Ultrasound in Med. & Biol., Vol. ■, No. ■, pp. 1–18, 2015

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2015.03.027

● *Original Contribution*

SIMULATION OF LOW-INTENSITY ULTRASOUND PROPAGATING IN A BEAGLE DOG DENTOALVEOLAR STRUCTURE TO INVESTIGATE THE RELATIONS BETWEEN ULTRASONIC PARAMETERS AND CEMENTUM REGENERATION

Behzad Vafaeian,* Saleh Al-Daghreer,[†] Marwan El-Rich,* Samer Adeeb,* and Tarek El-Bialy[‡]

*Department of Civil & Environmental Engineering, Faculty of Engineering, University of Alberta, Edmonton, Alberta, Canada; [†] Department of Orthodontics, Faculty of Dentistry, King Abdulaziz University, Jeddah, Saudi Arabia; and [‡] Department of Dentistry, Faculty of Medicine and Dentistry, University of Alberta, Edmonton, Alberta, Canada

(*Received* 6 *November* 2014; *revised* 12 *March* 2015; *in final form* 27 *March* 2015)

Abstract—The therapeutic effect of low-intensity pulsed ultrasound on orthodontically induced inflammatory root resorption is believed to be brought about through mechanical signals induced by the low-intensity pulsed ultrasound. However, the stimulatory mechanism triggering dental cell response has not been clearly identified yet. The aim of this study was to evaluate possible relations between the amounts of new cementum regeneration and ultrasonic parameters such as pressure amplitude and time-averaged energy density. We used the finite-element method to simulate the previously published experiment on ultrasonic wave propagation in the dentoalveolar structure of beagle dogs. Qualitative relations between the thickness of the regenerated cementum in the experiment and the ultrasonic parameters were observed. Our results indicated that the areas of the root surface with greater ultrasonic pressure were associated with larger amounts of cementum regeneration. However, the establishment of reliable quantitative correlations between ultrasound parameters and cementum regeneration requires more experimental data and simulations. (E-mail: vafaeian@ualberta.ca) © 2015 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Finite-element method, Ultrasound, Root resorption, Cementum, Dentoalveolar structure.**

INTRODUCTION

Recognized as a common side effect of orthodontic treatment, orthodontically induced inflammatory root resorption (OIIRR) may affect the outcome of successful orthodontic treatment (Al-Daghreer et al. 2014; King et al. 2011; Lopatiene and Dumbravaite 2008). Reports suggest that 93% of adolescents undergoing orthodontic treatment experience some degree of root resorption (Inubushi et al. 2013; Kurol et al. 1996). However, root resorption becomes a clinical problem when more than one-quarter of the tooth root length (1–2 mm) is resorbed. This includes moderate to severe (1–3 mm) and severe (>3–5 mm) root resorption (Inubushi et al. 2013; Lopatiene and Dumbravaite 2008). According to prevalence reports, moderate resorption was observed in 15% (Kurol et al. 1996) and 16.5% (Linge and Linge 1991) of cases. Severe root resorption was observed in 10%–20% (Levander and Malmgren 1988), 3%–5% (Bartley et al. 2011) and 1%–5% (Lopatiene and Dumbravaite 2008) of different treatment cases. In severe root resorption, adverse consequences of resorption such as tooth mobility can occur; consequently, orthodontists may potentially be subjected to malpractice claims (El-Bialy et al. 2004).

Orthodontically induced inflammatory root resorption is a pathologic process during which destruction and removal of a thin mineralized layer of cementum and dentin occur depending on the severity of the resorption (Bartley et al. 2011). The mechanism and etiology of resorption are still not fully understood. However, it is suggested that OIIRR is a multifactorial and inflammatory process related to the cellular activity triggered in response to hyalinized and compressed regions of the periodontal ligament (Al-Daghreer et al. 2014; Inubushi et al. 2013; Lopatiene and Dumbravaite 2008;

Address correspondence to: Behzad Vafaeian, Department of Civil & Environmental Engineering, Faculty of Engineering, 5-042 Markin/CNRL Natural Resources Engineering Facility, University of Alberta, Edmonton, Alberta T6G 2W2, Canada. E-mail: vafaeian@ualberta.ca

Montenegro et al. 2012; Paetyangkul et al. 2011). The process may be reversible through new cementum regeneration if OIIRR has affected only the outer layer of cementum. However, if OIIRR has affected dentin, the process is irreversible (Inubushi et al. 2013; King et al. 2011; Lopatiene and Dumbravaite 2008).

Currently, no clinically applicable methods exist for the prevention or treatment of OIIRR (Al-Daghreer et al. 2014; Inubushi et al. 2013). However, the advantages of low-intensity therapeutic ultrasound as a potential prevention method/treatment for OIIRR have recently been reported (Al-Daghreer et al. 2014; El-Bialy et al. 2004; Inubushi et al. 2013). Using a specific protocol, El-Bialy et al. (2004) found that the application of low-intensity pulsed ultrasound (LIPUS) on a human tooth subjected to orthodontic treatment not only minimized the resorption, but also led to accelerated healing of the resorption by reparative cementum. Another *in vivo* study on a group of rats subjected to tooth movement experiments indicated that LIPUS significantly reduced the resorption, with no effect on tooth movement (Inubushi et al. 2013). Recently, Al-Daghreer et al. (2014) performed an *in vivo* animal study involving the application of LIPUS to teeth of beagle dogs subjected to a 4-wk period of orthodontic forces and movements. They observed regeneration of the precementum layer, cementum and reparative cellular cementum when LIPUS was applied. In addition to the human and animal studies, *in vitro* experiments have ascertained the effect of LIPUS on the proliferation and metabolism of cementoblast (Dalla-Bona et al. 2006, 2008) and periodontal ligament cells (Harle et al. 2001).

The mechanisms underlying the observed biological response of tissues to LIPUS have not yet been fully elucidated (Padilla et al. 2014; Rego et al. 2012). If the cavitation effect (local formation of vapor phase inside a liquid) of LIPUS is ruled out because of its low intensity (Humphrey 2007; Padilla et al. 2014), then mechanical stresses, fluid microstreaming in soft tissues, piezo-electric effects in hard tissues (like bone) and thermal effects are potentially the physical phenomena driving the tissue biological response (Duarte 1983; Khan and Laurencin 2008; Padilla et al. 2014; Rego et al. 2012; Romano et al. 2009). The effect of these phenomena on the cellular reactions should be biophysically explored at the inter- and intracellular levels to gain an understanding of the mechanisms underlying the success of LIPUS. In addition, macroscale modeling through continuum theories may also be informative in determining the effective magnitude of the mechanical signals stimulating the tissue response.

From a macroscale perspective, investigating the biological effect of LIPUS requires the study of acoustic wave propagation through soft tissues by use of the continuum assumption for these tissues. In this case, the acoustic stress field, velocity field, intensity field and so on can be correlated with the tissue-scale biological responses. A clarifying example in this context is Wolff's law (Wolff 1986) when regarded as a tissue-scale phenomenon; that is, bone deposition and resorption are associated with the mechanical stresses acting on it.

Hypothesizing that acoustic fields are correlated with tissue-scale biological reactions, the aim of this study was to numerically simulate LIPUS propagation in a beagle dog dentoalveolar structure. The simulations were based on use of the finite-element method to solve the linear mechanical wave propagation in the 3-D medium of the dentoalveolar structure. The simulated pressure and energy distributions of LIPUS over the root and periodontal ligament (PDL) surfaces were compared and correlated with the available histologic data (Al-Daghreer et al. 2014) on cementum thickness for control and LIPUS-treated teeth.

METHODS

In the present study, we intended to simulate LIPUS propagation in a typical dentoalveolar structure of one of 10 beagle dogs subjected to the *in vivo* experiment carried out by Al-Daghreer et al. (2014): Under a specific LIPUS exposure protocol, they attempted to investigate the effect of LIPUS on cementum regeneration and prevention of OIIRR in 10 beagle dogs. During the experiment, the mandibular fourth premolars (both left and right) of each dog were orthodontically moved by constant orthodontic forces for 4 wk. One of the premolars was intraorally exposed to LIPUS on its buccal side (LIPUS-treated tooth). The other premolar was subjected to constant orthodontic force without LIPUS (control tooth).

The LIPUS used (SmileSonica, Edmonton, AB, Canada) was generated from a square lead zirconate–titanate transducer (1.2×1.3 cm^2) with a spatial-average temporal-average intensity of $I_{\mathrm{SATA}} = 30$ mW/cm^2. Each pulse was a 1.5-MHz sinusoidal pulse lasting 200 μs with a duty cycle (pulse duration divided by repetition time between pulses) of 0.2.

Assumptions

Compared with the experimental situation, the configurations of the simulations underwent an idealization and a simplification. The idealization comprised assumption of a uniform pressure distribution on the transducer surface directly transmitted to the corresponding gingival surface. The simplification estimated the amplitude of the uniformly distributed pressure as