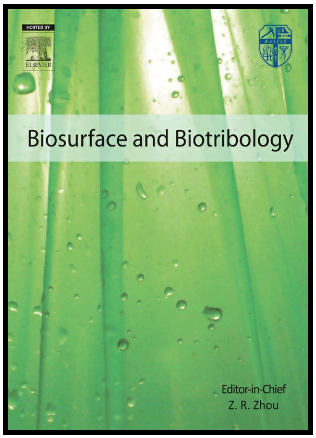

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Dental biotrobiology: Final thoughts and future directions

By

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This journal and the Tribology Research Institute at Southwest Jiaotong University hosted a workshop on dental biotribology in Chengdu, China on 20-22 October, 2017. The principal aim of the workshop was to bring together biotribologists and evolutionary biologists who study tooth wear. The first two days of the workshop were devoted to presentations, and the third day entailed an open discussion among workshop participants of how these disciplines might inform one another, and what directions we might take moving forward, with an eye toward future collaborations. Papers following the presentations are included in this special issue, and some salient points raised in each are summarized and integrated in the introductory editorial piece.

In the workshop discussions, it was agreed that all interested participants could present a brief synopsis of their "take home" message from the workshop, or their impressions of future steps that might be taken to move the study of dental wear forward. These synopses are presented here, unedited.

Paul Constantino, Saint Michael's College, USA.

I believe the most important outcome of this workshop sprung directly from its great success. That is to say this workshop was strong confirmation that, if we truly want to understand the processes responsible for tooth wear, we need to have formal collaborations between biologists and materials scientists / engineers. The biologists understand the variation of wear in nature and its associations with diet while the materials scientists can identify the variables responsible for wear through theory and experimentation. Although the two groups can learn from each other's work even without formal collaboration, this is seldom an effective way to move the science forward as the two sides are often asking different questions. Biologists focus on making correlations among patterns of wear without a solid understanding about the basic mechanics responsible for it. Meanwhile, materials scientists conduct simplistic examinations of wear without proper consideration of its complexity in biological systems. It is only through close dialogue, like that offered by this workshop, that the two groups can come to understand better the issues that need to be addressed in order to make significant leaps in our understanding of dental tribology. While it may not always be important for biologists to understand the fundamental mechanics that govern the wear patterns they see, nor for materials scientists to apply their results to actual biological systems, doing so will undoubtedly result in more transformational research than either group can accomplish on its own. As someone who regularly collaborates with a member of the "other group," and has done so for years, I can state with confidence that it is a wholly worthwhile endeavor. While overcoming disciplinary language barriers and coming to agreement about the importance of specific lines of research can be frustrating at times, there is no doubt that the collaboration has resulted in research directions that neither of us would have pursued otherwise, as well as greatly expanding both my interest and understanding in a more holistic view of tooth wear.

Mark Hoffman, University of New South Wales, Australia.

The tribology of teeth is a complex and poorly understood process with a strong need to identify the underlying mechanisms. The outstanding issues appear to be:

1) The cause and nature of surface films on teeth and their effect in reducing friction and hence mechanical degradation

2) The process of mechanical degradation of the teeth – is it a ploughing process or fracture, or both
3) The effect of diet on (1) and (2)

Identifying (3), there will be a major step towards finding a link between tooth wear surface observations and dietary history.”

Mugino Kubo, University of Tokyo, Japan.

The discussions were stimulating for me. Among them, I consider methodological standardization in dental microwear texture analysis (DMTA) to be important. In particular, I point to:

1. molding method
2. machine spec standardization
3. analytical procedures

For no.2, industrial standard specimens will improve the current situation, and facilitate comparison of DMTA data between machines.

The final goal is the sharing the 3D surface data on an online data archive, such as Dryad. I intend to send all of the 244 sika deer data used in my BsBt special issue paper to an online data archive.

Gildas Merceron, CNRS and University of Poitiers, France.

Mark Teaford asked how we jump from understandings of macroscale to microwear and to nanoscale-wear between two bodies (enamel and foods). Teaford gave a clear example: based on his in vivo experiments, large pits does not seem to appear in once, so he presumes that these form as a result of cumulative effect of multiple small pits generates large pits.

To address multi-scale analyses, I think we will gain a lot from 1) a controlled food experiment on living animals in which the communities of dental microwear and nanoindentation researchers could work together and 2) the study of the way these animals use to masticate foods.

1. Based on stomach contents and fecal analyses of animals used in microwear experiments, we could pinpoint a set of particles with different dimensions, shapes and hardness that are potentially responsible of dental microwear. We could then generate an *in vitro* experiment to analyze wear at both the micro- and nano-scales with each of the particle sets.
2. Based on the experiment I piloted on sheep, I found out that masticating clover and grasses generate different microwear. But is this difference due to foods themselves or/and the way the animals masticate them? Some data from wild game are also surprising. In some case and for certain variables, it might be difficult to discriminate grazers from certain browsers (e.g., perhaps the ones incorporating low amount wood particles or/and the one browsing on tough dicots leaves). The way to resolve this is to integrate a cineradiographic study with the proposed controlled food experiment. Do sheep crush clover and shear grasses or do they shear both types of fodder? Also, do they masticate the same way if they gather small or large mouthfuls? I wonder whether controlled food testing on sheep eating large amount of fodder is appropriate to simulate dental abrasion of wild game browsing or grazing gathering small quantity of food per mouthful -- even if this does not concern mastication during period of rumination.

Mark Purnell, University of Leicester, United Kingdom.

Various presentations and discussions highlighted the gulf between the results of various experimental investigations (at a range of scales) and analyses of wear in natural systems (at micro and macro scales). This issue arises partly because experimental analyses are not designed to replicate and reproduce the complexity of natural systems and are of necessity simplified to make their execution tractable and their results interpretable. But even taking this into account, the opportunity provided by this meeting for researchers with different backgrounds to interact and discuss such issues made it clear that there is more to this problem. It seems we don't have answers to some fairly basic questions: how, for example, might the generation of scratches and indentations in enamel under controlled lab conditions scale up in terms of quantity to generate microwear textures, and in terms of volume to generate macro-scale wear. This issue is linked to the debate over recent years concerning the role of extraneous hard particles in the generation of tooth wear and microwear, particularly in herbivores, with lab studies suggesting that food is generally not hard enough to generate wear. It has been difficult to reconcile this work with the various analyses, including field and experimental feeding studies, that provide strong evidence that microwear textures record a dietary signal. To me, one of the most interesting ideas to emerge during the meeting, not entirely new (e.g. Lua et al 2015) but little explored, is the hypothesis that wear reflects how the potential of hard particles to produce scratches and indentations on teeth is mediated by the material properties of both tooth surfaces and the foodstuff being consumed. In other words, it is the hard particles that generate microwear, but the nature of the texture they generate reflects the material properties of the diet. This is a hypothesis worth further exploration and testing (an ideal subject for investigation through development of more sophisticated chewing machines, perhaps? – the focus of other intesting discussions at the meeting).

Eugeniusz Sajewicz, Białystok University of Technology, Poland.

For me as an engineer, the most important element in understanding tooth wear is the chewing machine. In my opinion, the focus should be development of a general methodology for *in vitro* research that would allow reproduction of *in vivo* conditions. This would require selection of key parameters and the environment that simulates natural conditions, including appropriate food substitutes.

Gordon Sanson, Monash University, Australia.

Biological dental tissues are hierarchical, a nanostructure organized into a microstructure that sustains a macrostructure, which has remarkable wear resistant and functional processing properties. Some teeth can chew 20,000 to 40,000 times a day, perhaps for 15 years, a staggering 10^8 times, processing materials of different hardness, toughness and strength, while absorbing the wear from around 10^6 potentially abrasive particles per contact cycle, often in an antagonistic chemical environment. In other words, teeth operate in a hostile dirty environment and must maintain functional efficiency over their life. There is much to learn from such a remarkable system.

Within the animal kingdom there is a wealth of different systems built from different tissues that process different substrates with different abrasive contaminants. These include mollusk radulae, echinoderm “teeth”, arthropod mandibles and vertebrate teeth. The arthropod systems have not developed the hard structures of the vertebrates but, in many instances, process the same kinds of foods. How is this possible?

All these examples operate at different scales of the "tooth" and the food. While there is a literature on these systems it is not a systematic exposition that is open to revealing commonalities. This is partly because different aspects are often explored by researchers with different interests in mind. Big Data systems have the potential to reveal patterns not obvious from isolated studies. Therefore, an important opportunity is the development of standardized techniques and protocols that are fed into a common database capable of being interrogated for pattern.

The Dental Biotribology Workshop brought together a unique set of participants with, at first sight, disparate interests and research programs. However, it was apparent that many of the obstacles and challenges faced by the different research groups had some commonalities. Discussion centered on these factors and it was concluded that there is merit in pursuing the interactions among the different hierarchies represented. For example, these hierarchies ranged from the nano and microwear investigators interested in the predictability and causes of the features they examine. At the same scale, investigators reported on the wear resistant properties and remineralizing capabilities of the dental tissues in different chemical environments. This was described as both a self-repair and sacrificial process. At the micro scale, enamel prism orientation and mesowear features were of interest. At the macro scale the shape and geometry of interacting cusps and crests with each other, and with foods of different properties, were the focus. Do the nano to macro interactions scale? Are there qualitative differences of wear and function between the scales? At the nano scale, evidence was presented that increases in load changed the fracture characteristics from microcracking to delamination. Is this kind of qualitative change characteristic at larger scales? Evidence of micro to macro fracture of teeth in hominids suggests there are qualitative changes which, suggests that microwear is more than the sum of nanowear. If so this means that predictions from nano wear to macro wear have limitations. We need to know those limitations.

Teeth serve to process food, that is their predominant function, but this function must be investigated more holistically and across scale in a systematic way. There was some consensus of the benefits of establishing a broad scale research program around a “chewing machine” or a Biological Tribilogy Instrument. This would need to be capable of handling realistic loads, velocities, vectors, and material phases that would include liquid to solid putative abrasive inclusions and different shapes and materials of artificial teeth.

While various models of “chewing machines” exist for relatively specific purposes it is probable that none cover the full range of conditions that this proposal seeks to cover. Biomimetics is potentially a powerful stimulator of engineering possibilities for the development of new products and processes. However, there is also a feedback from biomimetically induced engineering principles to deduction of improved biological explanation. Biomimetics is often seen as a one-way feed from biology to engineering. However, because of the limitations of biological knowledge the deduced engineering solutions are necessarily constrained by the biological knowledge. This proposal seeks to feed back the engineering outcomes to a better biological understanding that in turn informs a more sophisticated and accurate engineering understanding. The deliberate formation of a team of biologists and engineers that can pursue a long term inductive-deductive cyclic research program has not been envisaged before and may be a model for biomimetic research in the future.

Ellen Schulz-Kornas, Max Planck Institute for Evolutionary Anthropology, Germany.

Through the talks and discussions I learned that most of the participants worked on very particular and very interesting research questions and there have been a lot of new results acquired during the last 5 years. Especially interesting were the findings in the morphology/construction of teeth and abrasive tissues on the nanoscale, in the field, the variety of methods used, and the different views and approaches on wear and material analysis. It seems that new findings bring us back to core (old) questions that arose in each discipline from time to time over the last 70 years (whether engineering, anthropology, dentistry, paleontology or biology). These include how materials interact, what is the mechanism of wear in general, and what are the most important key players that needs to be considered in that system. There is a need to re-evaluate the old terminology to find a language that crosses interdisciplinary borders (e.g. anti-wear function of saliva). The role of saliva is a topic that is highly under-researched and needs to be explored much more in the future. Much research has been done on different scales and fluidity phases. I see a need to develop a more holistic view, especially of the chewing process, that tackles the repetitive nature and the scaling problem to understanding which scale is important at which time step.

Each discipline considers on its own set of issues, but for future we need to focus the bigger picture to understand the process in general. Additionally, as suggested by Sun Yuchun and colleagues, there are clear opportunities to make progress in the development of biologically inspired materials that might be useful in dental and medical sciences in future. We could make a bigger impact and foster progress in science a lot if we bring our knowledge together and avoiding re-inventing the wheel multiple times. Identifying test case scenarios that could act as an example would be an important step forward. The time is ripe now for engineers and biologists to come of their disciplinary comfort zones because we need further discussions to identify these cases/frame conditions to be tested by chewing machine, feeding experiments, or museum collections. I find that we are at the limit of having appropriate material tests that reflect the heterogeneous nature of biological materials. I would like to see further discussion not only about a "smart" chewing machine, but also more realistic settings for that machine and further developments in material testing approaches.

Michael Swain, Kuwait University, Kuwait and University of Sydney, Australia.

A critical aspect of the wear and scratching damage of tooth enamel is the mechanism by which the apatite crystallites break and are removed from the surface during abrasion. Observations with sharp indenters, such as with pyramidal diamond Berkovich and corner-cube tips at low contact loads (<10mN), indicate that a metallic like "swarf" forms ahead of these abrasive proxies with limited damage either side of the scratch. The "swarf" appears to be composed of small apatite fragments (10 to 20nm ϕ) that form ahead of the cutting tip in a triangular wedge-like region and are weakly bonded together. The resulting in-vitro observations of the scratch with the diamond tips at low loads are very similar in their size and form with what has been reported from the fossil record as well as in-vivo animal and human observations of worn enamel. The sharp forms of the remnant scratch markings of enamel on the fossil as well as teeth of living creatures suggests that a hard (>enamel) fractured or faceted object with sufficient angulation and stiffness (E modulus > enamel) is required. The sharp micro-scratch patterns also suggest relatively low forces (<1-100mN) are operating on such particles as otherwise they would fracture or tumble during sliding engagement. It would also be anticipated that extensive enamel cracking about the scratch would occur at heavier loads. A major difference between current precision low load scratch tests and what is anticipated during in-vivo tooth abrasion are the sliding speeds as most current tests are at the μm/sec range (3 to 4 orders of magnitude slower than in-vivo), and the absence of an equivalent oral environment.

Here are my three wish list items/issues that I feel the need to follow up.

1. Understanding of the basic mechanisms by which enamel wears.
2. Development of a machine that measures the forces generated during the loading of teeth and that does have veracity with the actual observational domain. This instrument should be able to have appropriately angled occlusion and be able to “chew” the “real” diet of the species as well as the appropriate jaw motion. It will also need to be able to chew at observed frequencies with the presence of saliva and fluids generated from the food being chewed. The challenge will be to have the relevant loading range but also the sensitivity to detect “grit” and phytoliths in the diet. This device will need sophisticated loading as well as data recording and analysis facilities and may have to be developed over a series of iterations.
3. Further genuine discussions and collaborations between various members across the gaps of the groups involved in this area of research.

Mark Teaford, Touro University, USA.

The most interesting aspect of this workshop for me was not a single, specific conversation, but instead a recurrent theme that ran throughout it. While each investigator seemed to work within a specific scale of analysis, be it gross, micro, or nano, the presentations and discussions that followed showed ways in which we each might reach outside of those confines to gain new insights into our topics of research. Thus, for instance, the nano-level work by Zhou and Zheng (among others) seemed to be an exciting foundation on which we could ultimately build a far better understanding of the wear of dental materials. When combined with state-of-the-art empirical research at various scales of analysis, and new views of important concepts like the influence of organic films and different forms of wear, the net result could be an impressive growth of new perspectives in topics ranging from bionic design to clinical applications to basic biology and evolution.

Zhongrong Zhou, Jing Zheng, Linmao Qian, and Licheng Hua, Southwest Jiaotong University, China.

Wear has been the bottleneck to restrict the reliable running of instruments/equipment. Design of anti-wear system plays an increasingly significant role in modern engineering. As we all know, after half a billion of years of dental evolution, most animal teeth, including human dentitions have excellent wear-resistance properties. For humans, for example, tooth wear is very slight, about 20-38 μm per year, so their service time is very long, almost equal to the human lifetime. Thus, animal teeth are typical anti-wear bio-specimens from the perspective of bionic design, and thus it is necessary to investigate their anti-wear function formation mechanism in detail. Future studies should focus on the following:

1. For human teeth, some detailed and extensional results should be further improved, such as the correlations of tooth evolution, microstructure, dietary habit, and dental tribological behavior, and the influence of complex salivary components, aiming to reveal the underlying anti-wear mechanism fully.

2. More efforts should be made to explore the applications of dental anti-wear mechanisms in mouth rehabilitation, such as new dental materials and oral care products, and to improve the anti-wear properties of current engineering instrumentation and equipment.
3. Given that some animal teeth may have more complex tribological mechanisms than human teeth, future study should expand from human teeth to other representative animal teeth, such as the incisors of the bamboo rat, to investigate their tribological behaviors and function formation mechanisms to reveal the mutual effect of mechanical friction and wear on dental microstructure. At the same time, anti-wear bionic-design theory and its implementation solutions should be investigated systematically. For the biomimetic designing of materials, the emphasis should focus on how to develop new resin matrix composites with high anti-wear performance and the toughening of ceramic matrix composites based on studies of teeth. For high-performance anti-wear engineering instruments/equipment, future bionic design emphasis should focus on the synergistic friction-reducing and anti-wear ability of tribological systems.