Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Research Paper

An experimental and computational study of the hydrodynamics of high-velocity water microdrops for interproximal tooth cleaning

A. Rmaile[a,*], D. Carugo[b], L. Capretto[b], J.A. Wharton[a], P.J. Thurner[b], M. Aspiras[c], M. Ward[c], M. De Jager[d], P. Stoodley[a,e]

[a]nCATS, Faculty of Engineering and the Environment (FEE), University of Southampton, UK
[b]Bioengineering Science Research Group, Faculty of Engineering and the Environment (FEE), University of Southampton, UK
[c]Philips Oral Healthcare Inc. (POH), Bothell, WA, USA
[d]Philips Research, Oral Healthcare Research, Eindhoven, The Netherlands
[e]Center for Microbial Interface Biology, Departments of Microbial Infection and Immunity, and Orthopaedics, The Ohio State University, Columbus, OH, USA

ARTICLE INFO

Article history:
Received 24 November 2014
Received in revised form 28 January 2015
Accepted 1 February 2015
Available online 21 February 2015

Keywords:
Oral hygiene
Streptococcus mutans
Micro-computed tomography
Computational fluid dynamics
Dental plaque
Biofilm

ABSTRACT

The flow field and local hydrodynamics of high-velocity water microdrops impacting the interproximal (IP) space of typodont teeth were studied experimentally and computationally. Fourteen-day old *Streptococcus mutans* biofilms in the IP space were treated by a prototype *AirFloss* delivering 115 μL of water at a maximum exit-velocity of 60 m s^{-1} in a 33-ms burst. Using high-speed imaging, footage was generated showing the details of the burst, and demonstrating the removal mechanism of the biofilms. Footage was also generated to characterize the viscoelastic behavior of the biofilms when impacted by an air-only burst, which was compared to the water burst. Image analysis demonstrated the importance of fluid forces on the removal pattern of interdental biofilms. X-ray micro-Computed Tomography (μ-CT) was used to obtain 3D images of the typodont and the IP spaces. Computational Fluid Dynamics (CFD) simulations were performed to study the effect of changing the nozzle position and design on the hydrodynamics within the IP space. Results confirmed our previous data regarding the wall shear stress generated by high-velocity water drops which dictated the efficacy of biofilm detachment. Finally, we showed how CFD models could be used to optimize water drop or burst design towards a more effective biofilm removal performance.

*Corresponding author.
E-mail address: amir.rmaile@gmail.com (A. Rmaile).

http://dx.doi.org/10.1016/j.jmbbm.2015.02.010
1751-6161/

1. Introduction

Dental caries is formed in part due to acids produced by oral bacteria metabolizing fermentable sugars such as sucrose, glucose or fructose (Moore, 1983; Touger-Decker and van Loveren, 2003). The formation of dental plaque biofilms by these bacteria plays a major role in the etiology of dental caries (Jakubovics et al., 2014; Van Houte, 1994; Marsh et al., 2011). Microelectrode studies show that through respiration and fermentation acidophilic bacteria in dental plaque biofilms can create highly localized acidic anaerobic microenvironments on the underlying enamel, where the pH can drop below 5 within 5 min of a sucrose pulse (Von Ohle et al., 2010). If allowed to proliferate at, or below, the gum line, plaque can also cause gingivitis and periodontitis, and are also associated with pre-term delivery, low birth weight and endocarditis (Bjarnsholt et al., 2011).

Resistance of bacterial biofilms to mechanical clearance is a likely basis of the tenacity of biofilm infections (Stewart, 2014). Mechanical removal through multiple daily toothbrushing is an established method of managing dental plaque; however, even with good practice plaque can build up in difficult-to-reach areas, such as the interproximal (IP) spaces between the teeth. String flossing and IP brushes are used to help remove plaque from the IP spaces and prevent the plaque build-up to protect against the formation of cavities on the proximal surfaces of the teeth. Another mechanical approach for controlling biofilm accumulation is the use of fluid shear stress (Stewart, 2012), where the removal of biofilm can be obtained by generating sufficiently high fluid shear forces (Sharma et al., 2005; Paramonova et al., 2009; Rmaile et al., 2013). High-velocity water droplets (Cense et al., 2006; Rmaile et al., 2014), entrained air bubbles (Sharma et al., 2005), water jets generated by oral irrigation (Lyle, 2011), and currents in the fluid surrounding the teeth generated by powered brushing (Adams et al., 2002) have also been shown to be able to remove bacteria and biofilms from surfaces. More recently the use of high-velocity micro-drops has been introduced for removing IP plaque to create sufficient shear and normal mechanical forces whilst minimizing time and water volume (Rmaile et al., 2013, 2014).

We previously reported the influence of high-velocity water microdrop impact on the detachment of artificial plaque from the IP spaces of a typodont model to demonstrate how a real biofilm might detach (Rmaile et al., 2013). We also reported an experimental and numerical study on the impact of high-velocity water microdrops on the detachment of *Streptococcus mutans* biofilms from the same typodont model (Rmaile et al., 2014). In the present research we use the same in-vitro model to better characterize the hydrodynamics of high-velocity water microdrops, and employ computational fluid dynamics (CFD) to model and predict the flow field in the IP space and the spatial distribution of wall shear stress over the tooth surface by varying the nozzle shape and placement. The research we reported previously (Rmaile et al., 2014) aimed at quantifying biofilm removal, using confocal microscopy as the main technique to measure the biofilm remaining at the end point of the exposure to the high-velocity burst. The experimental work reported in the present manuscript is instead based on experimental high-speed videography, with the aim of characterizing the detachment process of viscoelastic biofilms, and the high-speed hydrodynamics of the burst and its interaction with the biofilm.

2. Materials and methods

2.1. *Bacteria and growth media*

Biofilms were grown from *Streptococcus mutans* UA159 (ATCC 700610). Stock cultures of *S. mutans* were stored at −80 °C in 10% glycerol in physiological buffered saline (PBS, Sigma-Aldrich, UK). Biofilms were cultured using sucrose (2% w/v) supplemented brain heart infusion (BHI+S) medium (Sigma-Aldrich, UK) and incubated at 37 °C and 5% CO_2.

2.2. *Typodont model*

A realistic anatomical geometry of the IP space of patients suffering from periodontitis was recreated by growing biofilms on teeth 8 and 9 (i.e., the upper central incisors) removed from a training typodont (A-PZ periodontal dental model 4030025, Frasaco GmbH, Germany). The typodont teeth were autoclave sterilized and then placed in Falcon tubes (Fig. 1A). An inoculum was prepared by adding 0.5 mL of *S. mutans* from the stock solution to 10 mL of sterile BHI

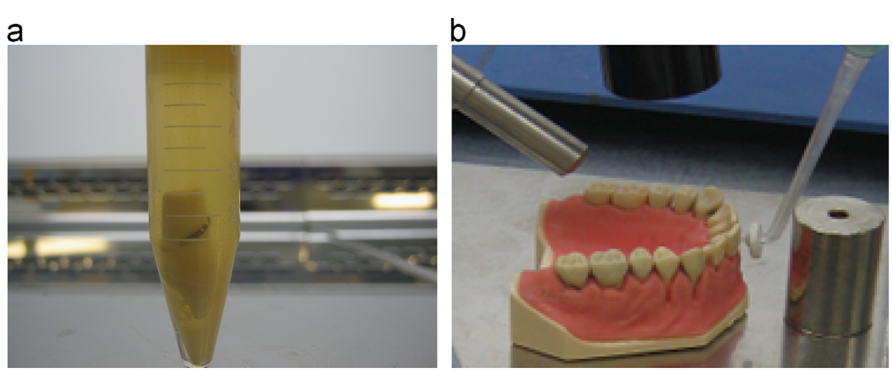

Fig. 1 – (a) Photograph showing a typodont tooth in a Falcon tube, where fresh medium with a new bacterial inoculum was added daily to grow the biofilm on the proximal surfaces. (b) Photograph showing the experimental set-up and the position of each of the pt-*AirFloss*, high-speed camera (in black), and the light source with respect to the typodont.