An Engineering Study of a Non-Invasive Dermabrasion's Fault Analysis and Solution

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Abstract: In medical aesthetic clinics, various skin rejuvenation procedures are performed to improve skin health and appearance. Among these, Hydrafacial treatment is widely used for skin cleansing and hydration. In recent years, Hydrafacial procedures have increasingly relied on advanced Hydrafacial machines that operate using multiple probes and combine electrical and mechanical energy for effective skin treatment. The paper presents the working principle of a Hydrafacial machine, with particular emphasis on the dermabrasion probe, which is one of the most frequently affected components during operation. The likelihood of mechanical faults in the machine increases with repeated clinical use and the number of treatments performed. The Hydrafacial procedure generally consists of three main stages: cleansing, hydration, and skin rejuvenation, where dermabrasion plays a critical role in deep skin cleansing. The dermabrasion probe functions by delivering serums onto the skin while simultaneously applying controlled suction to remove impurities. The internal operation of the Hydrafacial machine is based on a combination of pneumatic and hydraulic systems driven by electrical and mechanical energy. Key components include an air pump responsible for suction generation and a solenoid-based directional control valve that regulates airflow. The occurrence of dermabrasion-related faults is closely associated with the performance and internal condition of the air pump and the overall suction mechanism. The study focuses on analyzing the mechanical working of the dermabrasion system and identifying the causes of common faults, with the aim of improving operational reliability during Hydrafacial treatments.

Keywords: *Hydrafacial Machine, Pneumatic System, Air Pump, Solenoid Valve, Fluid Flow Control, Air–Water Interaction, Mechanical Fault Analysis.*

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I. INTRODUCTION

A. Overview of Hydrafacial Treatment

In medical aesthetic clinics, various non-invasive procedures are performed for skin rejuvenation and dermatological care. Among these procedures, Hydrafacial treatment is widely used for skin cleansing, hydration, and overall skin improvement [1]. This treatment involves the procedure of specialized serums in combination with mechanical exfoliation, enabling effective removal of impurities while maintaining skin hydration. Modern Hydrafacial treatments are carried out using advanced Hydrafacial machines that operate through a combination of electromechanical energy.

The Hydrafacial machine employs multiple probes, each designed for a specific function. The dermabrasion probe plays a central role in treatment by delivering serums onto the skin surface while simultaneously applying suction to remove debris and dead skin cells. This combined action enhances treatment effectiveness and skin rejuvenation outcomes.

B. System Architecture and Power Distribution

Hydrafacial machines are designed to operate safely using low-voltage electrical systems. Typically, the machine consumes approximately 500 W of power, while the main control and sensor boards operate on a regulated 24 V DC supply. The internal power supply converts a 220 V AC input into 24 V DC and 5 V DC outputs, which are distributed to various components of the system.

Although the system operates at low voltage levels, certain components, particularly the air pump connected to the dermabrasion probe, draw relatively higher current during operation. The control board serves as the central unit, distributing power and control signals to all probes and accessories. The display unit is also connected to this board, enabling system monitoring and user interaction.

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Fig 1 Shows the Hydrafacial Machine Used for Non-Invasive Skin Rejuvenation Treatments.

C. *Probes Used in the Hydrafacial Machine*

The Hydrafacial machine incorporates multiple probes designed to perform different skin treatment functions [2]. Each probe operates based on a specific physical principle and is controlled through the main sensor board.

- *Hand 1 – Skin Scrubber Probe:*

Also known as an ultrasonic skin scrubber, this probe is used for the removal of blackheads and whiteheads. It operates by generating high-frequency vibrations through an internal generator circuit, which assists in skin exfoliation and cleansing [3].

- *Hand 2 – Ultrasound Probe:*

This probe is used to improve blood circulation within the skin. It operates by emitting high-frequency ultrasonic waves that stimulate tissue response and refresh the skin. Frequencies in the range of 20–50 MHz are applied for deeper skin interaction [4].

- *Hand 3 – Cold Therapy Probe:*

The cold therapy probe is designed to provide a cooling effect during treatment. It incorporates a Peltier module or cooling plate along with a DC fan operating at 5 V to dissipate heat efficiently.

- *Hand 4 – RF+EMC Probe:*

Also referred to as a bio-lifting probe, this unit utilizes radio frequency and electromagnetic compatibility techniques for non-invasive skin lifting and tightening [5].

- *Hand 5 – Non-Invasive Probe:*

This probe is used to deliver serum into the skin without needle penetration, enabling non-invasive treatment.

- *Hand 6 – Dermabrasion Probe:*

The dermabrasion probe is the most critical component of the Hydrafacial machine. It consists of two internal pipelines: one for serum delivery and the other for suction. The suction assists in extracting serum from the bottle and enables effective deep cleansing of the skin.

D. *Working Principle of the Dermabrasion System*

The dermabrasion probe operates using a combination of pneumatic and hydraulic principles. Liquid serum is delivered through one internal pipe, while suction is applied through the second pipe [6]. The suction force is generated by an air pump and regulated by solenoid direction control valves. When the probe is applied to the skin, vacuum pressure is created, which draws serum from the selected bottle and facilitates controlled application.

The effectiveness of dermabrasion treatment depends on stable suction pressure and uninterrupted serum flow. Parameters such as skin–electrode impedance also influence treatment quality [7]. Any disturbance in suction or serum delivery directly affects treatment performance.

Fig 2 Presents the User Interface of the Hydrafacial Machine Along with the Treatment Tools Used During Clinical Operation.

E. *Serum Selection and Pressure Control Mechanism*

As shown in Figure 2, the Hydrafacial machine includes three control knobs mounted on the outer body. Two knobs are used to regulate air pressure and liquid pressure, while the third knob is used to select serums labeled A, B, C, or D. Serum bottles A, B, and C are mounted externally beneath the control panel, whereas bottle D is positioned at the rear of the machine near the waste liquid container.

Bottle D contains distilled water (H_2O_2), which is primarily used to clean the serum pipelines [6]. All serum pipelines are connected to the liquid selection knob, which directs the selected serum into the system. The liquid pressure control knob regulates the output pressure delivered to the dermabrasion probe. A similar mechanism is used to regulate

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air pressure through the air control knob connected to the solenoid valve.

F. Pneumatic System and Suction Control

The pneumatic system plays a crucial role in dermabrasion operation. Suction air is generated by an air pump and regulated using solenoid valves controlled by the main board. The suction line passes through the waste liquid bottle, where vacuum pressure is established before reaching the dermabrasion probe. This arrangement enables effective serum extraction and impurity removal during treatment.

The solenoid valves operate on a 24 V DC supply provided by the control board. These valves control air direction between the pump, tank, and waste liquid bottle, forming the basis of the suction mechanism.

G. Common Dermabrasion Faults and Their Causes

One of the most common operational issues in Hydrafacial machines is related to the dermabrasion probe. Typical faults include reduced suction pressure or insufficient serum flow. Since suction pressure directly influences serum delivery, any decrease in suction results in reduced treatment effectiveness.

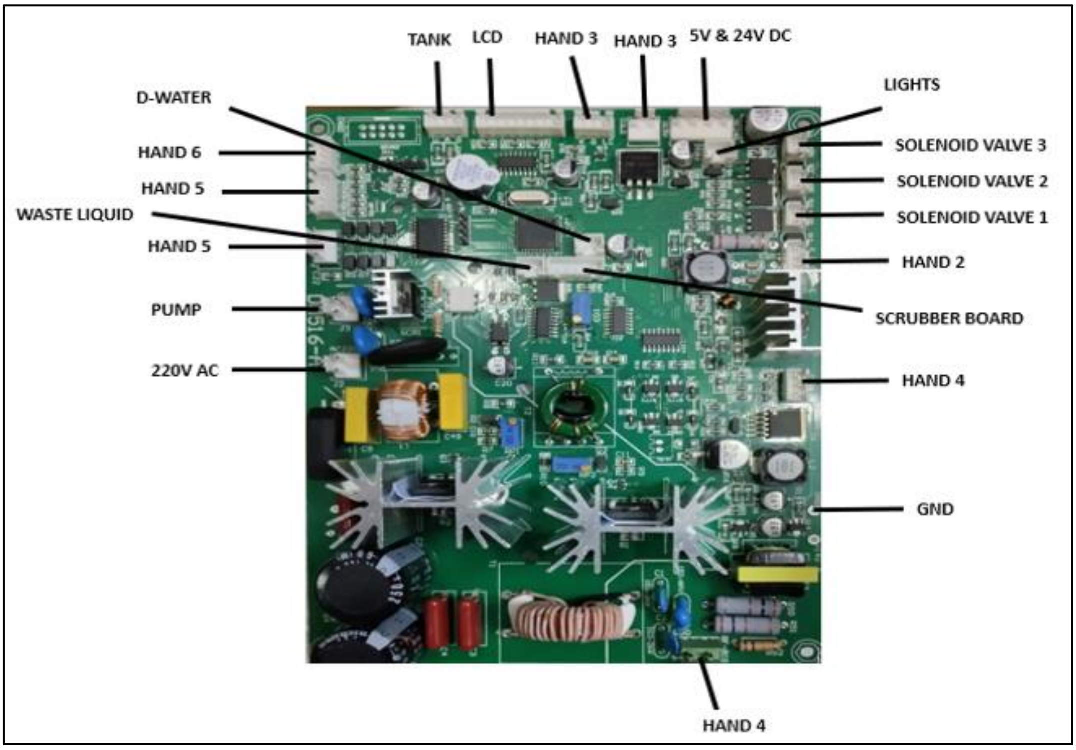

Fig 3 Control Board of the Hydrafacial Machine Illustrating Power Distribution, solenoid Valve Connections, and Sensor Interfaces.

Possible causes of reduced suction include dust accumulation, blockages within air pipelines, leakage from the air pump, or obstruction in solenoid valves. Continuous airflow may also lead to internal corrosion and increased resistance due to collisions within the piping system. Similarly, prolonged serum flow can cause corrosion or damage to liquid pipelines, resulting in restricted flow.

H. Fault Mitigation and Maintenance Considerations

To minimize dermabrasion faults, regular maintenance of the Hydrafacial machine is required. This includes cleaning or replacing pipelines, removing blockages, and inspecting the air pump and solenoid valves. Proper maintenance improves system reliability and ensures consistent treatment performance [8].

The Hydrafacial machine incorporates sensors connected to the main control board to monitor system operation. These sensors detect physical parameters and convert them into electrical signals for system feedback and safety monitoring [9]. Liquid level sensors in the waste bottle and distilled water bottle trigger alerts when maintenance is required [10].

I. Control Board and Electrical Integration

The main control board distributes power and control signals throughout the system. It receives 5 V DC and 24 V DC from the internal power supply. The 5 V DC supply powers sensors associated with Hand 2 to Hand 6 probes, while the 24 V DC supply operates solenoid valves and the scrubber board for Hand 1. The air pump is powered directly from the 220 V AC supply [11].

This integrated electrical and pneumatic architecture enables coordinated operation of all probes and ensures safe and reliable functioning of the Hydrafacial machine.

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Table 1: Hydrafacial Probes and Their Functions

Probe	Name	Operating Principle	Power Supply	Primary Function
Hand 1	Skin Scrubber	Ultrasonic vibration	24 V DC	Blackhead/whitehead removal
Hand 2	Ultrasound	High frequency	AC supply	Blood circulation
Hand 3	Cold Therapy	Peltier cooling	5 V DC	Cooling effect
Hand 4	RF+EMC	RF/EM signals	5 V DC	Skin lifting
Hand 5	Non-invasive	Fluid delivery	Controlled DC	Serum injection
Hand 6	Dermabrasion	Pneumatic suction	Pump + valves	Deep cleansing

II. MACHINE WORKING AND ELECTRICAL CONTROL

A. Control Board Operation

The internal working of the Hydrafacial machine mainly depends on the control board of the machine. When a 220 V AC voltage is applied at the input, the machine turns ON and the control board becomes operational. The continuous and sustainable working of the machine depends on the biosensors integrated within the system, which monitor different operating conditions during treatment [12]. These sensors ensure that the machine functions within safe and predefined limits.

Fig 4 Internal Components of the Hydrafacial Machine Including Pump, Solenoid Valves, and Piping Network.

All probes of the Hydrafacial machine are connected to the control board. The board provides the required operating voltages along with power signals to activate and control the probes. The internal power supply converts the 220 V AC input into regulated DC voltages, which are distributed to different components. The display unit of the machine is also connected to the same control board, allowing visualization of operating parameters and treatment status.

B. Power Supply and Signal Distribution

The Hydrafacial machine operates using a combination of AC and DC power supplies. The scrubber board is used to operate the scrubber handpiece and receives a 24 V DC supply from the power supply unit along with a power signal from the main control board. The ultrasound probe takes a power signal from the control board, which enables the generation of ultrasonic waves at the output. Similarly, the cold therapy handpiece and the RF+EMC handpiece are connected to the control board and receive their respective power signals.

The control board acts as the central signal distribution unit, ensuring that each probe receives appropriate voltage and control signals. The probes are electrically linked with one another through the board, allowing coordinated operation. The use of low-voltage DC supplies improves safety while maintaining effective performance of the machine.

III. PROBE INTEGRATION AND DERMABRASION MECHANISM

A. Functional Operation of Probes

The Hydrafacial machine includes several probes designed for different skin rejuvenation treatments. Hand 1, known as the skin scrubber probe, is operated using a separate scrubber board. This probe produces high-frequency vibrations that are used to remove blackheads and whiteheads from the skin. The scrubber board operates on a 24 V DC supply and receives control signals from the main control board to regulate its operation.

Hand 2 is the ultrasound probe, which is used to improve blood circulation in the skin. This probe operates by generating high-frequency ultrasonic waves, allowing deeper interaction with the skin layers [4]. Hand 3 is the cold therapy probe, which produces a cooling effect using a cooling plate and a DC fan operating on a 5 V supply. Hand 4 is the RF+EMC probe, also known as the bio-lifting probe, which is used for non-invasive skin tightening and lifting [5].

Hand 5 is a non-invasive probe used to deliver liquid serum into the skin without the use of needles. All these probes are connected to and controlled by the main control board, which ensures proper functioning during treatment.

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B. Dermabrasion Working Principle

The dermabrasion probe (Hand 6) is one of the most important probes in the Hydrafacial machine and is used for deep cleansing of the skin. This probe operates using both liquid serum and suction air. Two pipes are embedded inside the probe: one pipe is used for serum flow, while the second pipe is used for suctioning air. The serum is applied to the skin surface, while the suction removes impurities and dead skin cells.

The suctioning air is generated by the air pump and controlled through solenoid valves. When the dermabrasion probe is placed on the skin, a vacuum pressure is created, which draws serum from the selected serum bottle. The quality of the treatment depends on the stability of suction pressure and uninterrupted serum flow. Any disturbance in either air or liquid flow directly affects treatment performance.

C. Dermabrasion Fault Diagnosis

Dermabrasion-related faults are the most commonly observed issues in Hydrafacial machines. These faults mainly involve reduced suction pressure or insufficient serum flow. The air used in dermabrasion flows through hard silicone pipes, while the liquid serum flows through soft silicone pipes. Continuous serum flow can damage or corrode liquid pipes, while continuous air flow can introduce dust particles that obstruct smooth airflow.

To diagnose dermabrasion faults, the first step is to remove the dermabrasion probe from the machine and turn ON the dermabrasion function. If suction is present at the probe connection point, the fault lies within the probe itself. In this case, the probe must be cleaned thoroughly, as blockages inside the probe pipes are often caused by continuous air and liquid flow. Once cleaning is completed, normal operation is possible, however suction or liquid flow is still not observed within the machine, the air and liquid pressure control knobs should be adjusted. If increasing pressure does not resolve the issue, internal inspection of the machine is required. Before opening the machine, all external power sources must be disconnected and serum bottles must be removed safely to ensure operator safety and machine efficacy [13].

Table 2: Common Dermabrasion Faults, Causes, and Engineering Solutions

Fault Observed	Mechanical Cause	Impact on Performance	Proposed Engineering Solution
Vacuum loss	Worn pump seals	Non-uniform exfoliation	Seal replacement, periodic inspection
Nozzle clogging	Serum residue	Reduced fluid flow	Improved filtration, cleaning protocol
Motor overheating	Continuous duty cycle	Device shutdown	Heat dissipation design, duty limits

IV. PNEUMATIC SYSTEM AND MAINTENANCE STRATEGY

A. Solenoid Valve and Air Pump Operation

There are two major parts of the machine that plays a crucial role in the working of dermabrasion probe in Hydrafacial machine. After opening the machine, all internal pipelines should be cleaned to remove any blockages. If piping is found to be clean, the solenoid valve connected to the waste liquid bottle must be inspected and cleaned. The solenoid valve is an electromechanical device that operates on the principle of electromagnetism [14]. When a 24 V DC supply is applied, the solenoid coil becomes energized, causing the internal piston to move and allow air to flow. When power is removed, the coil de-energizes and the piston blocks the airflow.

The fast electromagnetic response occurs precise regulation of suction and pressure, directly influencing the consistency of serum delivery during dermabrasion. Any degradation in solenoid performance can therefore lead to noticeable variations in treatment effectiveness.

Fig 5 Depicts the Solenoid Valve Used in the Hydrafacial Machine

The solenoid valve as shown in Figure 5 is used in the Hydrafacial machine, is a 3/2 direction control valve, consisting of three ports and two operating states. The inlet port P(1) receives pressurized air, the outlet port A(2) directs air to the system, and the exhaust port R(3) releases air from the valve. The air pump connected to the solenoid valve draws atmospheric air and compresses it, generating high pressure of approximately 850 kPa [15]. This suction air is directed to the waste liquid bottle, creating vacuum pressure required for dermabrasion.

Fig 6 Shows the Air Pump Used to Generate Suction within the Hydrafacial Machine.

B. Control Board Architecture

The control board of the Hydrafacial machine, as shown in Figure 3, controls all major operations of the system. The board operates the air pump using a 220 V AC supply and controls sensors and solenoid valves using 5 V DC and 24 V DC supplies. Three solenoid valves are mounted on the control board. VA1 is connected to the pump and tank, VA2 is connected to the tank and Hand 5, and VA3 is used for suction control by directing air from the pump to the waste liquid bottle while exhausting air through a filter.

Sensors connected to the D-water bottle and waste liquid bottle are interfaced with the control board. These sensors detect liquid levels and trigger audible alerts when the waste liquid bottle becomes full, enabling real-time monitoring and safety [16]. The grounding of the control board and scrubber board is interconnected to maintain electrical safety.

C. Preventive Maintenance and Performance Evaluation

The scrubber board is connected to the main control board and is used to operate Hand 1. It produces high-frequency vibrations required for scrubber probe operation under the control of signals from the main board. Microelectronic components on both boards generate and transmit the necessary control signals [17]. The main control board ensures electromechanical compatibility throughout the system [18] and enables optimized operation through efficient signal processing on the printed circuit board [19].

All electronic and biomedical components of the Hydrafacial machine require preventive maintenance for long-term operation. Preventive maintenance focuses on identifying and resolving issues before machine failure occurs [20]. Figure 7a illustrates the reduction in suction pressure as the number of treatments increases before fault elimination. Figure 7b shows the performance of the machine after fault elimination, where suction pressure remains stable despite increased usage.

The comparison in Figure 7 demonstrates the importance of preventive maintenance in maintaining machine efficiency, reliability, and long-term performance.

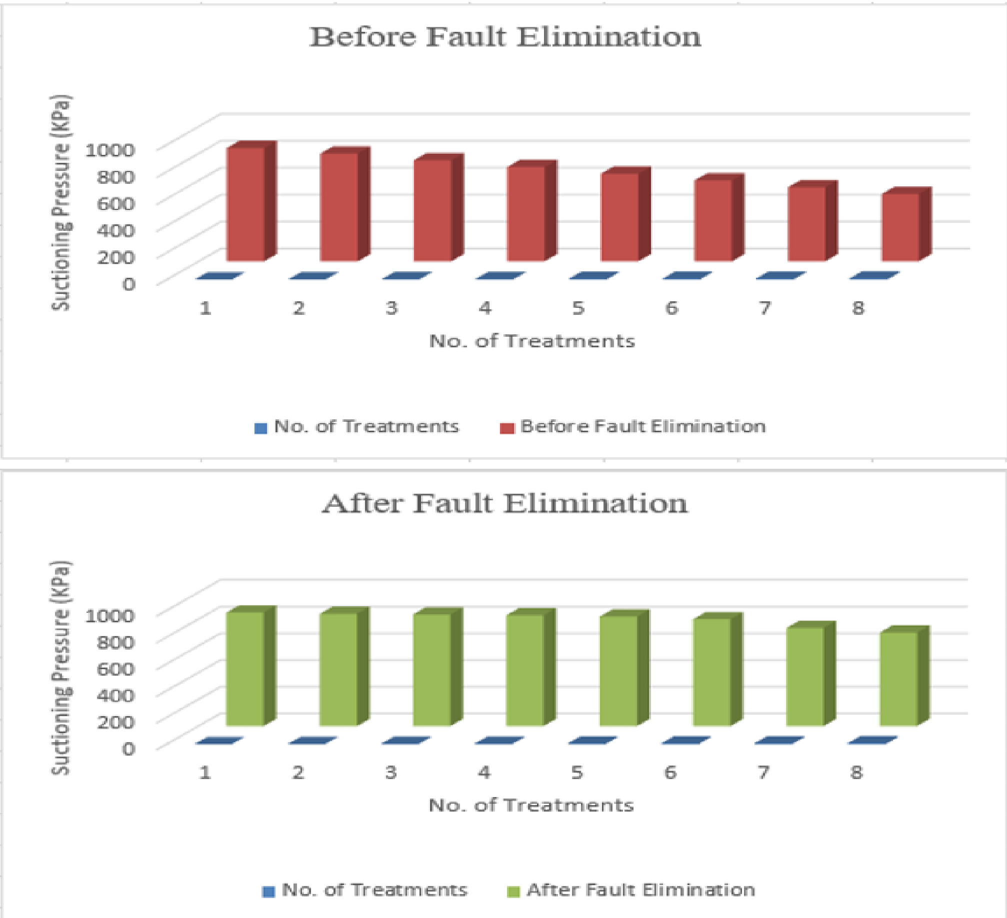

Fig 7 Estimated Reduction in Dermabrasion Faults After Implementation of Preventive Maintenance.

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V. CONCLUSION

The fault analysis of the dermabrasion system in a Hydrafacial machine is strongly influenced by the frequency and number of treatments performed. As machine usage increases, the probability of faults related to suction, serum flow, and probe performance also increases. Therefore, preventive maintenance plays a critical role in minimizing operational errors and ensuring consistent treatment quality.

Timely cleaning of the waste liquid bottle is essential and should be performed before it reaches its maximum capacity. Unusual sounds observed during machine startup may indicate pump-related issues, and such conditions require immediate inspection and cleaning of the pump to restore smooth operation. The proper functioning of all probes should be examined regularly, and any malfunction should be diagnosed systematically. Cleaning of the dermabrasion probe, internal piping, and solenoid valves is necessary to maintain uninterrupted air and serum flow.

The Hydrafacial machine utilizes six probes, referred to as Hand 1 through Hand 6. For effective maintenance, the power supply should be turned off, and all probes should be removed for physical inspection and cleaning. In most cases, these probes require only minor maintenance. The cold therapy and ultrasound handpieces can be accessed and cleaned by opening the front cover of the machine. The Hydra tips used with the dermabrasion probe must be cleaned regularly and replaced after each treatment to maintain hygiene and treatment efficiency.

The nozzles used for serum delivery and the piping connecting the serum bottles should be cleaned at appropriate intervals. After each treatment cycle, D-water should be used to flush and clean the internal piping of the machine. Since prolonged serum flow may degrade or damage pipes, the use of distilled water helps remove residue buildup and ensures smoother serum flow during subsequent treatments. Proper care of the airflow system and pipeline network significantly reduces the likelihood of malfunction.

Preventive maintenance is essential for the long-term reliability and performance of the Hydrafacial machine. Regular inspection allows early identification of damaged or defective components and enables timely corrective action. During preventive maintenance, thorough examination of the piping, solenoid valves, air pump, and related components should be performed both before and after servicing. If any part is found to be defective, appropriate repair or replacement procedures must be followed to restore optimal machine performance.

Overall, systematic preventive maintenance improves machine efficiency, extends operational lifespan, and ensures consistent and reliable dermabrasion performance in clinical applications.

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