Ultrasonic Dental Therapy: Trends and Prospects

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ABSTRACT
Ultrasound has been applied therapeutically, diagnostically, and surgically in medicine for many years. This paper reviews specifically the therapeutic ultrasound applications that have been used experimentally and commercially in dentistry since the mid-twentieth century. Topics included in this review are the biological/physiological processes induced by ultrasound therapy, their relation to the advancement of tissue/bone healing, and the methods/tools with which they are applied. This paper presents a direction of the development of the ultrasound transducer for dental healing.

Keywords: Ultrasound Therapy, Dentistry, LIPUS, BioMEMS, Microtransducer

1. INTRODUCTION
Ultrasound is widely recognized by the general public for its diagnostic imaging capabilities (Ng 2002); however, ultrasound is also inherent in a variety of therapeutic medical procedures that have accrued attention in recent decades. In particular, ultrasound has been used to enhance the effectiveness of drug delivery (Ng 2002), reduce the recovery time of injuries, improve muscle mobility, decrease joint stiffness, reduce muscle pain, and has been shown to accelerate and enhance bone fracture healing (Rubin 2001). Although its usefulness has been widely accepted throughout the general medical industry, ultrasound therapy is not yet deemed common practice in commercial dentistry. Researchers, however, have found uses for ultrasound therapy in dentistry. For example, by taking advantage of ultrasound’s biological effects on bone ossification, researchers have applied ultrasound therapy to promote osseointegration between dental implants and alveolar bone tissue (Li 2011). Having confirmed benefits on the ossification process, ultrasound therapy offers promising treatment options for a variety of dental procedures. Understanding the biological and mechanical effects of ultrasound on tissue repair is imperative in further implementing ultrasound therapy in dentistry. The subsequent sections of this paper detail the history of ultrasound therapy in dentistry, a summary of its physiological/biological effects, its application methods, and the current status of its procedural instrumentation. This paper concludes with a discussion on the limitations of current ultrasound instrumentation as well as trends towards miniaturization in medicine, and in particular, how miniaturized ultrasonic transducers may find utility in future dental ultrasound therapy.
2. HISTORY OF ULTRASOUND THERAPY IN DENTISTRY

2.1 Prior to 1990

The foundation of ultrasound research was laid in the late 1800s when brothers Jacques and Pierre Curie observed that high-frequency sound waves can be produced by certain crystals when subjected to an alternating current at their resonant frequency (Schortinghuis 2003). Paul Langevin in 1926 was the first to report the biological effects of ultrasound after observing the violent and fatal reaction of fish to strong ultrasound fields (Schortinghuis 2003). Ultrasound research then became the focus of many engineers and scientists but did not find therapeutic uses for a number of decades. The majority of the pioneering ultrasound use in dentistry focused on dental diagnostics, not therapy. However, in following decades ultrasound found therapeutic utility in a variety of medical fields. In the late 1940’s it was used to treat chronic osteomyelitis\(^1\), osteoradionecrosis\(^2\), and a variety of other infectious conditions (Schortinghuis 2003). Ultrasound therapy was proposed to be potentially helpful in the removal of plaque and calculus from human teeth as early as 1955 and was used not long after to treat disorders of the temporomandibular joint (Plotino 2007).

Approximately a decade after the Curie brothers’ work on ultrasound production was recorded, Julius Wolff theorized that the bones of a healthy person will adaptively remodel themselves to accommodate the types of mechanical loads that they most commonly endure—it is for this reason that practitioners of Muay Thai\(^3\) exhibit increased bone density in striking areas of their body, such as their tibias. In 1952, researchers found that an application of ultrasound can act as a surrogate to the mechanical loads that are described by Wolff’s law, enhancing the callus formation of a healing bone without posing a risk to its structural integrity (Rubin 2001). In 1957 this principle was applied specifically to mandibular fractures and was found to lessen pain and improve healing of the fracture site (Schortinghuis 2003). As an understanding of the physiological and biological effects of ultrasound on tissue began to improve, applications of ultrasound therapy to bone repair began to attract more attention in the 1980’s.

2.2 1990 - Present

In the early 1990’s ultrasound continued to be researched for its potential therapeutic effects on maxillofacial bones—the majority of these studies report favorable results (Erdogan 2006). Reports were published in the 1990’s that confirm the ability of ultrasound therapy to improve healing of mandibular fractures, treat mandibular osteoradionecrosis, and increase human gingival fibroblasts\(^4\) and mandibular osteoblast\(^5\) proliferation (Erdogan 2006). In 2004 a study was published demonstrating the ability of ultrasound therapy to gentrify the healthiness of roots that have suffered from resorption due to orthodontic tooth movement, providing a noninvasive method for reducing root resorption in humans thus minimizing orthodontic malpractice litigations (El-Bialy 2004). In 2008 and in 2011, separate studies were published hypothesizing the potential of ultrasound therapy to promote bone formation around dental implants, increasing the likelihood of successful implantation and shortening the patients rehabilitation time (Li 2008, Nakanishi 2011). Since 1990, the Journal of Endodontics has produced 19 publications to date that contain the term “ultrasound” in their abstracts. Many of these studies employ ultrasound for irrigational methods or diagnostic imaging; however, two studies published in 2012 report the use of ultrasound as a means of

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1. **Osteomyelitis**: an infection of the bone or bone marrow.
2. **Osteoradionecrosis**: the absence of reparative capacity of bone due to radiation therapy.
3. **Muay Thai**: a combat sport focused on striking, similar to kick boxing.
4. **Fibroblast**: a cell common in connective tissue; important in wound healing.
5. **Osteoblast**: a type of fibroblast responsible for bone formation.
therapeutic intervention. One of which applied a combination of ozone and ultrasonic agitation to endodontic disinfecting procedures as a means of treating root canals (Case 2012). Another study characterized the biological influences of low-frequency ultrasound on dental tissues and concluded that the observed effects, particularly those on odontoblast-like cell proliferation and differentiation, may provide a therapeutic means of repairing dental pulp and dentine (Man 2012). This increasing repository of clinical work supporting ultrasound therapy has opened the door to a variety of promising studies and potential uses for ultrasound in dentistry. And according to a prospective review on dental ultrasound applications published in 2012, continuing advances in ultrasound therapy will likely yield exciting future developments given sufficient focus on instrumentation and procedural improvements (Rai 2012).

3. PHYSIOLOGICAL/BIOLOGICAL EFFECTS OF ULTRASOUND THERAPY

In order to fully appreciate ultrasound as a therapeutic tool in dentistry, it is helpful to get an understanding of its biological effects on bone and other tissues. Ultrasound is an acoustic pressure wave with a frequency that exceeds the upper limit of the human hearing range. As an ultrasonic wave passes through tissue, changes may occur in the biological system due to heat, acoustic microstreaming, radiation forces, etc. (Schortinghuis 2003). It is suggested that the minute vibrations caused by ultrasound irradiation give some biological signals to cells which elicit healing responses during bone formation. The energy absorbed by tissue advances fluid movement across surfaces—a process known as acoustic streaming—which may mechanistically enhance signal-transduction pathways (Rubin 2001). At the most basic level, this enhancement in fluid movement leads to an increase in nutrient delivery and waste removal at the healing site (Rubin 2001). This acoustic streaming may also modify the local environment of a cell causing an alteration in the concentration of gradients near an extracellular membrane; this concentration change may ultimately account for recorded changes in potassium and calcium content of cells after an exposure to ultrasound (Ter Haar 1999). It is worth noting that because protein molecules absorb ultrasound energy at different rates collagenous tissues can be targeted directly and preferentially, enhancing precision of ultrasonic applications (Ter Haar 1999). Although the entire causal pathway between ultrasound therapy and its effects on healing tissue is unknown, the differential absorption between tissues may be what establishes the sufficient mechanical strain and micromotion to stimulate periosteal bone formation (Li 2008).

Ultrasound therapy has also been demonstrated to stimulate growth factors, up-regulate bone proteins, and increase specifically the production of vascular endothelial growth factor (VEGF); these effects play an essential role in the maintenance and repair of dental tissues, osteoclast\(^6\) differentiation, bone resorption, and possibly the dentine\(^7\)-pulp\(^8\) complex (Scheven 2009). This makes ultrasound a novel candidate for the stimulation of dentine regeneration and a variety of other therapeutic dental applications.

4. METHODS AND INSTRUMENTATION OF ULTRASOUND THERAPY IN DENTISTRY

Ultrasound in medicine is applied at a variety of frequencies with varying instrumentation and methodologies. As the understanding of ultrasound’s effects on biological tissue has evolved, so have the instrumentation with which ultrasound is applied. Handheld ultrasonic instrumentation was first introduced to dentistry in 1955 as a probe design that was suggested in the form of a modified scaling tip for cavity preparations (Nakanishi 2011). It was first realized and demonstrated in 1957 and ultrasonic scalers of this type still find wide clinical use today (Laird 1991).

\(^6\) Osteoclast: the complement to osteoblasts; responsible for bone resorption.

\(^7\) Dentine: hard, major portion of the tooth; between the pulp cavity and the enamel.

\(^8\) Pulp: softer, inner substance of the tooth containing arteries, veins, nerves, etc.
Although they are used primarily for dental diagnostics, the majority of ultrasound utilization in dentistry is realized by virtue of dental handpieces. There are two fundamental methods of ultrasound production used in dentistry; magnetostriction and piezoelectric manipulation. Magnetostriction converts electromagnetic energy into mechanical energy by virtue of vibrations in magnetostrictive metal strips produced via an alternating magnetic field (Plotino 2007). Ultrasound production of the piezoelectric variety stems from an understanding of the dimensional change of crystals when applied with an electric charge; an observation first reported by the aforementioned Curie brothers.

Early handheld ultrasonic units in dentistry relied on magnetostriction and had tips that moved in an elliptical motion, less desirable for either surgical or endodontic\textsuperscript{9} use; a transition to piezoelectric units offered the advantage of more cycles per second and less heat generation (Plotino 2007). Further benefits of piezoelectric units include their light weight and their lack of reliance upon water cooling (Kwan 2005). Magnetostrictive technology is still widely used as it is generally more affordable than piezoelectric; it is also preferred by some due to the convenience of its pop in/out inserts, as opposed to piezoelectric devices’ non-recyclable screw-in tips (Kwan 2005). Further, magnetostrictive handpieces offer swivel capabilities, superior power distribution, and are amenable to manual tuning (Kwan 2005).

In 2004 researchers utilized a 2.5 cm lead zirconate-titanate transducer equipped with acoustic absorbers to create an acoustic window in the transducer’s center; they then applied low-intensity pulsed ultrasonic stimulation (LIPUS) to treat orthodontically induced root resorption (El-Bialy 2004). In 2011 a report was published detailing the application of ultrasound therapy to dental implants using a portable tabletop-style ultrasound device with a commercially available handheld transducer (Nakanishi 2011). These portable devices are widely available and commonly used today for ultrasonic therapy in a variety of clinical settings.

The dosages for ultrasound therapy vary widely. The frequency and intensity of ultrasound when used therapeutically is much smaller than that used for general imaging, but the exact exposures used in clinical trials are determined empirically depending upon the depth and type of the target to be treated. Most physiotherapy ultrasound units are capable of maintaining transducer operation frequencies between 0.75 and 5 MHz and offer spatial average intensities up to 3 W·cm\textsuperscript{-2} and (Ter Haar 1999), however, frequencies as low as 30 kHz applied at a variety of intensities have been shown to successfully upregulate the VEGF expressions and secretion useful for tissue repair and regeneration (Scheven 2009). Pulse exposures are often chosen to minimize thermal effects. Commonly available pulsing regimes on commercially available physiotherapy units are 2:2 and 2:8 (Ter Haar 1999), however a large diversity of pulse regimes have shown to be effective in clinical trials.

5. MINIATURIZED ULTRASOUND DEVICES

Each of the aforementioned therapeutic ultrasonic instrumentation requires a coupling medium between the target and transducer and is often awkwardly applied. This is especially true in cases requiring prolonged dosages on uneven or hard-to-reach surfaces. For lengthy ultrasonic exposures researchers have attached transducers to patients by a variety of means, including adhesives and Velcro. If therapeutic ultrasound applications are to be further incorporated into commercial dentistry, patients’ comfort levels must be more heavily considered. A shift in ultrasound applications towards miniaturized instrumentation provides the possibility of increasing patient comfort during treatment. Further, miniaturized therapeutic instrumentation offer the benefit of requiring less operating power and being implantable. Once implanted, the miniaturized instrumentation is amenable to outpatient dosage administration by simple activation or deactivation of the ultrasonic device. Dosages administered at home require fewer doctor visits and ultimately

\textsuperscript{9} Endodontics: a branch of dentistry concerned specifically with dental pulp.
save patients’ time and money. It is foreseeable that miniaturized ultrasonic transducers may have the potential to improve patients’ therapy experience as well as the precision and convenience of their dosages.

Implantable ultrasonic stimulators can be positioned by a physician at an ideal location tailored to each patient’s therapeutic needs, where it may remain during the entirety of treatment (Bock 1996). This would allow the patient to administer dosages accurately, without requiring the dexterity or skill necessary in general ultrasonic therapy (Bock 1996). There are a variety of reasons a patient may need dental implants, such as tooth loss from periodontal disease, and dental implants have been installed often in recent decades (Li 2008). Rehabilitation can be uncomfortable, lengthy, and susceptible to bacterial infection (Bock 1996). A reduction in rehabilitation time is imperative to increasing procedural success rate and patient comfort (Li 2008). In such dental implant procedures, posts are installed into the jawbone onto which artificial teeth are attached by means such as cementing or screwing; being that LIPUS has been hypothesized to improve the osseointegration between dental implant posts and the jawbone (Li 2008), an miniature implantable ultrasonic stimulator embedded between the post and implant crown may provide a cost effective means of reducing rehabilitation time, increasing patient comfort, and further advancing ultrasonic therapy in dentistry.

6. DISCUSSION

Ultrasound therapy has been proven to enhance the speed and success rate of healing in a variety of injuries and bone infections. Beginning in the mid-twentieth century, dental ultrasound therapy instrumentation has progressed from basic tools to portable handheld transducers with increasing precision, features, and usability. Although the dosages and methods with which ultrasound therapy is applied vary widely, the majority of successful clinical trials used low-intensity pulsed ultrasonic stimulation. Current ultrasound usages in dentistry often manifest themselves as dental diagnostic procedures but the repository of studies supporting therapeutic benefits suggests that ultrasound therapy in dentistry will likely become more common. Further research is necessary to clarify the exact cellular response of the dentine-pulp complex to ultrasound therapy; however, the understanding of the biological/physiological mechanisms driving ultrasound’s interaction with tissues in general has evolved sufficiently in the last century such that further advancements in dental therapeutic ultrasound are to be expected. It’s foreseeable that these advances may take the form of miniaturized implantable transducers, given their potential for benefiting the cost, comfort, convenience, and precision of ultrasonic dosages.

REFERENCES


