage (Vhi): The high voltage, as seen on the oscilloscope screen when the signal is on, represents the peak value of the high logic level. At current intensities of 20 mA and 30 mA, it is approximately 45.6 volts. The Vhi test results on the oscilloscope screen are close to the device's 50-volt operating voltage.
5) Period: indicates the length of time required for the signal to complete one full cycle from rising, falling, and returning to its initial state. At a current intensity of 20 mA, one signal cycle takes 515 milliseconds or 0.515 seconds. Meanwhile, at a current intensity of 30 mA, one cycle takes 509.6 milliseconds or 0.5096 seconds. The period test results on the oscilloscope screen are close to the time when the electrical voltage is applied to the nerve, between 0.2 and 0.3 ms.

The consistent signal shape, despite the different currents used, is due to the device module operating at a constant 50 volts. This constant voltage serves as the primary trigger for the signal, ensuring the waveform remains stable despite current variations. The use of a constant-voltage supply aims to ensure that the signal produced by the stimulator circuit maintains a constant shape and is not affected by changes in current.

E. NEUROMUSCULAR BLOCKADE TESTING ON THE HAND AT 20 mA AND 30 mA

TABLE II
NEUROMUSCULAR BLOCKADE TESTING ON THE HAND WITH A CURRENT OF 20 MA

No.	Name	Age	Current Setting	Measurement Results	Description
1.	Sample 1	22	20 mA	99.23 %	Normal
2.	Sample 2	22	20 mA	100.00 %	Normal
3.	Sample 3	22	20 mA	100.00 %	Normal
4.	Sample 4	22	20 mA	100.00 %	Normal
5.	Sample 5	22	20 mA	100.00 %	Normal
6.	Sample 6	21	20 mA	100.00 %	Normal
7.	Sample 7	21	20 mA	100.00 %	Normal
8.	Sample 8	21	20 mA	100.00 %	Normal
9.	Sample 9	22	20 mA	96.96 %	Normal
10.	Sample 10	22	20 mA	100.00 %	Normal

After testing the current intensity and signal shape on the device module, the device can perform neuromuscular blockade testing on the respondent's hand. The results of neuromuscular blockade testing on the hand with a current of 20 mA are shown in Table II, and with a current of 30 mA in Table III.

TABLE III
NEUROMUSCULAR BLOCKADE TESTING ON THE HAND WITH A CURRENT OF 30 MA

No.	Name	Age	Current Setting	Measurement Results	Description
1.	Sample 1	22	30 mA	100.00 %	Normal
2.	Sample 2	22	30 mA	100.00 %	Normal
3.	Sample 3	22	30 mA	100.00 %	Normal
4.	Sample 4	22	30 mA	91.75 %	Normal
5.	Sample 5	22	30 mA	100.00 %	Normal
6.	Sample 6	21	30 mA	96.84 %	Normal
7.	Sample 7	21	30 mA	85.51 %	Abnormal
8.	Sample 8	21	30 mA	97.82 %	Normal
9.	Sample 9	22	30 mA	100.00 %	Normal
10.	Sample 10	22	30 mA	100.00 %	Normal

Based on Table III, sample 7 showed a test result of 85.51%, which was categorized as abnormal. This abnormal condition occurred in respondents because, during tests with different current intensities, they were either tense or not relaxed, thereby affecting the measurement results, which were diagnosed as abnormal.

According to the Clinical Standards Advisory Group (C.S.A.G.," a neuromuscular recovery percentage in the range of 90% - 100% indicates that the nerve-muscle connection has recovered well and is considered normal, especially in conscious individuals without anesthesia. Conversely, a percentage below 90% can be interpreted as abnormal. The following is the interpretation of the TOF ratio values based on the Clinical Standards Advisory Group (C.S.A.G.) standards, as shown in Table IV below:

TABLE IV
INTERPRETATION OF TOF RATIO VALUES

TOF Rasio Percentage	Diagnosis Measurement Results	Description
≥ 90% (90% – 100%)	Normal	Indicating that neuromuscular transmission has recovered, the patient is ready to be transferred or extubated.
< 90%	Abnormal	There is still neuromuscular blockade, the patient is at risk of respiratory distress, aspiration, RNMB (Residual Neuromuscular Block).

IV. CONCLUSION.

Based on the research conducted, the following conclusions were drawn:

1) The design and development of a portable neuromuscular transmission monitor for monitoring patient consciousness after anesthesia based on a microcontroller has been completed.
2) Measurement and testing results for current intensity using an avometer at 20 mA were 19.72 mA, while at 30 mA, they were 29.70 mA. The error value for current intensity testing was 0.7, with a percentage error of 1.4% and an accuracy of 98.6%.
3) The results of the signal-shape test using an oscilloscope showed a square-pulse waveform.
4) The results of neuromuscular transmission testing on the hand with low currents of 20 mA and 30 mA indicated that the NMT device functioned properly.

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