Ultrasonics Sonochemistry xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Ultrasonics Sonochemistry

journal homepage: www.elsevier.com/locate/ultson

Sonochemical and high-speed optical characterization of cavitation generated by an ultrasonically oscillating dental file in root canal models

R.G. Macedo [a,*], B. Verhaagen [b], D. Fernandez Rivas [c], J.G.E. Gardeniers [c], L.W.M. van der Sluis [d], P.R. Wesselink [a], M. Versluis [b]

[a] Department of Cariology, Endodontology & Pedodontology, Academic Center for Dentistry Amsterdam, University of Amsterdam and VU University, Gustav Mahlerlaan 3004, 1081LA Amsterdam, The Netherlands
[b] Physics of Fluids Group and Institute for Biomedical Technology and Technical Medicine MIRA, University of Twente, P.O. Box 217, 7500AE Enschede, The Netherlands
[c] Mesoscale Chemical Systems Group, MESA+ Research Institute, University of Twente, P.O. Box 217, 7500AE Enschede, The Netherlands
[d] Department of Conservative Dentistry and Endodontics, Paul Sabatier University, 3 chemin des Maraîchers, 31062 Toulouse, France

A R T I C L E I N F O

Article history:
Received 24 September 2012
Received in revised form 25 February 2013
Accepted 2 March 2013
Available online xxxx

Keywords:
Dentistry
Endodontics
Ultrasonic cleaning
Cavitation
Sonoluminescence
Sonochemiluminescence

A B S T R A C T

Ultrasonically Activated Irrigation makes use of an ultrasonically oscillating file in order to improve the cleaning of the root canal during a root canal treatment. Cavitation has been associated with these oscillating files, but the nature and characteristics of the cavitating bubbles were not yet fully elucidated. Using sensitive equipment, the sonoluminescence (SL) and sonochemiluminescence (SCL) around these files have been measured in this study, showing that cavitation occurs even at very low power settings. Luminol photography and high-speed visualizations provided information on the spatial and temporal distribution of the cavitation bubbles. A large bubble cloud was observed at the tip of the files, but this was found not to contribute to SCL. Rather, smaller, individual bubbles observed at antinodes of the oscillating file with a smaller amplitude were leading to SCL. Confinements of the size of bovine and human root canals increased the amount of SL and SCL. The root canal models also showed the occurrence of air entrainment, resulting in the generation of stable bubbles, and of droplets, near the air–liquid interface and leading eventually to a loss of the liquid.

1. Introduction

Ultrasound is frequently used in dentistry in a wide range of therapeutic applications. Examples are the cleaning and disinfection of the inner and outer surface of a tooth, termed root canal therapy and periodontal scaling, respectively [1]. Ultrasonic agitation of disinfecting solutions in the root canal is called Ultrasonically Activated Irrigation (UAI) [2]. It has been shown to improve the chemical and mechanical efficiency of root canal cleaning procedures [2,3] and it promotes organic tissue dissolution during endodontic therapy [4]. In UAI an endodontic instrument is driven at 30 kHz and it has been shown to induce acoustic microstreaming and cavitation. These two phenomena are claimed to be the working mechanisms of ultrasonic irrigation [5–7].

The occurrence of cavitation during UAI has been discussed frequently over the past two decades. Cavitation has been demonstrated to occur around ultrasonically oscillating endodontic instruments in an unbounded medium [7–13]. Ahmad et al. [9] argued that cavitation is unlikely to occur inside the root canal, because space restrictions limit the amplitude of oscillation of the endodontic file. In a recent article [14], however, cavitation was shown to occur around the tip of an ultrasonically oscillating file, even within the confinement of a root canal, although only at high driving powers that are not commonly used clinically. Cavitation may also cause the enhancement of sonochemical reactions around dental scalers [7]. However, no clear data on the number, size, location and nature of cavitating bubbles during UAI exists. Furthermore, it is unclear how the confinement of the root canal affects the formation of cavitating bubbles.

Other than in pure liquids, cavitation is typically generated from nuclei, small pockets of air trapped in hydrophobic dirt particles or crevices in a wall. Bubbles can grow when the applied pressure drops below the ambient pressure minus the vapor pressure of the liquid [15,16]. The negative pressure needs to be generated by the oscillating endodontic file, similar to hydrodynamic cavitation which is known to occur for ship propellers and pumps[11,17–19]. The file moves with an oscillatory velocity $U = 2\pi fA$ (with f the oscillation frequency and A the amplitude of oscillation) and the fluid around the file is assumed to have a similar velocity. Near the trailing edge of the file, the fluid velocity equals zero, leading to low-pressure areas there [20]. The potential for cavitation to be generated is then characterized by the cavitation number Ca [15]:

* Corresponding author. Tel.: +31 614481420.
E-mail address: r.macedo@acta.nl (R.G. Macedo).

1350-4177/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultsonch.2013.03.001

$$Ca = \frac{P_{\text{ambient}} - P_{\text{vapor}}}{\frac{1}{2}\rho U^2} \quad (1)$$

where ρ is the density of the liquid. Under the condition that nuclei with radii larger than a critical radius are available, cavitation can occur when $Ca < 1$, for which the velocity needs to exceed 15 m/s [15] in water. The typical frequency of oscillation for endodontic devices is 30 kHz, thus the threshold oscillation amplitude is approximately 80 μm. This is a value that endodontic devices are able to reach at high power settings [21,22].

A distinction can be made between transient cavitation, involving a violent collapse of a bubble, and stable cavitation, which involves more gentle radial oscillations [15]. Typically, transient cavitation is involved in sonochemistry (chemistry induced by sonication) [23–25] and surface modifications (cleaning, erosion) [26], whereas stable cavitation can lead to local enhancement of streaming and mixing [27,28].

It is also known that transient cavitating bubbles can emit light (*sonoluminescence*, SL) [29–32]. For SL to occur, the pressure and temperature conditions inside the collapsing bubble have to satisfy the conditions for ionization and subsequent light emission [33]. $OH^{\cdot}$ radicals are formed when the conditions inside a bubble allow for the dissociation of water molecules (with dissociation energy $\Delta H = -5.1$ eV):

$$H_2O \overset{\Delta H=-5.1\ \text{eV}}{\rightarrow} OH^{\cdot} + H^{\cdot} \quad (2)$$

Some chemiluminescents react with $OH^{\cdot}$ radicals and produce light emission, a process known as *sonochemiluminescence* (SCL) [34,35]. Cavitating bubbles can generate SL or SCL, or both [36]; the population of SL and SCL active bubbles are not exactly the same and can strongly overlap [37–39]. The light emissions are generally faint, although SCL signals can be several orders of magnitude more intense than SL [37]. Dark conditions and the use of sensitive photo-multipliers are needed in order to detect SL or SCL, which then provide a measure of the amount of SL or SCL producing cavitation bubbles. Long exposure photography can be used as well, to obtain information on the spatial distribution of cavitating bubbles that produce SCL [40]. Temporal information on the cavitating bubbles can be obtained e.g. with a passive acoustic detector [41,42], however here we will use high-speed imaging [43], in order to obtain information on both spatial and temporal scales, and on the nature and onset of cavitation around the oscillating endodontic file.

The aims of this study were to quantify and to visualize the occurrence of cavitation around endodontic files. Using sensitive sonochemical methods for detecting SL and SCL, the occurrence of cavitation at various power settings is investigated, as well as the influence of the confinement of the root canal. Using a range of file types, the influence of different cross-sectional shapes, diameters and lengths of files on SL and SCL are studied. Measurements of the acoustic power density radiated by those files are provided by calorimetry. The SL and SCL measurements can provide information on the nature and characteristics of the bubbles. Long-exposure SCL photography and high-speed imaging provide additional visual support on the location and behavior of cavitating bubbles at different operation and confinement conditions.

2. Materials and methods

2.1. Ultrasound setup

A light-tight box with dimensions $1.2 \times 1.0 \times 0.5$ m was constructed (see Fig. 1); dark conditions inside were verified by long-exposure photography. Inside the box, an endodontic file was positioned in a $1.0 \times 1.0 \times 4.0$ cm cuvette (Plastibrand, Brand, Wertheim, Germany) or in a glass root canal (RC) model of bovine or human dimensions, manufactured in-house. The models were submerged and fixed inside the cuvette. The bovine-sized model was a cylindrical closed-end tube of diameter 2.3 mm and a length of 29 mm. The human-sized model was a cone of apical diameter 0.3 mm, a taper of 6% and a length of 20 mm. The two root canal models allowed for the investigation of the influence of confinement on the occurrence of cavitation. The light transmission coefficient through these glass models was measured and corrected for.

Fig. 2 shows a picture of an endodontic file and the different cross-sections; Table 1 gives an overview of the various files that have been tested. The first number in the name of the file indicates the diameter ($\times 10$ μm), the second number indicates the length (in mm). The K-files (Satelec Acteon, Merignac, France) have a square cross-section and are twisted along the length of the file, leading to rotation of the cross-section; the orientation of the cross-section at the tip of the file varies. The IrriSafe (IS) files (Satelec Acteon) also have a square cross-section but with rounded edges (with a radius of curvature of approximately 0.25× file radius); the ET25L (Satelec Acteon) has a circular cross-section [44]. One K-file (K15/25) was polished by the manufacturer to the same cross-section as IrriSafe files, in order to compare directly the influence of cross-section.

All files were driven with a commercially available endodontic ultrasound device (P-Max, Satelec Acteon, Merignac, France). The power settings on that device range (from low to high) from 'Green' via 'Yellow' and 'Blue' to 'Red', each with 10 steps. A previous study showed that the oscillation amplitude increased with power settings, with overlap between '10' and '1' in consecutive power color settings [14]. In the sonochemical experiments, the power setting was either increased (three measurements) or decreased (three measurements) between consecutive experiments, in order to investigate the presence of hysteresis. Each measurement group was measured three times; for each measurement a new file and fresh irrigant were used. Files that were suspected to have fractured (apparent from a sudden drop in SL/SCL signal) were also replaced.

The ultrasound device was switched on and off in cycles with a period of 10 s, consisting of 3 s ON and 7 s OFF (duty cycle of 30%). The rest phase in between pulses allows the fluid to return to its initial state with respect to its temperature and gas content. These pulses were generated with a pulse-delay generator (TGP110, TTi, Huntingdon, UK).

2.2. Sonoluminescence and Sonochemiluminescence

For measurements of the sonoluminescence (SL), the cuvette and root canal models were filled with MilliQ air–saturated water. A photomultiplier tube (PMT; R508, Hamamatsu Photonics, Hamamatsu, Japan) was placed next to the cuvette. The PMT received an electrical voltage of 1.6 kV from a DC power supply (6516A, Hewlett–Packard, Palo Alto, CA, USA). The PMT output was recorded at a rate of 300 kHz with a high-speed data acquisition device (DAQ; USB-6356, National Instruments, Austin, TX, USA), which was also recording the pulse signal. Calibration showed a linear response of the PMT up to an output voltage of 1 V, above which saturation occurs. Typical pulse and PMT signals are shown in Fig. 1c. The PMT signal was filtered with a running average with Gaussian weighing over 11 samples; the average value during each pulse was used as final SL or SCL value.

For sonochemiluminescence (SCL), air–saturated aqueous luminol (0.1 mM luminol in 0.1 M NaOH [both Merck, Whitehouse Station, NJ, USA]) solution was used, of which more details can be found elsewhere [37]. The SCL signal was measured using the same PMT equipment as for SL. Simultaneously, photos near the file were taken with a CMOS photocamera (D300, Nikon, Tokyo, Japan) and 50 mm, f/1.8 lens (Nikon) with an aperture of 1.8. The camera

Please cite this article in press as: R.G. Macedo et al., Sonochemical and high-speed optical characterization of cavitation generated by an ultrasonically oscillating dental file in root canal models, Ultrason. Sonochem. (2013), http://dx.doi.org/10.1016/j.ultsonch.2013.03.001