EUROPEAN ENDODONTIC JOURNAL

ORIGINAL ARTICLE

Advanced Electrochemical Reamer (*EC-Reamer*) for Root Canal Treatment

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ABSTRACT

Objective: According to the American Association of Endodontists (AAE), 22 million endodontic procedures have been performed annually. Root canal treatment is needed to prevent infection and restore function when a tooth is severely infected or decayed. This procedure is the only way to preserve the natural tooth and avoid artificial replacement (implant, denture, etc.). The current study aims to develop an electrochemical reamer (EC-Reamer or EC-R) that can help to disinfect the canal system and thus improve the success rate of root canal treatment.

Methods: The COMSOL Multiphysics software was utilized to simulate the experimental setup and confirm the current flow in the electrolyte. The benchtop experimental approach follows a specific electrochemical protocol, (i) open circuit potential to monitor the electrochemical stabilization and (ii) potentiostatic scan at –9.0 V as the treatment stage. Identification of feasible reference electrode (RE) and insulation material for the exploratory benchtop studies considered platinum (Pt) and gold (Au) wire as the REs and hot melt adhesive (HMA) and liquid tape as the insulation materials. The antimicrobial effects of EC-R were analysed using *Enterococcus faecalis* (*E. faecalis*). One-way ANOVA with the Tukey post hoc test and a significance level of $P<0.05$ is used to compare the groups with an experimental duration of 60 seconds.

Results: The findings showed that magnitude and current fluctuations created by Pt wire are promising when compared to Au wire, while Pt–HMA pair is chosen considering Pt's good electrochemical inertness and HMA's easy handling, availability, and non-hazardous features. The use of potentiostatic duration of 1 s and 3 s resulted in >99.99% *E. faecalis* reduction. Duration at 5 s and above resulted in a total bacterial kill. Statistical analysis confirmed a significant difference among the groups tested with commercial and custom-built potentiostats.

Conclusion: The outcome provided preliminary data for developing an EC-R prototype to enhance the antimicrobial effect during root canal treatment potentially.

Keywords: Bacterial eradication, electrochemistry, reamer, root canal treatment, simulation model

HIGHLIGHTS

- The electrochemistry-based approach can support 99.99% bacterial eradication.
- Guarantee a prolonged lifetime of endodontic procedures such as root canal treatments.
- Reamer-HMA-Pt file shows desirable electrical current in an electrochemical *in-vitro* setup.

INTRODUCTION

Root canal treatment (RCT), one of the most common endodontic procedures, is a straightforward procedure to relieve pain and save natural teeth. A recent study reported that more than 25 million root canals treatment is performed yearly in the United States (1). This treatment aims to eliminate bacteria inside the root

Please cite this article as:
Ramachandran RA, Li W, Khande S, Shylendra A, Trivedi AR, Xie Q, Wu C, Mathew MT. Advanced Electrochemical Reamer (*EC-Reamer*) for Root Canal Treatment. Eur Endod J 2023; 8: 79-89

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Received January 04, 2022,
Revised April 06, 2022,
Accepted May 30, 2022

Published online: September 02, 2022
DOI 10.14744/eej.2022.86094

canal system and prevent future infection by cleaning, chemomechanical preparation, and sealing the canals of diseased teeth. The successful elimination of microorganisms from an infected root canal is a complex task because of the canal system's lack of host defence responses, complex anatomy, resistance to antimicrobial agents, and shear forces. Failure to effectively eradicate bacteria before obturation leads to the recurrence of infection (2). A recent American Association of Endodontists (AAE) survey reported that 40% of US adults had damaged their tooth, filling, or crown while eating a holiday treat, signifying the relevance of an efficient RCT (3).

Examinations have shown that the root canal system comprises many irregulars and complex structures with numerous dentinal tubules and lateral canals (4). It is reported that bacteria can penetrate deeply into dentinal tubules up to half the distance between the root canal walls and the cementum-dentine junction (5). These dental tubules and the irregularity of the canal system provide a hiding place for the microorganisms without completely eradicating them from root canal treatment. A relapse in microbial disinfection is evidence of inefficiency in the treatment method and, ultimately, results in retreatment of the tooth (6,7). Consequently, many challenges, such as the complex anatomy of dentine's root canal and composition, must be addressed for a successful RCT procedure (8).

Sodium hypochlorite (NaOCl) is used to disinfect the root canal as it is cost-effective. However, it has many disadvantages, including cytotoxicity towards periradicular tissues (9), inability to eliminate bacteria (10–13), and its adverse influence on the properties of dentine (14,15). Different adjunct agitation techniques have been investigated to assist the irrigant solutions in penetrating the complexities of the root canal system. Passive ultrasonic irrigation, multi-sonic agitation, sonic activation, and apical negative pressure irrigation systems have been reported superior to conventional needle irrigation in smear layer removal, antimicrobial effect, and postoperative pain. However, most of these techniques are quite expensive, and there's a lack of evidence of efficacy in improving the outcome of RCT (16–18).

Bacterial contamination or colonization is a very challenging problem in biomedical applications. For example, even with antibacterial coatings on implants, the possibility of bacterial adhesion or colonization is high due to biocorrosion occurring in these implants or the temporary inhibitory effects of surrounding tissues. Also, conventional treatment methods such as antibiotic treatments might not be sufficient to reduce the chances of infections due to the development of various antibiotic-resistant bacteria. While various treatment methods have been reported for treating infections in medical devices or implants (19,20), eradicating microbial pathogens using low-level current or potential is useful where conductive materials are in place for medical treatments (21–24).

Electrochemistry has been used as an alternative minimally invasive approach in medicine and dentistry to kill germs and to reduce adherent bacteria from surfaces, including the disinfection of catheters, orthopaedics, and dental implants (25–28). Our previously reported research showed that an electrochemical setup system could achieve total eradication (>99.99%) of *E. faecalis* at -9 V for 5 min in 0.85% (saline) to 5% NaCl solution in the absence of NaOCl and did not show cytotoxicity to human osteoblasts (29). However, this electrochemical treatment may add extra clinic chairside treatment time. Thus, in this study, critical attention is given in the following areas: 1) to understand the current flow in the electrolyte using an electrochemical simulation model, 2) to optimize the modified electrochemical dental reamer (EC-R) using different reference electrode combinations, 3) to identify the method of insulation, 4) to develop a custom-made miniature potentiostat prototype as an independent voltage source for the anticipated model. The ultimate goal is to develop a dental reamer that functions in an electrochemical setup and can generate an electrical current in the electrolyte. The study utilizes an intelligent combination of ionization effect and fluid mechanics to penetrate oral pathogens and improve root canal bacterial disinfection.

MATERIALS AND METHODS

Simulation Model

As shown in Figure 1, COMSOL Multiphysics simulation software was used to develop an electrochemical numerical model of a two-electrode system to represent the current flow on an applied potential. In this model, the reamer file is the working electrode (WE), platinum (Pt) wire acts as the reference electrode (RE)–counter electrode (CE) combination (RE+CE), and phosphate buffer saline (PBS) solution is the electrolyte. An external potential of –9.0 V has been applied to depict the system's current flow, and both primary and secondary current distributions are taken as the physics interface. The choice of –9.0 V potential was based on our previous pilot study (29). This control model shows the transport of charged ions in the PBS solution of uniform composition and current conduction in electrodes using Ohm's law. This model's primary current distribution interface neglects activation overpotentials due to charge transfer reactions, while the secondary current distribution observes the activation overpotentials. A time-dependent study for 30 s has been performed and solved for 5698 (plus 3466 internal DOFs) degrees of freedom. Mesh generation considers tetrahedral and triangular elements from a physics-controlled perspective with finer mesh element size. Figure 1 also shows corresponding mesh statistics with the number and type of elements used to solve this finite element model.

Electrochemical Model

As shown in Figure 2a, the main components associated with this experiment are a prototype RCT system with a potentiostat to perform the electrochemical potentiostatic scan with an initial and final stabilization phase and a data acquisition system that captures the experimental data. The proposed method considers a modified reamer that combines the original reamer file and platinum wire of length 2 inches separated with a non-conductive thin layer immersed in a solution of PBS, the electrolyte. The reamer file was connected to the working electrode (WE), and the Pt or metal wire was connected to the reference and counter electrode of the potentiostat. Thus, the proposed scheme acts as a two-electrode system. Figure 2b

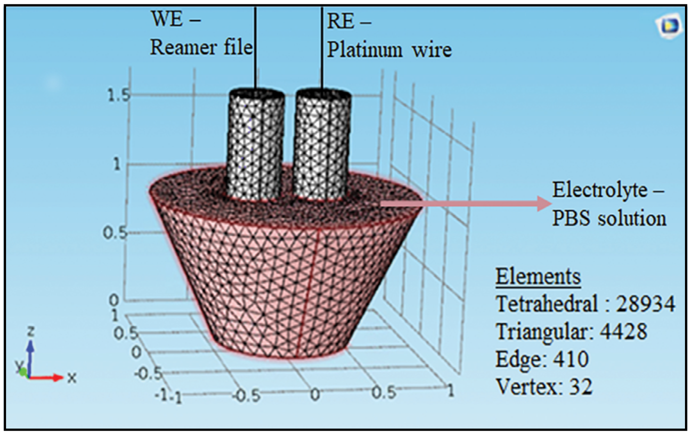

Figure 1. Numerical simulation model of a two-electrode system to represent the current flow in an electrolyte. This model considers, reamer file as the working electrode (WE), Pt wire as the combination of reference electrode (RE) and counter electrode (CE), and PBS solution as the electrolyte. Mesh statistics is also shown with its number and type elements used to model the system

PBS: Phosphate buffer saline

depicts the experimental protocol for this root canal disinfection method in which an open circuit potential (OCP) test was conducted for 30 s to monitor the evolution of free potential as a function of time and to check the feasibility and electrochemical stability of the system, termed as the initial stabilisation phase. A potentiostatic scan (PS) was conducted for a specific period (0 s, 1 s, 3 s, 5 s, 15 s, 30 s, 60 s) as the treatment option, and finally, an OCP for 30 s was monitored at the final stabilisation phase to stabilize the experiment.

The initial system developed had its reamer file and the RE+CE electrode combination separated, as represented in Figure 1. But this setup resulted in some limitations, including the increased diameter of the reamer-file-electrode combination and the broken circuit during the potentiostatic scan. That is, during the potentiostatic scan, as current flows through the solution, hypochlorite bubbles are generated, which increase with an increase in the current flow. These bubbles drive the metal wire electrode out of the electrolyte, resulting in a broken circuit leading to the entire system breaking down. A new system was developed to connect the reamer file and the metal wire as a single unit. However, the current flow should be guaranteed and maintained smoothly; for this, the reamer file and metal wire should be separated with some method of non-conductive insulation.

The initial experimental design considers two metal wires -Pt, and gold (Au) as the RE. As a non-conductive insulator, hot melt adhesive (HMA) and liquid electrical tape have been considered. The metal wire (RE) and the reamer file (WE) were insulated from one side, and the other side was exposed to the solution, as it was found that the area exposed to the solution was directly proportional to the current flow experienced in the solution. Trial methods have also followed the protocol (Fig. 2b), but only for 30 s, and the results are validated against each other. The results were good for Pt and Au with HMA or liquid tape insulation methods. However, Pt-HMA pair is chosen for further trials considering Pt's good electrochemical inertness, ease of making into many forms, and HMA's easy handling and availability. Even though Au has the same configurations as Pt and both are expensive, Pt was selected be-

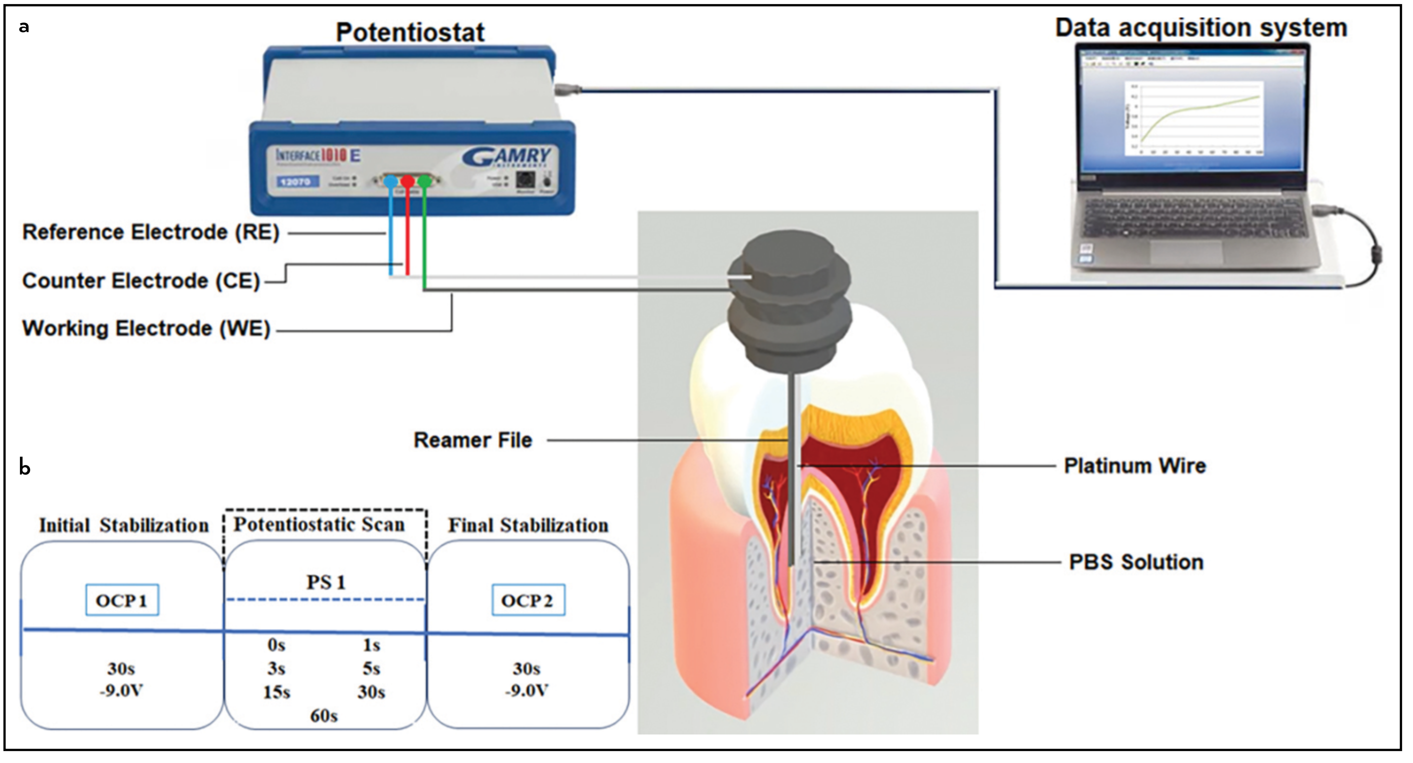

Figure 2. (a) Schematic diagram of the electrochemical model of the bacterial eradication system, (b) illustration of standard protocol used in this experiment

OCP: Open circuit potential, PBS: Phosphate buffer saline

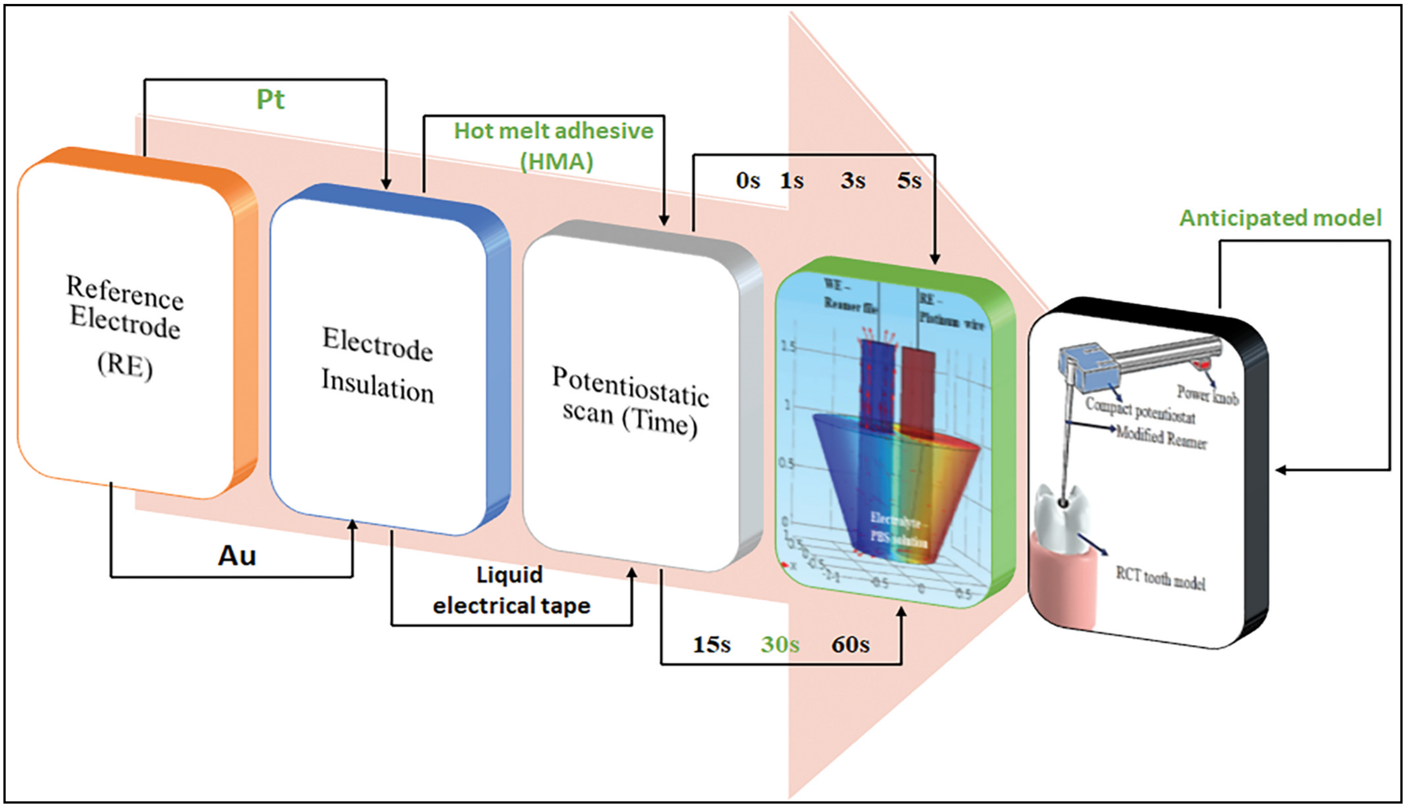

Figure 3. Overall experimental flow of the system represented as a flow chart from the reference electrode selection, non-conductive insulator selection, and finally the decision of potentiostatic scan time parameter for a 99.99% bacterial eradication

Pt: Platinum, Au: Gold, RCT: Root canal treatment, WE: Working electrode, RE: Reference electrode

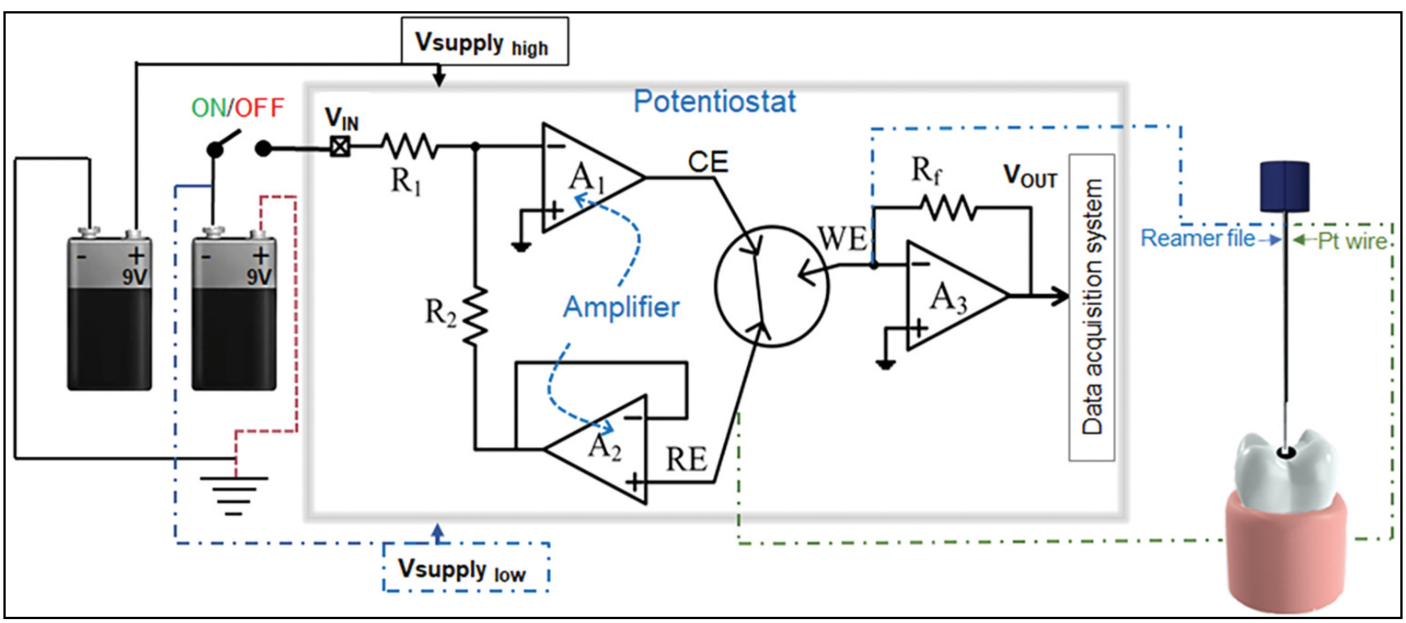

Figure 4. Schematic diagram of custom-made potentiostat connected to the EC-R file

EC-R: Electrochemical reamer, CE: Counter electrode, RE: Reference electrode, WE: Working electrode, Pt: Platinum

cause of its inertness and speed by which most electrode reactions occur at its surface (30). In clinical procedures, the liquid electrical tape seems harmful and may eventually lead to a fatal accident if consumed made its way out of the selection, even though we have good results in bacterial eradication. The overall experimental design of the system is represented in Figure 3 as a flowchart.

Design of Miniature Potentiostat

A miniature potentiostat is another crucial component in designing a smart system that deals with bacterial eradication in the root canal procedure. The schematic diagram of the potentiostat implementation shown in Figure 4 controls the potential of the reamer, the working electrode relative to the platinum wire, and the reference electrode. Although this model uses

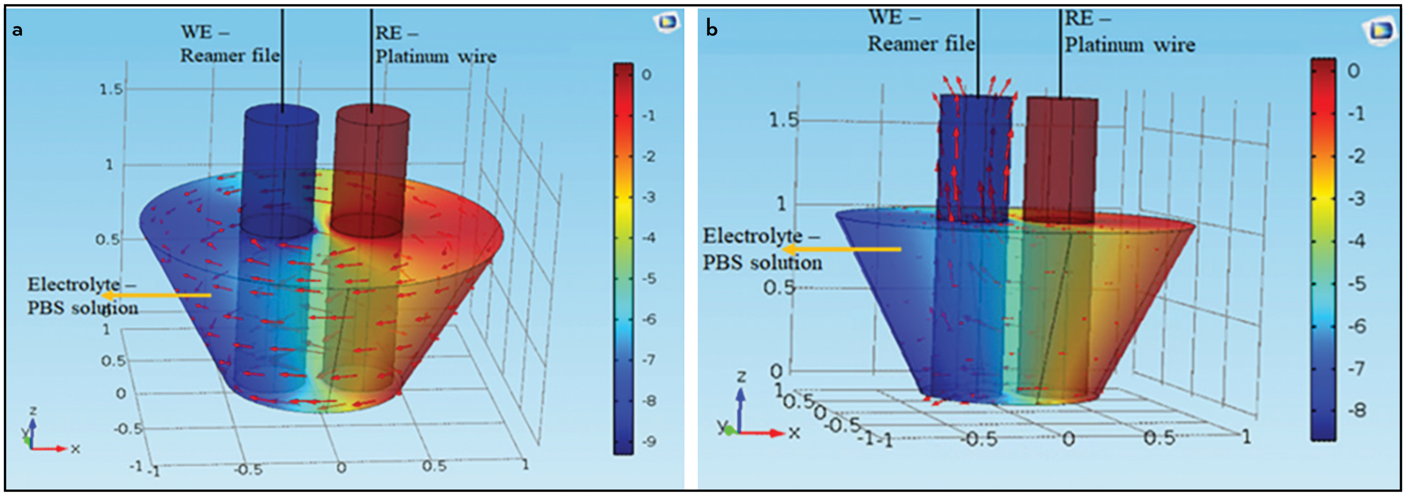

Figure 5. Schematic representation of the current flow of (a) the primary current distribution, and (b) the secondary current distribution in the electrochemical numerical model on applied potential of -9.0 V

WE: Working electrode, RE: Reference electrode, PBS: Phosphate buffer saline

inputs from an external power supply or alkaline batteries, the final miniaturized smart system will obtain the input voltage from a Lithium coin battery (capacity: ~200 mAh). In Figure 4, A_1, A_2, and A_3 denote identical operational amplifiers (OPAMPs) used, and R_1, R_2, and R_f represent the resistors used in the design of the miniature potentiostat. V_{IN} and V_{OUT} are the voltage input and output of the potentiostat, respectively. $Vsupply_{high}$ and $Vsupply_{low}$ are the input voltages used to power up the amplifiers. Batteries and functions ultimately drive the system shown in Figure 4 as a standalone portable system. The current magnitude or electrical fluctuations generated with this custom-designed potentiostat is comparable with the commercially available potentiostat and thus confirm its feasibility.

Bactericidal Test

Enterococcus faecalis (ATCC 29212) was used as test bacteria in this study. *E. faecalis* was grown in a Brain Heart Infusion medium (BHI, Becton, Dickinson and Co., Sparks, MD, USA) at 37°C aerobically for 24 hours. The bacterial cells were collected by centrifuge for 5 min at 8000 rpm, washed with PBS buffer (0.05 M, pH 6.8), and adjusted to 1×10^8 CFU/ml in PBS. The cell suspension was then aliquoted 600 µl into a 0.5 ml microcentrifuge tube and used for the bacterial killing test. The tube was then fastened on a rack and an electrode containing an Endo Hand File (Size 10, 25mm stainless-steel, C-file, Lexicon, Johnson City, Tennessee, United States) and Pt wire (0.5mm in diameter, same length as C-file) was inserted. The endodontic file was connected to WE, and the Pt wire was connected to RE+CE for potentiostat treatment. Caution was taken to ensure the electrode was submerged in the bacterial suspension. The individual bacterial suspension was then treated with a potentiostat cycle for 0 to 60 seconds, and the treated bacterial suspension (100 µl) was added to 900 µl of stop solution (5% $Na_2S_2O_3$). The viability of treated bacteria was determined after serial dilution and plating on BHI agar at 37°C for 48 hours.

Ethics Committee Approval and Informed Consent

This study used a lab-scale, *in vitro* model to explore the efficacy of bacterial eradication in root canal treatment. Any ethical committee approval was not required for this study.

Statistical Analysis

All experiments in this study were staged in triplicate with N=3. Statistical analysis performed in SigmaPlot 14.0 (Systat Software Inc., CA, USA) analysed the average current experienced in the electrolyte. One-way ANOVA with the Tukey post hoc test confirmed the significant difference among the groups with a significance level of $P<0.05$.

RESULTS

Current Flow in the Simulation Model

Two different simulation models have been created to confirm and represent the current flow in the proposed scheme. The first model that considers the primary current distribution neglects the charge transfer reactions, and the resulting model, Figure 5a, shows the current flow (red arrow) in the electrolyte from the RE to the control file (WE). That is, in this scheme, only the current flow in the solution has been taken into consideration.

But in the real-world scenario, the chances of erosion-corrosion must be considered, and thus the electrode kinetics. So, another model has been developed with the secondary current distribution in its physics interface, considering electrode kinetics with the solution resistance. Figure 5b depicts the current distributions (red arrow) observed in the electrochemical cell, especially in the control file (WE) that helps in bacterial eradication. Thus, with an applied potential of –9.0 V and an equilibrium potential of 300mV for a duration of 30 s, the simulated models show compromising current flow from the RE through the electrolyte to the control file, which will be the main motive of the proposed scheme for bacterial eradication in the root canal procedure.

Current Evolution for the Selection of Electrode

A selection was made between the Pt wire and Au wire (Fig. 3) based on the amount of current generated by each of these electrodes with reference to RE in the proposed system. This approach considers the current generation for 60 seconds. Figure 6 represents the magnitude of current obtained when a) electrolyte empty run (no bacteria), b) electrolyte with bac-

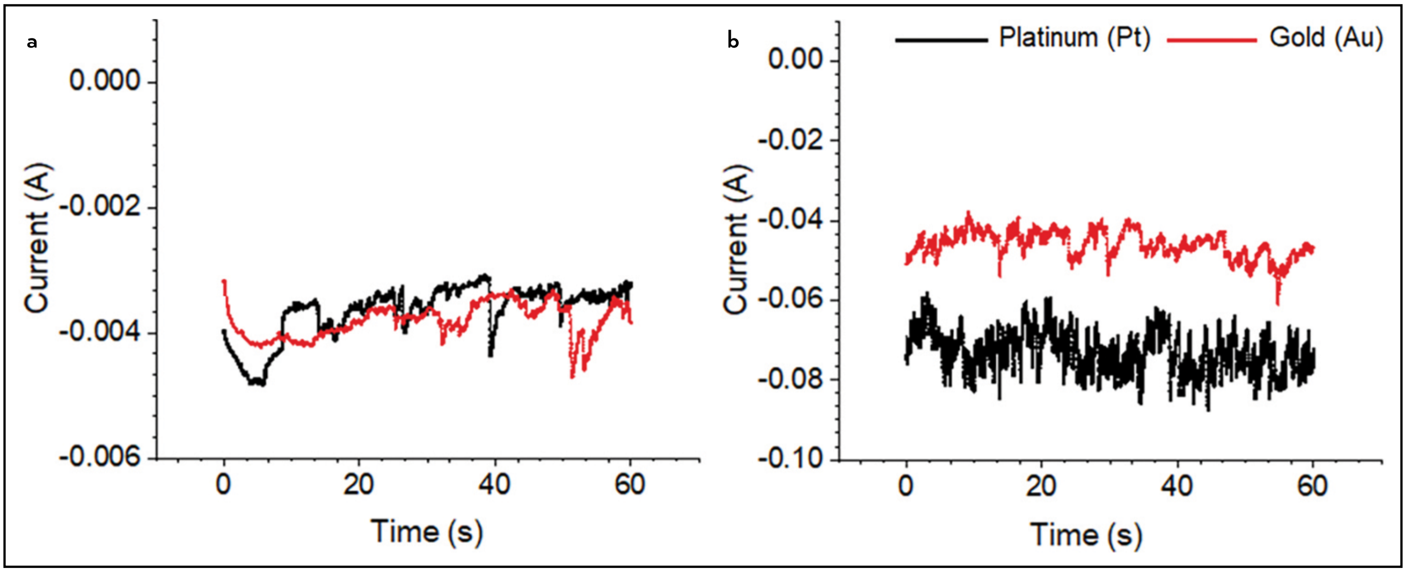

Figure 6. Graphs representing the current (A) magnitude for (a) empty run (without bacteria), (b) with bacteria; where red plots represent the results for Au wire and black plots represent the results for Pt wire

Au: Gold, Pt: Platinum

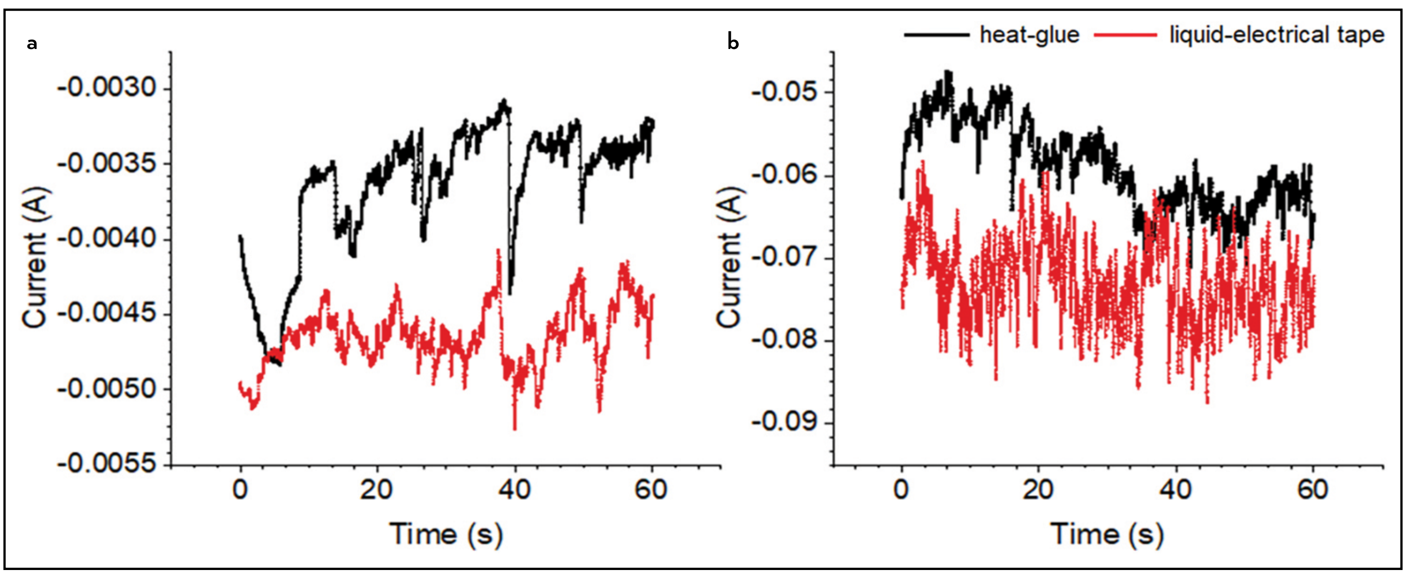

Figure 7. Graphs representing the current (A) magnitude for (a) empty run (without bacteria), (b) with bacteria; where red plots represent the results for liquid-electric tape and black plots represent the results for heat-glue (HMA) setup

HMA: Hot melt adhesive

teria. For an empty run (Figure 6a), the current generated for both electrodes fluctuates between 0.005 A and 0.003 A. Figure 6b shows that the setup with Pt wire experiences more current generation with a magnitude of around 0.08 A, whereas the current generated is in the range of 0.04 A for Au when the electrolyte is a bacterial solution. These results also lead us to decide on Pt as the RE for further experiments.

Current Evolution for the Method of Insulation

The insulation method is critical in these experiments as it is difficult to insert the reamer file and RE separately into the root canal with a small diameter for bacterial eradication. Trials are mainly considered with two insulation methods: HMA and liquid electrical tape (Fig. 3). Data obtained are plotted in Figure 7, showing the electrochemical current flow on applying the same −9.0 V potential. This mode considers only bacterial suspension as the electrolyte and Pt as the RE for 60 seconds.

In Figure 7, current (A) generated a) with test bacteria and b) without test bacteria is plotted where HMA (black plots) and liquid electric tape (red plots) have been used to provide insulation between the control file and RE. This setup reduces the diameter of the system used to insert the root canal module. With an empty run, the liquid electric tape arrangement gives better current magnitudes in the range of 0.0040–0.0050 A. The HMA arrangement provides a current magnitude of 0.0030–0.0040 A. In the bacterial suspension, the current magnitude ranges from 0.05–0.07 A for HMA and 0.06–0.08 A for liquid electrical tape. Based

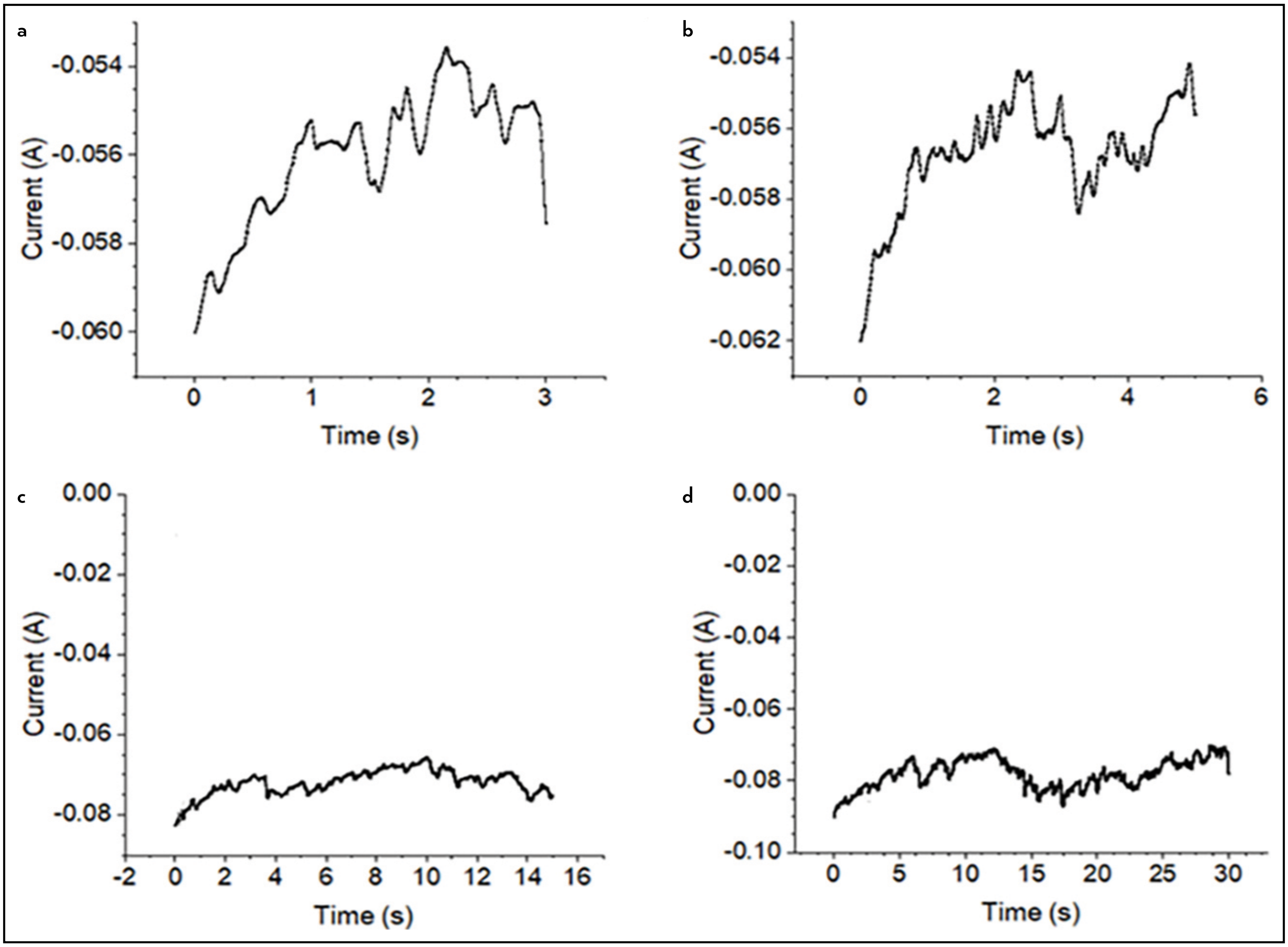

Figure 8. Graphs representing the current (A) magnitude with bacteria solution for (a) 3 s, (b) 5 s, (c) 15 s, and (d) 30 s duration. Here Pt electrode glued to control file with HMA has been used to generate the current flow in the electrolyte

HMA: Hot melt adhesive

on these results, the HMA insulation mode is selected for further experiments since it has sufficiently good current generation as liquid electric tape in the bacterial solution. The HMA method is comparatively more straightforward and has no adverse effect when applied in future clinical trials. However, the liquid electric tape may cause toxic and adverse effects in humans.

Current Evolution for Varying Periods

As represented in the Figure 3 flow chart, experiments were conducted for 0 s, 1 s, 3 s, 5 s, 15 s, 30 s, and 60 s with bacterial and 30 s without bacteria in the electrolyte. Here Pt glued to the control file using HMA, as confirmed from the previous trials, has been taken as the working system. Representative current generation obtained on some of these trials is presented in Figure 8 a-d. These trials aimed to determine the optimal exposure time to achieve >99.99% bacterial kill (Fig. 9). The current evolution for all these trials showed acceptable values except for the 0s and 1s; the current conductions resulted in > 99.99% killing of the test bacteria, Table 1.

As shown in Table 1, a potentiostatic duration of 1s and 3s resulted in >99.99% *E. faecalis*. Duration at 5 s and above resulted in a total bacterial kill. One-way ANOVA with Tukey posthoc test confirms a significant difference for other treatment groups compared to the control group ($P<0.05$).

Comparison with a Commercial Potentiostat and Custom-made Miniature Potentiostat

The results shown in the previous sections are based on the commercially available potentiostat. However, the ultimate focus of our proposed scheme is to develop an integrated potentiostat to guarantee the portability, easiness, and repeatability of the trials in real-world applications. A prototype of the miniature potentiostat has been developed and tested for the Pt-HMA-Reamer pair using PBS solution to address this. Figure 10a is a comparison of the current magnitude obtained with and without test bacterial PBS solution from an off-the-shelf potentiostat and without test bacterial PBS solution from the custom-made potentiostat. Compared to the off-the-shelf potentiostat, custom-designed potentiostat drives higher current through the no-bacterial PBS solution, demonstrating its efficacy in working as an independent system.

In Figure 10a, current magnitude (A) is in the range of (0.019, 0.023), (0.0030, 0.0048), (0.047, 0.070) for custom-made po-

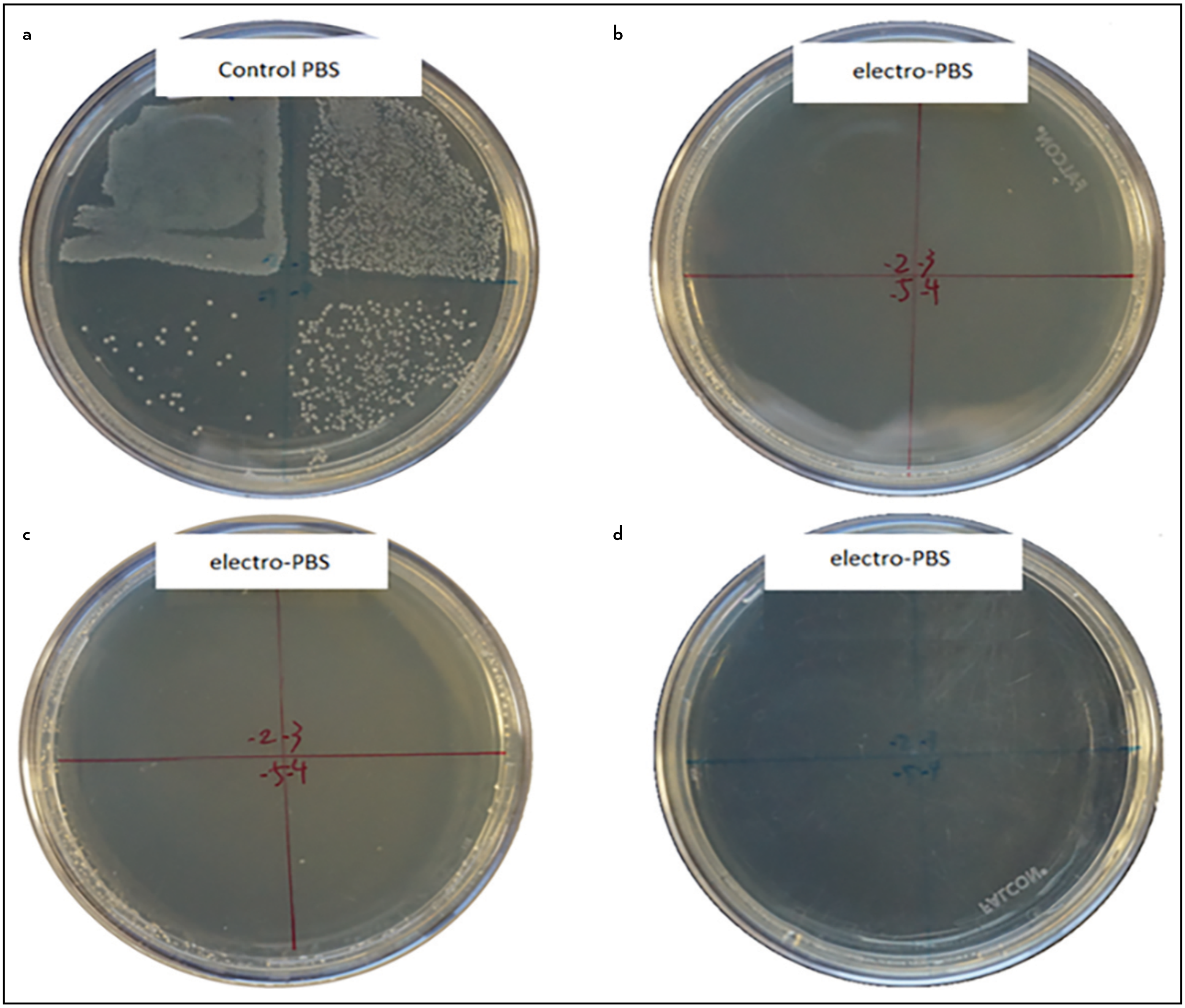

Figure 9. Representative CFU captured for (a) non-treatment control shows no or 0.00% bacterial eradication; and treatment for a time duration of (b) 5 s, (c) 15 s, (d) 30 s shows 99.99% bacterial eradication, for the same Pt-Reamer File electrode combination

PBS: Phosphate buffer saline, Pt: Platinum

tentiostat without test bacteria, commercial potentiostat without test bacteria, and commercial potentiostat with bacteria, respectively. Meanwhile, average current magnitudes from experimental trials with no-bacterial PBS solution (Fig. 10b) show that the custom-made potentiostat was competent enough to provide a higher current for the same Pt-HMA-Reamer pair. A remarkable increase in the current magnitudes in commercial potentiostat advocates custom-designed potentiostat to drive higher current through the bacterial solution leading to complete bacterial kill. One-way ANOVA with the Tukey post hoc test also confirms this significant difference ($P<0.05$) among the groups. This highlights the significance of the reported study.

DISCUSSION

The application of electrochemistry in root canal disinfection is practical *in vitro* tooth models, where a potentiostatic scan has been performed to generate the current for bacterial eradication (29). The presented study is an extension of this work and has taken various assessments to identify the optimum feasible electrode, method of insulation, and time upon which the potentiostatic scan needs to be performed. Because the diameter of the canal space is minimal, ranging from 0.10 mm to a maximum of 0.70 mm, the diameter of the developed treatment-reamer (EC-R) needed to be small (31). This study used the standard reamer as the WE in the EC-R setup. However, it is essential to place both WE and RE with some insulation to facilitate the current flow in the electrolyte.

The success of root canal treatment procedures depends on eliminating microorganisms in the canal system. Failure to disinfect the canal system adversely affects the outcome of RCT (6). Thus, any microbial infections in the root canal system must be adequately addressed to avoid reinfection. Introduc-

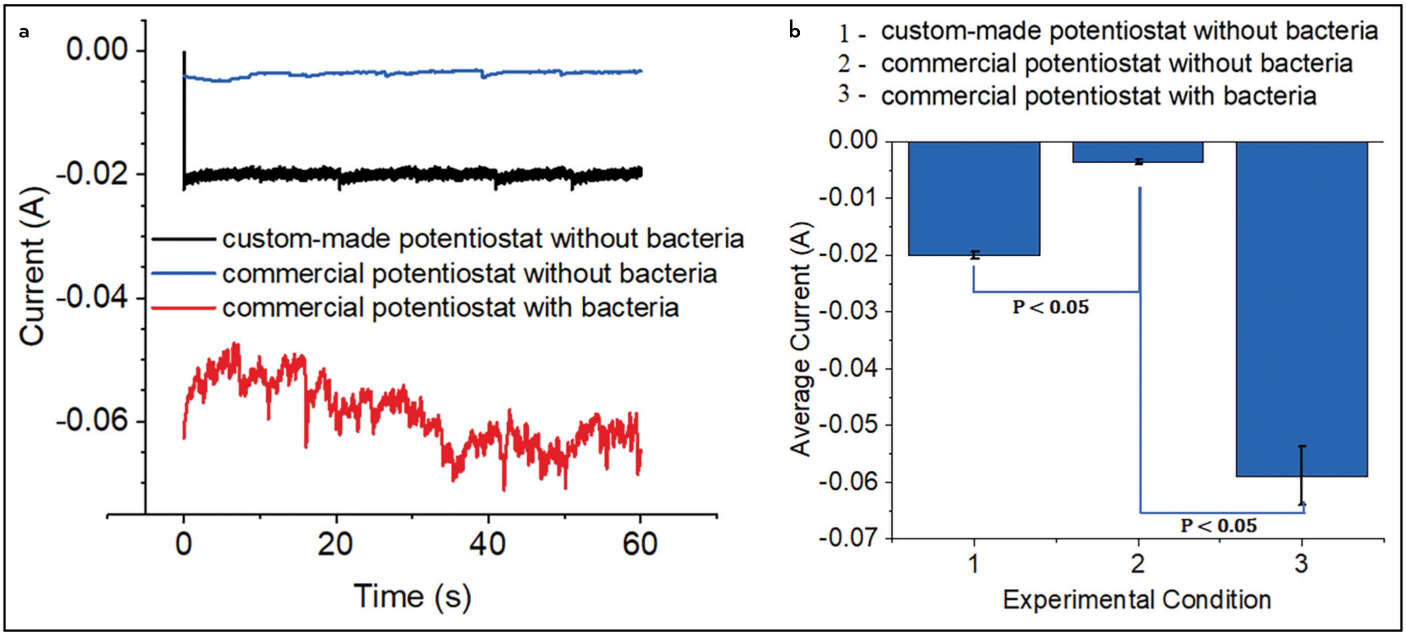

Figure 10. (a) Graphs representing the current (A) magnitude for empty run (without bacteria) using the custom-made potentiostat (black), empty run (without bacteria) using commercial potentiostat (blue), and with bacterial solution using commercial potentiostat (red); (b) Average current magnitudes with its standard deviation (black error bar) observed for three different conditions, with and without bacterial culture

ing electrochemical treatment to the current RCT procedure will potentially help to eliminate microorganisms inside the canal system. (24,29,32). The present *in vitro* study guarantees 99.99% bacterial eradication in 3 seconds.

Common causes of root canal treatment failure include bacterial residue in the root canal system due to anatomy variations, areas accidentally left untouched, microorganisms withstanding antibiotics or intracanal disinfecting methods. It shows the importance of developing a treatment that can be used as often with limited or no burden to perform it. It also reveals the significance of this study, where the small diameter reamer-electrode setup (EC-R) will send electric signals which can reach the bottom of the root canal and traverse across the tissue, as shown in Figure 5 and disinfect and eradicate any bacterial contamination in the root canal area. As shown in our simulation study (Fig. 5), an applied potential of −9.0 V generates some electric fluctuations in the PBS electrolyte mainly due to the presence of chloride ions (33,34). Similar behaviour is observed with the commercially available, and the custom-made potentiostat model also provided promising current magnitudes and contributed to the efficacy of the presented study.

Mechanism and Clinical Significance

With the developed scheme, teeth disinfection is made possible with the electrochemical method having a two-electrode system consisting of Platinum wire as a reference electrode (RE) and counter electrode (CE) combination, R-Files dental reamer as a working electrode (WE), and a conductive solution (PBS) as the electrolyte. The reference electrode Pt wire continuously connected the potentiostat and reamer in the root canal through the electrolyte. This setup allowed us to apply an electrical potential to produce a localized effect throughout the root canal system, even in the dentinal tubules and

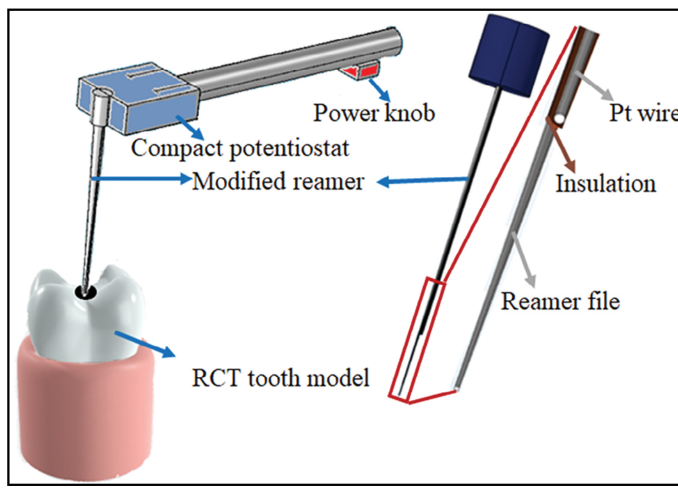

Figure 11. Representation of the anticipated smart electronic device for total bacterial eradication in root canal procedure. In this setup, the modified reamer file is a combination of Reamer and Pt wire separated with an insulation along the joint

RCT: Root canal treatment, Pt: Platinum

surfaces that files could not touch. The initial and final viability of bacteria has been tested for varying pulse duration for an electrochemical potential of −9.0 V. The optimal combination of about −9.0 V voltage with a pulse duration of 30 seconds is identified on the studied tooth sample.

As per our understanding, the *reference electrode + electrolyte + working electrode* forms a galvanic couple and establishes a current flow in the electrolyte. As the duration of application is limited to 30 seconds, the chances of creating any tissue failure are considered feeble. Since the galvanic couple formed generates electrical fluctuations in the electrolyte, its effect can be experienced in the dentinal tubules, accessory canals,

TABLE 1. The effect of potentiostatic cycle duration on *E. faecalis* viability. One-way ANOVA with Tukey posthoc test shows a significant difference between the control group and other treatment groups with a p-value of <0.05

Cycle duration (Second)	Trials	Viable bacteria (CFU/ml)	Control %	Reduction (%)
0 (Control)	1 2 3	9.12×10^7	100	0
1	1 2 3	2.53×10^2	0.0003	>99.997
3	1 2 3	1.82×10^2	0.0002	>99.998
5	1 2 3	0	0	100
15	1 2 3	0	0	100
30	1 2 3	0	0	100
60	1 2 3	0	0	100

and up to the apical constriction. In our previous study, our findings showed the minimum risk of toxicity with apoptotic and necrotic activity data (29). However, ongoing studies address its influence and the possibility of adverse reactions in the surrounding tissues.

Figure 11 shows the schematic of the proposed prototype disinfection device. This device will comprise ON/OFF switches, disinfection intensity, duration, and external calibration. RE in the device will be attached to the WE (EC-R) with electrical insulation to guarantee the minimal or limited diameter criteria and located close to the tip. The WE will be shaped like a needle and placed at the tip. During operation, the RE–WE combination is immersed into the root canal so that it touches dental metal filling and the irrigant solution to make it a complete circuit. In the current setup, a voltage magnitude of −9.0 V has been applied at the RE using an external power source and/or alkaline batteries, while the final working model will be based on a Lithium coin battery.

Limitations and Future Scope

Since microbial infections are one of the most common causes of endodontic failures, developing a device to guarantee the complete eradication of bacteria has the utmost importance in root canal procedures. The current study only tested the antimicrobial effect of the device on planktonic bacteria. It is well known that oral microorganisms most commonly exist in complex biofilm communities, which are challenging to eradicate and more resistant to antimicrobial agents compared to their planktonic counterparts; future studies will be needed to test the antimicrobial efficacy in a biofilm tooth model. The developed potentiostat is in its early phase and utilises an external power source or alkaline batteries, compromising the anticipated size. The futuristic studies consider an electrochemical cell such as a Lithium coin battery (capacity: ~200 mAh) as a power source to make it more compact and portable. Apart from using HMA as an insulating material, other 3D printed profiles that can hold the WE and RE with appropriate insulation and have minimal size should be developed. Developing an electronic device handy (Fig. 11) and allowing it to be used by a layman can guarantee higher success rates in endodontic procedures. The developed prototype is focused only on *in-vitro* models, although actual clinical trials are being considered. While in a real scenario, the system must be evaluated *in-vivo*, its feasibility should be studied, and a miniaturised model must indeed be developed, which has an in-built potentiostat and replaceable reamer-electrode (EC-R) setup. Using a regulator unit, the reference electrode will self-determine the applied voltage magnitude by accounting for tooth and saliva variability among patients. A practitioner has additional control to set the intensity and duration of the applied voltage using current reference and timer circuits. The device's small size is critical for the convenience of root canal operations, and the final system will be optimised accordingly. All these aspects are under investigation and are part of our future venture.

CONCLUSION

This study proves the capability of an electrochemistry-based device in the total eradication of bacteria in *in-vitro* models. It could potentially improve the success rates of root canal treatment even with the challenges such as complex anatomy and resistant bacterial infection. The main findings of this study include a) simulating an electrochemical experiment using COMSOL software provides a good profile of the current flow from the reference electrode to the working electrode through the electrolyte, b) platinum (Pt) is identified as the ideal candidate for the reference electrode, c) HMA can work as a good insulator for the electrochemical experiments, d) −9.0 V voltage with a pulse duration of 30 seconds is optimal for root canal bacterial disinfection.

Disclosures

Acknowledgments: The authors acknowledge the Office of Technological Management for providing funding for the project [Royalty fund (code 200258)], Divya Bijukumar, PhD of UIC at Rockford for supporting this study.

Conflict of interest: The authors deny any conflict of interest.

Ethics Committee Approval: This study used a lab scale, *in vitro* model to explore the efficacy of bacterial eradication in root canal treatment. Any ethical committee approval is not required for this study.

Peer-review: Externally peer-reviewed.

Financial Disclosure: Royalty fund (code 200258) - Office of Technological Management, University of Illinois at Chicago.

Authorship contributions: Concept – M.T.M., Q.X., A.R.T.; Design – M.T.M., C.W., A.R.T., Q.X.; Supervision – M.T.M., C.W., A.R.T.; Funding - None; Materials - None; Data collection and/or processing – R.A.R., S.K., W.L., A.S.; Analysis and/or interpretation – R.A.R., W.L.; Literature search – R.A.R., S.K.; Writing – R.A.R.; Critical Review – M.T.M., C.W., Q.X.

REFERENCES

1. American Association of Endodontists, New study shows root canal treatment's bad rap may become a thing of the past, reports American association of endodontists. Available at: https://www.prnewswire.com/news-releases/new-study-shows-root-canal-treatments-bad-rap-may-become-a-thing-of-the-past-reports-american-association-of-endodontists-300893358.html. Accessed 29 Dec, 2020.
2. Plotino G, Venturi M, Grande NM. Complications due to root canal filling procedures. In: Jain P, editor. Common Complications in Endodontics. Springer, Cham; 2018. p. 101–46. [CrossRef]
3. AAE Releases New Infographic Just in Time for the Holidays. AAE Newsroom. Available at: https://newsroom.aae.org/featured-stories/aae-releases-new-infographic-just-in-time-for-the-holidays/. Accessed 11 Nov, 2020.
4. Torabinejad M. Root canal irrigants and disinfectants clinical newsletter - AAE. Available at: https://www.aae.org/specialty/newsletter/root-canal-irrigants-disinfectants/. Accessed 29 Dec, 2020.
5. Torabinejad M, Handysides R, Khademi AA, Bakland LK. Clinical implications of the smear layer in endodontics: a review. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2002; 94(6):658–66. [CrossRef]
6. Siqueira JF Jr. Aetiology of root canal treatment failure: why well-treated teeth can fail. Int Endod J 2001; 34(1):1–10. [CrossRef]
7. Ricucci D, Siqueira JF Jr, Bate AL, Pitt Ford TR. Histologic investigation of root canal-treated teeth with apical periodontitis: a retrospective study from twenty-four patients. J Endod 2009; 35(4):493–502. [CrossRef]
8. Mohammadi Z, Abbott PV. The properties and applications of chlorhexidine in endodontics. Int Endod J 2009; 42(4):288–302. [CrossRef]
9. Gomes BP, Ferraz CC, Vianna ME, Berber VB, Teixeira FB, Souza-Filho FJ. *In vitro* antimicrobial activity of several concentrations of sodium hypochlorite and chlorhexidine gluconate in the elimination of Enterococcus faecalis. Int Endod J 2001; 34(6):424–8. [CrossRef]
10. Siqueira JF Jr, Machado AG, Silveira RM, Lopes HP, de Uzeda M. Evaluation of the effectiveness of sodium hypochlorite used with three irrigation methods in the elimination of Enterococcus faecalis from the root canal, *in vitro*. Int Endod J 1997; 30(4):279–82. [CrossRef]
11. Sjögren U, Figdor D, Persson S, Sundqvist G. Influence of infection at the time of root filling on the outcome of endodontic treatment of teeth with apical periodontitis. Int Endod J 1997; 30(5):297–306. [CrossRef]
12. Shuping GB, Orstavik D, Sigurdsson A, Trope M. Reduction of intracanal bacteria using nickel-titanium rotary instrumentation and various medications. J Endod 2000; 26(12):751–5. [CrossRef]
13. Shabahang S, Torabinejad M. Effect of MTAD on Enterococcus faecalis-contaminated root canals of extracted human teeth. J Endod 2003; 29(9):576–9.
14. Sim TP, Knowles JC, Ng YL, Shelton J, Gulabivala K. Effect of sodium hypochlorite on mechanical properties of dentine and tooth surface strain. Int Endod J 2001; 34(2):120–32. [CrossRef]
15. Grigoratos D, Knowles J, Ng YL, Gulabivala K. Effect of exposing dentine to sodium hypochlorite and calcium hydroxide on its flexural strength and elastic modulus. Int Endod J 2001; 34(2):113–9. [CrossRef]
16. Buldur B, Kapdan A. Comparison of the EndoVac system and conventional needle irrigation on removal of the smear layer in primary molar root canals. Niger J Clin Pract 2017; 20(9):1168–74. [CrossRef]
17. Park SY, Kang MK, Choi HW, Shon WJ. Comparative analysis of root canal filling debris and smear layer removal efficacy using various root canal activation systems during endodontic retreatment. Medicina (Kaunas) 2020; 56(11):615. [CrossRef]
18. Alamoudi RA. The smear layer in endodontic: To keep or remove – an updated overview. Saudi Endod J 2019; 9(2):71–81.
19. Darouiche RO. Treatment of infections associated with surgical implants. N Engl J Med 2004; 350(14):1422–9. [CrossRef]
20. Zhao L, Chu PK, Zhang Y, Wu Z. Antibacterial coatings on titanium implants. J Biomed Mater Res B Appl Biomater 2009; 91(1):470–80. [CrossRef]
21. Niepa TH, Snepenger LM, Wang H, Sivan S, Gilbert JL, Jones MB, et al. Sensitizing Pseudomonas aeruginosa to antibiotics by electrochemical disruption of membrane functions. Biomaterials 2016; 74:267–79.
22. Niepa TH, Wang H, Dabrowiak JC, Gilbert JL, Ren D. Synergy between tobramycin and trivalent chromium ion in electrochemical control of Pseudomonas aeruginosa. Acta Biomater 2016; 36:286–95. [CrossRef]
23. Ghasemian S, Asadishad B, Omanovic S, Tufenkji N. Electrochemical disinfection of bacteria-laden water using antimony-doped tin-tungsten-oxide electrodes. Water Res 2017; 126:299–307. [CrossRef]
24. Parry-Nweye E, Onukwugha NE, Balmuri SR, Shane JL, Kim D, Koo H, et al. Electrochemical strategy for eradicating fluconazole-tolerant Candida albicans using implantable titanium. ACS Appl Mater Interfaces 2019; 11(44):40997–1008. [CrossRef]
25. Dargahi M, Hosseinidoust Z, Tufenkji N, Omanovic S. Investigating electrochemical removal of bacterial biofilms from stainless steel substrates. Colloids Surf B Biointerfaces 2014; 117:152–7. [CrossRef]
26. Schneider S, Rudolph M, Bause V, Terfort A. Electrochemical removal of biofilms from titanium dental implant surfaces. Bioelectrochemistry 2018; 121:84–94. [CrossRef]
27. Canty MK, Hansen LA, Tobias M, Spencer S, Henry T, Luke-Marshall NR, et al. Antibiotics enhance prevention and eradication efficacy of cathodic-voltage-controlled electrical stimulation against titanium-associated methicillin-resistant staphylococcus aureus and pseudomonas aeruginosa biofilms. mSphere 2019; 4(3):e00178–19. [CrossRef]
28. Schmidt-Malan SM, Karau MJ, Cede J, Greenwood-Quaintance KE, Brinkman CL, Mandrekar JN, et al. Antibiofilm activity of low-amperage continuous and intermittent direct electrical current. Antimicrob Agents Chemother 2015; 59(8):4610–5. [CrossRef]
29. Segu A, Bijukumar D, Trinh T, Pradhan MN, Xie Q, Cortino S, et al. Total eradication of bacterial infection in root canal treatment: an electrochemical approach. ACS Biomater Sci Eng 2018; 4(7):2623–32. [CrossRef]
30. Libretexts, Standard electrodes - chemistry libretexts. Available at: https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Electrodes/Standard_Hydrogen_Electrode, 2013. Accessed 30 Dec, 2020.
31. Martos J, Tatsch GH, Tatsch AC, Silveira LF, Ferrer-Luque CM. Anatomical evaluation of the root canal diameter and root thickness on the apical third of mesial roots of molars. Anat Sci Int 2011; 86(3):146–50. [CrossRef]
32. Froughreyhani M, Salemmilani A, Mozafari A, Hosein-Soroush M. Effect of electric currents on antibacterial effect of chlorhexidine against Entrococcus faecalis biofilm: An *in vitro* study. J Clin Exp Dent 2018; 10(12):e1223–9. [CrossRef]
33. Toparli C, Hieke SW, Altin A, Kasian O, Scheu C, Erbe A. State of the surface of antibacterial copper in phosphate buffered saline. J Electrochem Soc 2017; 164(12):H734. [CrossRef]
34. Hudak EM. Electrochemical evaluation of platinum and diamond electrodes for neural stimulation (dissertation). Cleveland (OH): Case Western Reserve Univ; 2011.