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ORIGINAL ARTICLE

Pulp ablation therapy by inductive heating: heat generation characteristics in the pulp cavity

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OBJECTIVE AND METHODS: This study was performed to clarify the usefulness of inductive heating system for the new endodontic therapy. Dextran magnetite complex (DM) suspensions were injected into the root canal of a permanent tooth, and the tooth was heated up to about 55.0°C by alternating-current magnetic field.

RESULTS AND CONCLUSION: The time until the temperature in the pulp cavity reached 55.0°C was 328 ± 26 s (mean ± s.d., $n = 8$) in the 56 mg as Fe ml^{-1} of DM concentration. The temperature in the pulp cavity could be maintained at 53.5–59.0°C for 1200 s by changing the magnetic field intensity safely, while temperature elevations of the dental surface on the coronal and apical sides were 4.9° and 3.7°C, respectively. Thus, this inductive heating system, which has the possibility of selective heating, might be useful for eliminating residues of pulp as a new ablation therapy.
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Keywords: inductive heating; endodontic therapy; pulp cavity; dextran/magnetite; magnetic fluid

Introduction

As a result of marked recent advances in heating techniques and thermometry, hyperthermia for cancer initiated in the 1960s has been applied to medical treatment in various areas of the body. Conventionally, hyperthermia was considered to be a treatment using the difference in the sensitivity to temperature of about 43°C between normal cells and cancer cells, and to have a few side effects on the body. Recently, superselective hyperthermia of the target tissue became possible (Jordan *et al*, 1993), and treatment at temperatures of ≥45°C has also been performed as hyperthermia, in a broad sense. Such treatment includes radiofrequency ablation therapy (RFA) for hepatocellular carcinoma. RFA, which can be repeatedly performed, causes a few side effects or complications, and is minimally invasive, is expected to play a central role as a new local therapy for liver cancer (Mazzaferro *et al*, 2004). We applied the inductive heating system using magnetic fluid, which was developed for cancer hyperthermia (Wada *et al*, 2001, 2003), to the pulp cavity covered with hard tissue and evaluated the possibility of pulp ablation therapy using this heating system. To the best of our knowledge, this is the first report of pulp ablation therapy by inductive heating using a unique magnetic fluid.

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Materials and methods

Materials

Twenty-four human natural mandibular anterior permanent teeth (14 central incisors, four lateral incisors, and six canines), extracted at the outpatient clinic of our department, were used in heating experiments. Teeth without a history of dental caries were selected for experiments.

Inductive Heating System and Thermometer

An inductive heating system (model TY-1; Yamamoto Vinyter Corporation, Osaka, Japan) was used (maximum output, 7 kW; fixed frequency, 500 kHz). In this system, an alternating-current magnetic field is generated by a four-turn pancake water-cooled hollow coil. Temperature was measured using a photosensor-type thermometer (model 3000; Luxtron Corporation, Mountain View, CA, USA).

Magnetic fluid

A dextran magnetite complex (DM: Meito Sangyo Co., Ltd, Aichi, Japan) (US Patent 4101435) was used as the

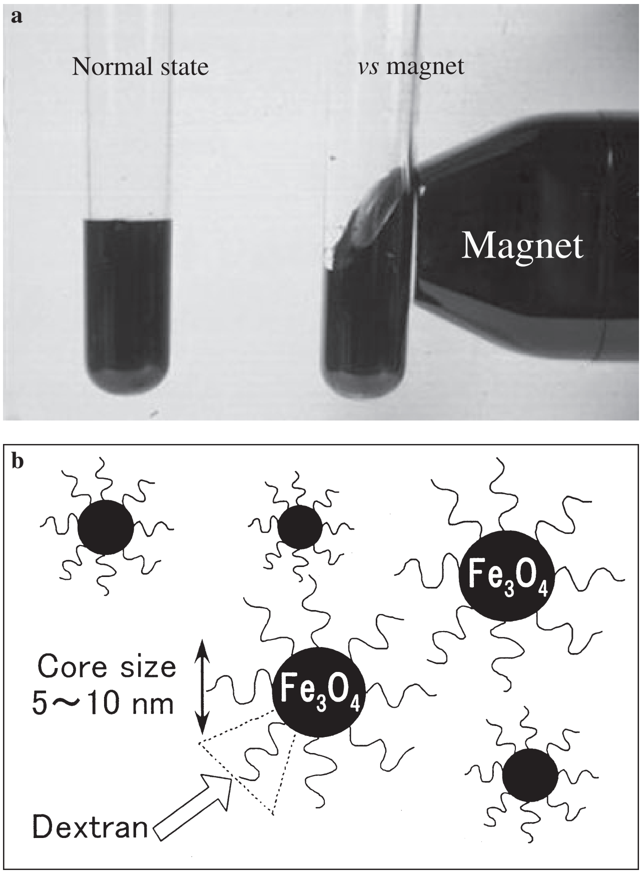

Figure 1 Dextran magnetite for inductive heating. (**a**) Undiluted DM solution (6 M as Fe): black viscous magnetic fluid showing high adsorption to magnets. (**b**) Assumed structure of dextran magnetite

magnetic fluid (Figure 1a). DM is stable as a colloid without aggregating or precipitating in various solvents or serums. The assumed DM structure consists of dextran molecules chemically bound to the circumference of superfine iron oxide particles (Figure 1b). As physicochemical characteristics, the mean particle diameter is 5–10 nm, the coercive force is 3 Oe, and the saturation magnetization is about 80–90 emu gFe^{-1}. Thus, despite very fine particles, the magnetic susceptibility is high. In addition, the LD50 of iron oxide is generally 300–600 mg as Fe kg^{-1}, but that of DM is 2000–6000 mg as Fe kg^{-1}, showing very low toxicity (Hasegawa and Hokkoku, 1978). DM was kindly supplied by Meito Sangyo, and DM suspension containing 335 mg ml^{-1} (6 M) iron at the time of manufacture was used as undiluted solution. This undiluted solution was diluted with sterile distilled water to obtain DM suspensions at iron concentrations of 112 mg ml^{-1} (2 M), 56 mg ml^{-1} (1 M), and 28 mg ml^{-1} (0.5 M) for experiments.

Preparation of heating

Perforation was performed by the routine method from the coronal side of the extracted teeth, and pulp tissue was removed using instruments such as reamers. Working length was established radiographically, and the root canal was enlarged using reamers to no. 45 in a funnel pattern, adequately to the area near the apex, but not beyond the apex, to avoid DM leakage from the pulp cavity via the apical foramen. DM suspension (30–90 μl according to the root canal volume) at each iron concentration was injected using a 30 G dental needle and a disposable syringe slowly, avoiding a mixture of air bubbles in the root canal. Thermometer probes were placed in the pulp cavity and on the tooth surface (coronal and apical sides). After these preparations, the perforation on the coronal side was closed with a dental material (zinc oxide eugenol cement). The pretreated tooth was fixed in a plastic board (thickness, about 1 mm) with dental impression material so that it would be placed at the center of the pancake coil (Figure 2). Induction of an alternating-current magnetic field was initiated, and changes in temperature at each site were recorded.

Optimal DM concentration in pulp cavity

Serial temperature changes using each DM suspension at each iron concentration were recorded at each site. The target temperature in the heating area was 55.0°C at

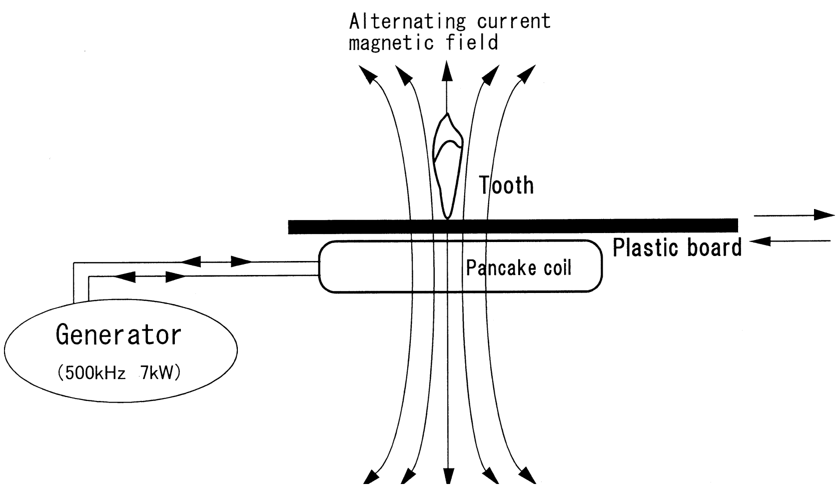

Figure 2 Scheme of the inductive heating system

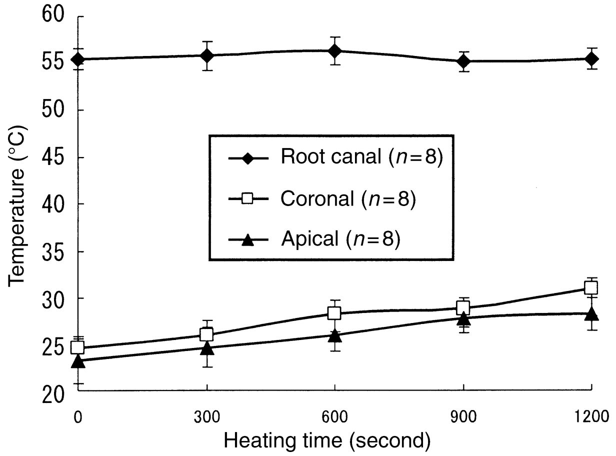

Figure 3 Maintenance of temperature in pulp cavity. The temperature in the pulp cavity could be maintained at 53.5–59.0°C for 1200 s.

which adequate pulp degeneration can be expected. For each DM suspension, the times until the temperature in the pulp cavity reached 40.0° and 55.0°C ($T^{40°C}$ and $T^{55°C}$) were measured.

Maintenance of temperature in pulp cavity
At the optimal concentration determined in an antecedent experiment, temperature maintenance experiments in the pulp cavity were performed. To maintain the temperature in the pulp cavity at 55.0 ± 3.0°C for 1,200 s (20 min), magnetic field intensity was decreased or increased, which was initiated when the temperature in the heating area reached 55.0°C during temperature monitoring. The temperature was changed by changing the horizontal distance between the heating area and the center of the pancake coil by moving the plastic board.

Tooth damage
After the completion of the temperature maintenance experiments, the teeth were observed to determine the presence or absence of DM leakage from the apical foramen or the perforation site on the coronal side because of thermal expansion changes of the tooth, DM suspension, and zinc oxide eugenol cement after heating. In addition, DM in the pulp cavity was washed away with water, and the tooth was fixed in 4% neutral buffered formaldehyde for 7 days and demineralized in 12.5% ethylenediaminetetraacetic acid (EDTA). Specimens were embedded in paraffin, cut into thin sections, and stained by hematoxylin–eosin. Possible damages (such as cracks) of the heated teeth were histologically evaluated by a microscope.

Results

Optimal DM Concentration in the Pulp Cavity
At each concentration, the temperature in the pulp cavity began to increase immediately after magnetic field induction. The $T^{40°C}$ was 174 ± 23 s (mean ± s.d., $n = 8$) in the 112 mg ml^{-1} group, 259 ± 26 s ($n = 8$) in the 56 mg ml^{-1} group, and 341 ± 31 s ($n = 8$) in the 28 mg ml^{-1} group. The $T^{55°C}$ was 244 ± 26 s in the 112 mg ml^{-1} group, 328 ± 26 s in the 56 mg ml^{-1} group, and 481 ± 36 s in the 28 mg ml^{-1} group. $T^{40°C}$ and $T^{55°C}$ decreased DM concentration dependently (Table 1).

Table 1 Heat generation characteristics of dextran magnetite in pulp cavity

DM concentration (mg/ml)	$T^{40°C}$ *(s)*	$T^{55°C}$ *(s)*
112 ($n = 8$)	174 ± 23	244 ± 26
56 ($n = 8$)	259 ± 26	328 ± 26
28 ($n = 8$)	341 ± 31	481 ± 36

Maintenance of temperature in pulp cavity
On the basis of the results of the antecedent experiment, temperature maintenance experiments were performed using 56 mg ml^{-1} DM, which had the most adequate viscosity for injection in the root canal. After the temperature in the pulp cavity reached 55°C or more, the temperature in the pulp cavity could be maintained at 53.5–59.0°C for 1200 s by changing the magnetic field intensity. The mean temperature in the pulp cavity in the entire heating process was 55.2 ± 0.9°C (mean ± s.d., $n = 8$). During the maintenance of temperature, the mean increase in dental surface temperature on the coronal and apical sides was 4.9° and 3.7°C, respectively (Figure 3).

Tooth damage
Macroscopically, no DM leakage from the heated teeth was observed at any DM concentration. Histological examination showed neither tooth cracks/coloring nor DM aggregation/remaining in the pulp cavity.

Discussion

In root canal treatment, the mechanochemical cleaning, disinfection, and tight filling of the root canal are the most important points. In particular, accurate root canal enlargement and preparation to the apex are indispensable in teeth with apical lesions (Gutmann and Lovdahl, 1997; Orstavik *et al*, 2004). However, root canal enlargement to the apical foramen is difficult in some patients. For the treatment of curved the root canals, the collateral root canals and the root canals in which instruments such as reamers were used, complete pulp removal is very difficult. In such teeth, drug application to the root canal is often repeated because of pain or bleeding in the root canal. As methods for such intractable cases, studies have shown the development and usefulness of various files (Contreras *et al*, 2001; Szep *et al*, 2001; Schafer and Schlingemann, 2003), various root canal laser treatment methods (Chang and Wilder-Smith, 1998; Elliott *et al*, 1999), and new application drugs for the root canal (Naenni *et al*, 2004; Okino *et al*, 2004). Thus, a supplementary system may be needed to obtain a more complete outcome of the root canal treatment.

Inductive heating uses the heat generation effects of various magnetic materials inserted or injected into tissue in an alternating-current magnetic field (Gilchrist *et al*, 1957; Jordan *et al*, 1993). DM is stable as a colloid without aggregating or precipitating in various solvents or serums. We previously compared heat generation characteristics in inductive heating at a frequency of 500 kHz between DM and iron oxide, pure iron, or ferrite and reported efficient heat generation at a lower concentration using DM (Masuko *et al*, 1995, 1997). In general, a magnetic material placed in an alternating-current magnetic field generates heat by eddy current loss and hysteresis when its major axis is at the millimeter level. However, the heat generation mechanism of magnetic particles such as DM and iron oxide slightly differs. With a particle diameter at the micrometer level, eddy current loss decreases, and heat generation by hysteresis becomes predominant. With a particle diameter at the namometer level, heat generation by both mechanisms decreases, and instead, the rotation of the magnetic vector of iron oxide particles and the physical rotation of the particles themselves are considered to be major mechanisms of heat generation (Jordan *et al*, 1993; Tazawa *et al*, 1995; Wada *et al*, 2001). In inductive heating experiments in this study, DM at various concentrations injected into the pulp cavity efficiently generated heat in an alternating-current magnetic field. When the iron concentration of DM was 56 mg ml^{-1}, the mean $T^{40°C}$ was 259 s, and the mean $T^{55°C}$ was 328 s, confirming very stable operability of this system. Miserendino *et al* (1989) reported that irreversible pulp tissue changes appeared when the increase in pulp temperature from the normal state was 5.5°C or more. In our study, the maintenance of temperature at 55°C for 20 min observed suggests the possible pulp necrosis induced by this system, sufficiently. On the other hand, for damage of periradicular structures, a 10°C rise sustained for 1 min is considered compatible with normal bone repair, but the load of higher temperatures or longer application times may cause bone necrosis and its replacement with fatty tissue (Eriksson and Albrektsson, 1983; Bailey *et al*, 2004). In our study, the mean increase in temperature on the tooth surface on the coronal and apical sides during this period was 4.9° and 3.7°C, respectively. It appears that this increase is because of heat conduction from the DM generating heat in the pulp cavity, taking into account of its linear and gradual temperature rise. We speculate that the differences between apical and coronal temperature rise may be caused by the difference in the thermal conductivity between the enamel and dentin or the distance from the root canal wall to the root surface. To elucidate the strict damages of periradicular structure and thermal distribution, further *in vivo* study using an experimental animal is necessary.

According to a recent study using high-frequency electrical pulses, traditional canal shaping and cleaning are considered to be essential to eliminate residues of pulp tissue to provide a physical stimulus to the aimed site (Lendini *et al*, 2005). In our heating system, sufficient preparation of the root canal to the apex is also better for the possible DM penetration into accessory canals. Moreover, to eliminate the residual pulp of a curved root canal or a root canal in which an instrument was broken, effectual enlargement of the pulp chamber at least is necessary for the expected DM penetration into the root canal. Applying this system to such teeth with residual pulp, where instruments are difficult to reach, may allow rapid pulp deactivation and alleviation of symptoms and decrease the incidence of root canal infection. Further detailed studies on DM permeability into the pulp tissue and pulp tissue damage in animals are indispensable for the clinical application of this heating system.

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