JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 30 (2014) 176–185

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Research Paper

# Revealing the structural and mechanical characteristics of ovine teeth

Simona O'Brien[a], Amanda J. Keown[b], Paul Constantino[c], Zonghan Xie[d], Mark B. Bush[b,*]

[a]Perth Institute of Business and Technology, Edith Cowan University, Joondalup, WA 6027, Australia
[b]School of Mechanical and Chemical Engineering, The University of Western Australia, Crawley, WA 6009, Australia
[c]Department of Biology, Marshall University, Huntington, WV, USA
[d]School of Mechanical Engineering, The University of Adelaide, North Terrace, SA 5005, Australia

ARTICLE INFO

*Article history:*
Received 1 August 2013
Received in revised form
10 November 2013
Accepted 12 November 2013
Available online 19 November 2013

*Keywords:*
Ovine
Sheep
Molar
Tooth properties
Enamel
Dentin
Indentation

ABSTRACT

The survival and function of dentition over the lifetime of an animal depends upon the ability of the teeth to resist wear and chemical erosion, and to withstand occlusal loading conditions without suffering debilitating fracture. Understanding how geometrical factors (radius, height, enamel thickness) and mechanical properties of the dental tissues (Young's modulus $E$, hardness $H$ and toughness $K_{IC}$ of enamel and dentin) combine to ensure the survival of an animal's teeth can provide great insight into the evolutionary history of the animal and its dietary adaptation. While the geometrical factors are beginning to be understood, the range of animals for which measurements of dental tissue properties are available is very narrow, being restricted almost entirely to humans and other primates. The absence of comparative data across a broader range of species makes it impossible to draw conclusions with any certainty. The present study expands knowledge of mammalian dental tissue properties by reporting the Young's modulus and hardness of ovine (sheep) enamel and dentin measured using nano-indentation.

We found that sheep molar enamel Young's modulus and hardness are both lower than those of human enamel, by approximately 30%, and 9% respectively, while the properties of dentin are similar. The combination of $E$ and $H$ makes the ovine enamel approximately 30% more resistant to wear than human enamel, which is an imperative in ruminant dentition. The results of this study are interpreted in terms of the ovine feeding ecology, and the structure of the ovine molar and its occlusal surface.



## 1. Introduction

Mammalian teeth take many different forms, shapes and sizes representing adaptations to the task of collecting and processing a wide range of foodstuffs. The ability of the animal to satisfy its nutritional requirements over a lifetime depends on the capacity of its teeth to function without suffering debilitating damage. Primates, for example, have rounded 'bunodont' molars, with a tooth height to radius ratio typically in the range 1–1.5, and a relatively thick

*Corresponding author. Tel.: +61 8 6488 7259.
E-mail address: mark.bush@uwa.edu.au (M.B. Bush).

1751-6161/$ - see front matter 
http://dx.doi.org/10.1016/j.jmbbm.2013.11.006

enamel layer. Bunodont teeth are also found in otters, pigs and some other mammals (Janis and Fortelius, 1988; Popowics et al., 2001, 2004; DeGusta et al., 2003; Lucas, 2004). The hard, stiff enamel provides the structural resistance to withstand high bite forces, and the tooth shape provides a crushing and grinding capability to process a variety of foodstuffs, from tough, soft foods (like raw meat or fibrous fruits) to hard, brittle foods (such as nuts). The enamel is brittle and susceptible to fracture when overloaded, however the tooth structure and the mechanical properties of the enamel act to contain damage. The mechanics of such fracture is now well documented (Lucas et al., 2008; Chai et al., 2009, 2011; Lawn and Lee, 2009; Constantino et al., 2010, 2011; Lee et al., 2010; Barani et al., 2011; Keown et al., 2012).

Understanding how geometrical factors (radius, height, enamel thickness) and mechanical properties of the tooth components (Young's modulus, hardness and toughness) affect the load bearing capacity and wear resistance can provide great insight into the evolutionary history of the animal and its dietary adaptation (Janis and Fortelius, 1988; Lucas et al., 2008; Constantino et al., 2011, 2012). Simple but powerful relationships have been developed for estimating fracture loads in primate molar teeth, which may be used to infer bite loads (Constantino et al., 2010; Barani et al., 2011, 2012; Chai et al., 2011; Keown et al., 2012). These relationships highlight the importance of tooth radius and enamel thickness as factors in resisting longitudinal cracking.

The mechanical properties of dental tissues also play a role in supporting the required bite loads, while resisting fracture. In the case of primates, it has been found that the modulus and hardness of enamel are remarkably uniform across species (Constantino et al., 2012). Changes in load bearing capacity have therefore largely been achieved by varying tooth size (radius) and enamel thickness. For example, both the gorilla and orangutan have enamel and dentin with properties similar to those of humans, yet the bite load capability is considerably higher. The higher occlusal loads are sustained by the considerably larger radius of the teeth.

The California sea otter also possesses a bunodont molar shape, but uses its teeth primarily to break down shellfish. Preliminary tests indicate that otter enamel may be less stiff and less hard than human enamel, but with higher toughness (Constantino et al., 2011). Furthermore, the average enamel thickness is half that of humans and the first molar radius is 50% greater. Interestingly, this combination of properties and geometry has produced a structure capable of withstanding bite loads similar to that of humans. While the differences in material properties between otters and primates may be a result of phylogeny rather than function, the combination of geometry and properties provides effectively similar capabilities for survival.

A complete understanding of tooth form and function therefore requires knowledge of how tooth geometry influences its capacity to withstand load, but interpreted in the light of the specific material properties of the tooth components. Nonetheless, the range of animal species for which mechanical properties of dentin and enamel has been reported is remarkably narrow. Significant information is now available on the properties of tooth tissues in humans (Cuy et al., 2002; Bajaj and Arola, 2009; Constantino et al., 2012), a range of other primates (Lee et al., 2010; Constantino et al., 2012) and the California sea otter (Constantino et al., 2011). The only ruminant for which mechanical properties of dental tissue have been reported is the cow (Ang et al., 2010; Bechtle et al., 2010a, 2010b, 2010c).

Most studies have produced measurements of modulus and hardness, generally obtained by micro-indentation. Measurements of toughness are more problematic and less common. Micro-indentation can be used to obtain point-by-point measurements of toughness (Anstis et al., 1981; Imbeni et al., 2005; Constantino et al., 2011). However, perhaps the most comprehensive study of toughness gradients in human enamel was undertaken using compact tension specimens cut from human molar enamel (Bajaj and Arola, 2009). A similar approach has been used to measure toughness of bovine incisor enamel, by applying bending to a notched micro-beam cut from the enamel (Ang et al., 2010; Bechtle et al., 2010a, 2010b, 2010c). The modulus of the enamel was also measured as an adjunct to determining the toughness, and was obtained using beam bending or uniaxial compression techniques applied to a segment of the enamel. These methods provide a measure of the average modulus of the bulk material, which can differ considerably from the local property measured by indentation. As a result, these bovine enamel modulus measurements cannot be compared directly with the indentation results from other animals, rendering cross species comparisons problematic.

The present study expands knowledge of non-primate dental tissue properties by measuring elastic modulus and hardness of ovine enamel and dentin using nano-indentation. We compare the measured properties with those of other animals and discuss the biological implications of the observed properties.

## 2. The structure and function of the ovine (sheep) molar

The ovine molar tooth has a columnar structure, consisting of two or three lobes fused together to form one tooth. A photograph of a typical molar used in this study is shown in Fig. 1. A diagram of the cross section is given in Fig. 2a and a photograph of an actual cross section in Fig. 3.

The enamel not only encloses the dentin, but also penetrates the dentin body to form internal enamel walls separated by a thick layer of cementum (Every et al., 1998). The result is a complex cutting and grinding occlusal surface made up of substances with differing properties (enamel, dentin and cementum) and featuring sharp projections of the harder enamel ('shearing crests'). The average lobe radius measured on the molar teeth used in this study was 4.1 mm and the average exterior enamel thickness was 0.58 mm. The enamel was notably thicker on the buccal side of the tooth (0.73 mm) compared to the lingual side (0.45 mm). The thin internal enamel wall on the buccal side of the cementum cavity had an average thickness of just 0.1 mm. The wall on the lingual side on the cavity was 0.53 mm thick.

Sheep and other ruminant animals, such as cattle and deer, have a much more specialized diet (grasses) than most primates, yet they lack the enzymes to break down cellulose.