WIP: A Study on the Development of Endodontic Micro Robot

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ABSTRACT

Endodontic therapy, also called root canal treatment, is a procedure that is performed to remove damaged tissue from the inner canal of a tooth, and then the canal is sealed to prevent this area from being a source of infection. A typical procedure includes access preparation, root canal preparation and root canal filling. The treatment process is time-consuming and prone to human error. The outcome relies on the clinician's expertise, which can only be gained through years of training and practice. The treatment success rate is 60-65% by general dentists and 90% by specialists. In order to improve the quality and reliability of endodontic therapy, the design and building of an endodontic micro robot is proposed. This computer controlled micro machine will need to be mounted on several teeth within a patient's mouth. With on-line monitoring and positioning control, this multi-purpose micro robot will automatically perform the treatment procedures including drilling, filing, cleaning and filling the open canal.

This paper will discuss the preliminary investigation of: the mechanical design and manufacture of the micro robot; the choosing and fabricating the embedded sensors and actuators using MEMS technology; and the control system design using an NC controller. The paper will also discuss the innovations involved from the traditional way endodonticsts treat root canal to science and technology based automation.

INTRODUCTION

Endodontic (root canal) treatment is common. Approximately 24 million root canal therapies are performed annually in the United States [1]. Endodontic treatment is performed to prevent a tooth from being a source of infection. Typically, endodontic

treatment involves root canal preparation and root filling. The root canal preparation, better known as preparing the root canal for root filling, can be divided into three phases: (1) access preparation, (2) coronal canal preparation, and (3) apical canal preparation. Figure 1 shows canal characteristics and the three phases in canal preparation for a posterior tooth.

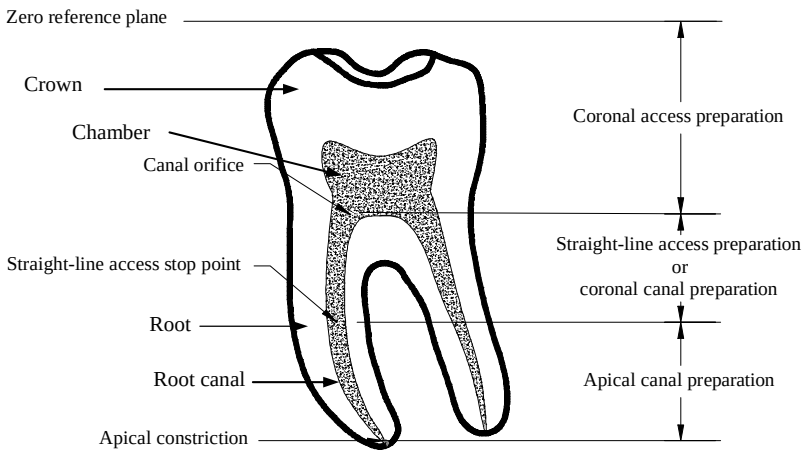

Figure 1. Canal Characteristics and Three Phases in Root Canal Treatment Preparation

The endodontic access preparation is to create an unimpeded passageway to the pulpal space and the apical portion of the root canal [2]. By using an access bur attached to a high-speed turbine hand-piece, the chamber is unroofed, and canal orifices are exposed. In order to obtain instrument control, the straight-line access to the apical portion of the root canal is created during access and coronal canal preparation [3]. Coronal and apical canal preparation is also called root canal cleaning and shaping. Successful cleaning entails the use of various instruments, the first will physically loosen and remove soft and hard tissue; the second is an irrigating system to flush loosened materials away, and the third will inject chemicals to dissolve the infection from the inaccessible regions. Root canal shaping is a mechanical process accomplished with a variety of instruments. This process is to establish a continuously shaped conical form from apical to coronal to facilitate the filling of the root canals with gutta-percha cones and sealer that are today's most commonly used filling materials [4].

The successful outcome of the preparation depends largely on the clinician's expertise, including his/her tactile sense and judgment. To expose the canal orifices and establish a straight-line access to the canal, a relatively large amount of the tooth structure must be removed during access preparation. This removal can be excessive and may weaken the tooth.

There are additional problems that can occur in the current endodontic techniques for canal preparation [5] [6]. The following are examples:

- Perforation and Furcal Perforation-This causes periodontal (surrounding tissues) destruction, weakens tooth structure, and often-subsequent loss of the tooth;
- Canal Ledging-This is an artificially created irregularity in the surface of the root canal wall that prevents the placement of instruments of proper length into the original canal path,
- Transportation of the Apical Portion of the Canal-Characterized by a normal curved canal that has been straightened, especially in the apical third;
- Stripping, or Lateral Wall Perforation-Primarily caused by overzealous instrumentation in the mid-root area
- Excessive Instrumentation Beyond the Apical Construction-causing damage to the periodontal ligament and alveolar bone
- Inadequate Canal Preparation-This is the failure to remove pulp tissue, dentinal debris, and microorganisms from the root canal system;
- Improperly Shaped Root Canal-Which prevents adequate filling.

The problems identified above cannot be resolved solely by training. Endodontics is a clinical specialty, but the great need for endodontic therapy makes it impossible for these specialists to handle all cases. These problems have created a need for advanced endodontic technology innovation by applying advanced engineering and computer aided technology to reduce the potential for human error and improve the quality of care during endodontic therapy.

The need for advanced endodontic technology prompted the research of "Advanced Endodontic Technology Development". The Advanced Endodontic Technology Development project consists of four sub-subjects:

(1) Development of a technique to thoroughly assess the tooth's condition using 2-dimensional x-ray images to build a computer 3-D tooth model, displaying state-of-the-art computer graphics;
(2) Develop an automatic prescription system from the 3-D root canal model, using computer-aided treatment procedure planning;
(3) Design and build a smart multi-purpose precision micro machine to perform automated root canal treatment;
(4) Develop a new ultrasonic cleaning tool with pressure assisted jetting/vacuum waste removal.

The development of an endodontic micro machine is the center piece of the Advanced Endodontic Technology Development project. The final implementation of this advanced endodontic technology will result in a micro machine with a precision beyond what the human hand can achieve. This computer-controlled machine will be mounted on several teeth within the patient's mouth. With on-line monitoring and intelligent control, the micro machine or robot will perform the automated drilling, cleaning, and filling of the root canal. All other sub-project results will be incorporated into this robotic operation.

This paper will focus on the preliminary study of the mechanical design of an endodontic robot, the choosing and fabrication of embedded sensors, and the design of the control system with an NC controller for robotic motion.

ESSENCES IN ENDODONTIC PROCESS AUTOMATION

Root canal shaping is a mechanical process that is currently done with hand files and reamers, along with drills of various designs and tools that attach to rotary engines of different speeds. In principle, though not in scale, it does not differ from the drilling/reaming process in the machining industry. The machining industry has moved from manual operation to Numerical Control (NC) and Computer Numerical Control (CNC). The quality and accuracy of a produced part is controlled by a computer program on an automatic precision machine. This master skill, so critical in the past, is no longer needed. Currently in endodontics, the success of the root canal shaping principally depends on the skill and thoroughness of the clinician. This is because endodontic therapy relies almost entirely on "feel" - the tactile sense of the clinicians [7]. The quality and accuracy of clinical care could be greatly enhanced by applying available technological advancements, such as process automation with NC controlled micro robot, to this therapy.

The tasks to develop this micro robot include:

(1) Defining the specifications and requirements for this robot;
(2) Mechanical design, manufacture, and mounting of the robot;
(3) Design, select or fabrication the sensors and actuators;
(4) Design and development of the control system.

ENDODONTIC MICRO ROBOT SPECIFICATIONS AND REQUIREMENTS

Specific objectives for micro robot design include: (1) reducing the reliance on the skills of the dentist, (2) minimizing human error, and (3) offering a method for precise diagnosis and treatment.

In order to determine the engineering features for the micro robot, a survey was developed and sent to dentists and endodontists in the greater Cincinnati area [8]. The survey results indicate that the machine should have the following features:

- A micro-position and orientation adjustment to ensure that the tools start at a precise point;
- An automatic feed rate and travel distance control to ensure that the tools can reach the required canal depth and stop at a designated point;
- Built-in micro sensors to monitor the probing and drilling/reaming process;
- Apex sensing and control to prevent root perforations or the potential to over shoot (exceeding the apex of the canal);
- Flexible drills or files to allow for cleaning and shaping curved canals;

- Vacuum attachments capable of sucking the debris or loose tissue from the root canal and/or pressurized solution jets to flush the chips away.

A preliminary quantitative study established the design requirements. In order to provide accurate positioning of the tool, with correct angular orientation, an ideal basic machine must have five degrees of freedom to control the following axes:

- X-axis, along the teeth row, with travel range of 5 mm;
- Y-axis, across the teeth row, with travel range of 4 mm;
- Z-axis, the tool advancement direction, perpendicular to the tooth occlusal surface, with a travel range of 15 mm minimum. When using a longer tool, the endodontic tool should be able to reach 28 mm from the tooth crown, covering the required range of treatment;
- The angular adjustment of the tool entrance angle of ± 12° in the X-Z plane;
- The angular adjustment of the tool entrance angle of ± 12º in the Y-Z plane.

In addition, the design must meet the following requirements:

- The size of the machine must be compact enough to fit into the patient's mouth and sit on the teeth between his/her two jaws. The dimension should be within 20 mm x 20 mm x 28 mm;
- The spindle must have the rotational power to drive the tool at speeds and torque used in endodontic treatment tools;
- The machine should be able to provide a thrust force not less than 500g (4.9 Newtons) for tool penetration into the crown and dentin.

ENDODONTIC MICRO ROBOT MECHANICAL DESIGN

There are many different potential machine configurations. A weighted decision matrix was completed to determine which design fits most closely to the design criteria and satisfies the engineering characteristics above. Figure 2 shows a winning mechanical design of a multi-purpose micro machine for root canal treatment. As indicated in the figure, this machine has five axes of motion: linear motion in the *X, Y, Z* directions, and rotational motion in θ_x, θ_y directions. The tilt angles θ_x, θ_y are controlled by additional linear actuators *X'* and *Y'*. There is another rotational motion provided for the spindle ω_z.

The machine has a saddle-shaped base. It will ride on a pair of reference brackets and the teeth. Before taking X-rays and mounting this machine, the brackets, in assorted sizes to fit the patients' teeth must be pre-clamped firmly on the tooth to be treated. Neighboring teeth may be used as support.

The bracket pair provides three radiopaque reference points for the machine registration, thus establishing a coordination system. Once the machine is seated on the reference bracket, the machine base will have no motion relative to the patient's teeth, regardless of the patient's head or jaw movements. The machine is designed to be compact and rigid so that the patient can bite on it. See Figure 3. There is no need for the patient to actively

keep his/her mouth wide open, nor is there a need for the patient to keep his/her head absolutely still. There are no sharp corners to hurt the patient, and a protective case (shown in the photo only, not in the drawings) will further enhance the safety.

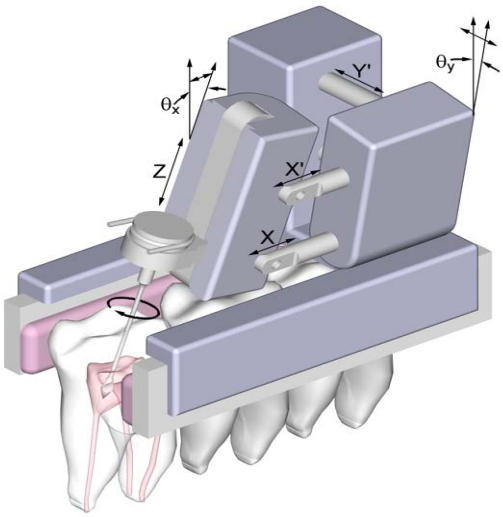

Figure 2. Multi-purpose micro-machine for automatic endodontic treatment

Designed for multi-purpose use, this machine can hold various endodontic tools and auxiliary devices. With a quick tool change approach, utilizing a cartridge design, different tools can be pre-mounted on a small modular unit, which can be inserted into a sliding adaptor on the Z axis.

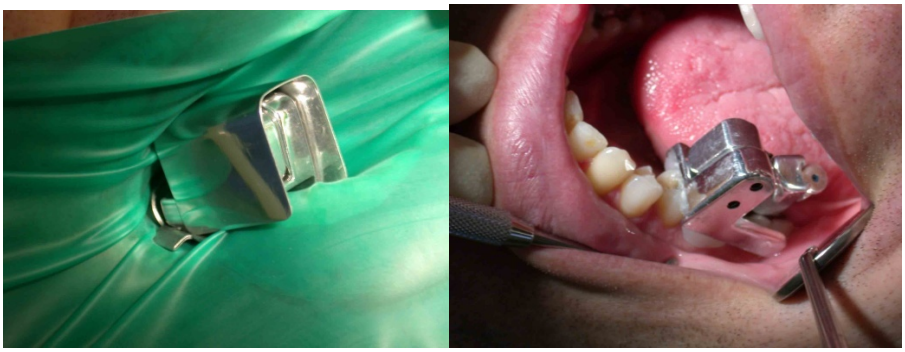

Figure 3. Machine model showing how it fits in the patient's mouth: to the left is the machine placed together with a rubber dam. The machine is protected by a stainless steel cover. To the right is the machine without cover or rubber dam, showing the relationship in size to the teeth.

MICRO SENSORS, ACTUATORS, AND CONTROL SYSTEMS

This machine design also incorporates sensors for intelligent monitoring of the treatment process. Because the compact features of the sensors, they can be fabricated using a surface micro machine method to produce silicon-on-insulator (SOI) wafers, which will

be embedded in the micro robot. Six micro actuators will be used to control the five axes (five degrees of freedom) and the on/off spindle of the tool. Each actuator is independently controlled by a digital NC controller. The controller should react the sensor signal quickly, typically in a few milliseconds. Choosing embedded microcontrollers or cord connected controller is to be determined by further research.

Auxiliary functions will be provided. These functions include: an irrigation nozzle for cleaning, a vacuum suction cup for chip and waste fluid removal, and/or optical fibers for lighting, imaging and observation. A manual remote control will be provided for the clinician, but a fully automatic operation with computer-aided treatment procedure planning and control is the ultimate goal for a zero-defect operation. An interface system will be provided for the clinician to interact with the machine control.

The computer-aided treatment process planning system, with functions similar to CAD/CAM programs in the machinery industry, will generate the standard NC codes (G codes and M codes) as output from a computer aided design file. These codes will control the movements of the robot through an NC digital controller. This computer prescription program is being developed to automatically select the appropriate tool and to determine: (1) the tool's starting point, position, and direction, (2) the tool's path, (3) the tool's stopping point, (4) the cutting parameters, such as speed and feed, and (5) the geometry of the 3-D tooth model after treatment. The computer program will plan the sequence of the operations using a variety of tools and motion control parameters to complete the preparation of the root canal. An optimization program will be integrated into this auto-prescription program to minimize the removal of tooth structure and to eliminate unnecessary tool change.

CONCLUSION

The development of an endodontic micro robot is the center piece of Advanced Endodontic Technology Development. Compared to conventional access methods for root canal treatment, this research presents a less invasive method using automated access and canal preparation during endodontic therapy. The automated treatment using micro endodontic robot prevents problems identified with conventional techniques (e.g., inadequate opening, overzealous tooth removal), and provides a safe, accurate, and reliable root canal treatment for patients. With on-line monitoring and intelligent control, this machine will perform the automatic probing, drilling, cleaning, and filling of a root canal. The success of the robot fabrication and integration into the Advanced Endodontic Technology Development plan will change the traditional method of root canal treatment. The new method will be a science and technology based automation system, and will result in the microelectronic mechanical (MEMS) technology being utilized in a new application area in endodontics.

This paper described the preliminary development of endodontic micro robot for root canal treatment, including specification and requirements, mechanical design, and controller systems. Further study is still needed, especially in the micro sensor and

actuator design and fabrication. It is expected that the new robot model, with embedded sensors and actuators, will be fabricated in the near future.

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REFERENCES

[1] American Dental Association, Survey of Dental Practice, S699 ed, Chicago, ADA 1999.

[2] Gutmann, JL and Lovdahl, PE: Problems Encountered in Tooth Isolation and Access to the Pulp Chamber Space. In Gutmann, JL, Dumsha, TC, Lovdahl, PE, Hovland, EJ, editors: *Problem Solving in Endodontics-Prevention, Identification, and Management*, ed 3, St Louis, Missouri, The C.V. Mosby, 1997, pp47-67.

[3] Walton, Richard E.: Torabinejad Mahmoud: Principles and Practice of Endodontics, Third edition, W.B.Saunders Company, 2002, pp192-197.

[4] Gutmann, JL, Dumsha, T: Cleaning and Shaping the Root Canal System. In Cohen, S, Burns, RC, editors: *Pathways of the Pulp*, ed 7, St Louis, Missouri, The C.V. Mosby Company, 1997, pp160-173.

[5] Burns, RC and Herbranson, EJ: Tooth Morphology and Cavity Preparation. In Cohen, S, Burns, RC, editors: *Pathways of the Pulp*, ed 7, St Louis, Missouri, The C. V. Mosby, 1997, pp 150-202.

[6] West, JD and Roane, JB: Cleaning and Shaping the Root Canal System. In Cohen, S, Burns, RC, editors: *Pathways of the Pulp*, ed 7, St Louis, Missouri, The C.V. Mosby, 1997, pp 203-257.

[7] Sen, BH; Piskin, B and Demirci, T: Observation of Bactreia and Fungi in Infected Root Canals and Dentinal Tubules by SEM, Endodontics and Dental Tranmatology, 1995, 11: pp6-9

[8] Everett, H: Feasibility Study of Single-Axis Micro Robot for Endodontic Treatment. University of Cincinnati. June 2007.

[9] Dong, J: Rule-based Planning for Automated Endodontic Treatment - From Dental Radiography, 3-D Computer Modeling, to Tool Selection and Path Control, Dissertation, Columbia University, 2003, pp149-153, pp18-47, pp216-230

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