Preservation of Human Dental Surface Micro-Topography with Three-Dimensional Non-Destructive Digital Imaging

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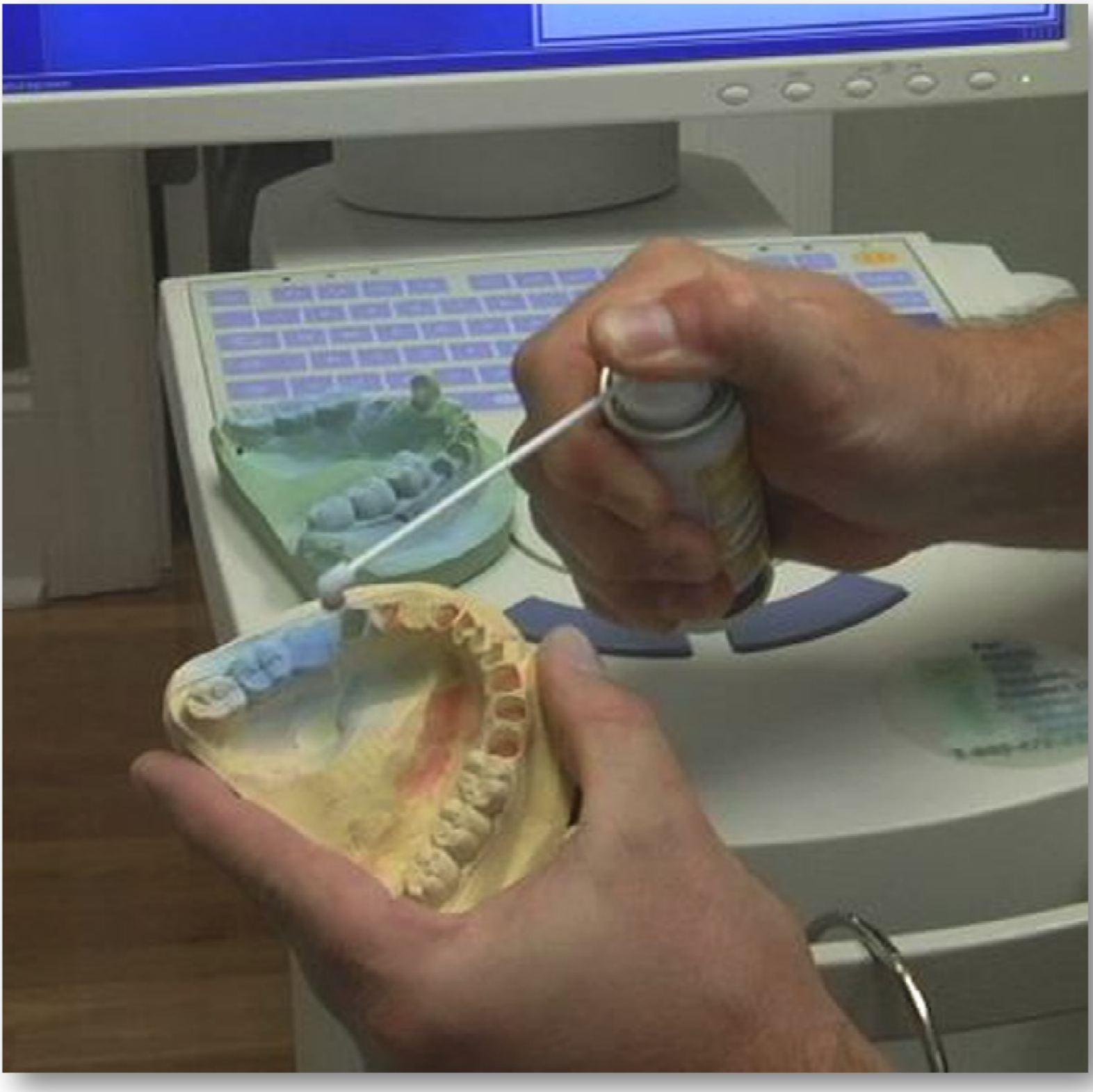

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Middle Tennessee State University

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EXECUTIVE SUMMARY

This project leverages a widely-available conventional technology in an unconventional way to preserve data from human skeletal remains. Our objective is to use commercially-available dental CAD-CAM systems, more typically used to create dental restorations, to digitize human teeth from archaeological contexts and produce microscopically-accurate porcelain replicas. Our goal for this Preservation Technology and Training (PTT) Grant project was to conduct a feasibility test to determine if such reproductions would be precise enough to serve as a research grade replica for use after an original specimen has been reburied. Accuracy and precision of the reproduction were critical since the idea is to essentially create a model of the tooth including all macroscopic and microscopic surface features.

The significance of this research to the preservation community stems from the contemporary parameters for bioarchaeological research using human skeletal remains in the U.S., including the federal mandate for repatriation of affiliated Native American skeletal remains, and the frequency with which newly-excavated remains are remanded for reburial, sometimes within hours or days, leaving little time for careful and verifiable data collection. After reburial, it is of course impossible to replicate observations or to engage new research hypotheses. Research-quality dental replicas have the potential to alleviate some of these concerns. Furthermore, this technique has the potential to streamline analyses that often delay legally-mandated reburial of human remains from archaeological sites. It may also eventually provide some answer to the curation crisis plaguing federal and state agencies in that the cost of curating digital data is minimal when compared to funding and space requirements for physical objects. Finally, for prehistoric human skeletal remains, this technique may in some small way provide one approach to preserve irreplaceable scientific data, while also respecting Native America's call for timely repatriation.

So again, we ask: "Can existing computer-aided design and manufacturing technologies (CAD-CAM) create digitally and physically accurate models of human dental micro-topography precise enough to serve as a research-grade replica for use after the original specimen has been reburied?" The answer is, "YES", with some limitations. This technique is able to capture surface details of the teeth to a resolution of 4 to 12 microns. This degree of precision is far finer than is necessary to capture the details of most pathological and cultural alterations to human teeth. We don't yet know if these replicas are appropriate for looking at perikymata or other incremental structures of the surface of the tooth. We do know that no internal features, damage, or pathologies are preserved in the replica, because this technique is intended to reproduce only surface detail.

Introduction

In 1990, Congress passed the Native American Graves Protection and Repatriation Act (Pub. L. 101-601, 25 U.S.C. 3001 et seq., 104 Stat. 3048), which sets forth guidelines for repatriation of human skeletal remains and other preserved tissues, related funerary artifacts, and objects of cultural patrimony which are held by public repositories and institutions which receive federal funds, to be returned to parties who make a repatriation claim upon and can demonstrate cultural affiliation with those remains or objects. These affiliated parties are typically federally recognized Native American tribes, and the remains are often reburied upon repatriation. Since the passage of this act, many states have also instituted regulations which cover the excavation, proper handling, and reburial of Native American and other human skeletal remains which are discovered in the course of public or private development, or other earthmoving activities. In general practice, these remains are avoided if at all possible, but if they must be removed to prevent their destruction, they are typically reburied within a specified time interval ranging from the same day to as much as one calendar year of their removal from their original burial location.

Anthropologically speaking, a human burial is one of the most informative finds an archaeologist can make (Peebles 1977). A burial often contains artifacts, both funerary objects and accidental inclusions in the grave fill, which can tell us much about the society which buried the individual. The grave may also contain food remains and pollen, which can tell us not only about the foodways of the culture, but something about the environment the person lived in and even the season of the year during which they were buried. The very layout of a grave or a cemetery gives clues about the social organization and lifeways of the culture which created it.

Most importantly, the burial contains skeletal remains, which can speak volumes about the biological history of an individual and a population.

This research seeks to contribute a partial solution to the problem of fulfilling competing goals of repatriation of archaeologically-recovered human skeletal remains, and the scientific community's desire to preserve the information that can be collected from these remains. We explore the potential uses of existing technology to create a permanent record of human teeth, allowing the original remains to be reburied according to the wishes of the Native American community and other interested parties, and in compliance with federal NAGPRA regulations. For this research, the National Center for Preservation Technology and Training Grant (PTT Grant) funded an evaluation of the effectiveness of existing computer aided design and manufacturing (CAD-CAM) technology to create digitally and physically accurate models of microscopic features found on surfaces of human teeth.

Research Question

Can existing CAD-CAM technology create digitally and physically accurate models of human dental micro-topography precise enough to serve as a research grade replica for use after the original specimen is no longer available for analysis?

Computer-Aided Design and Computer-Aided Manufacturing (CAD-CAM)

Computer-Aided Design and Computer-Aided Manufacturing (CAD-CAM) systems refer to a suite of technologies used to design products using multifunctional computer software which is also used to control machinery which manufactures the product. In cases where the

design process involves a hand-built prototype, there is often an imaging phase, which translates the prototype into digital data, which can then be reproduced as a three-dimensional physical model using the CAM technology. These technologies are widely used in design and manufacturing contexts worldwide, and have expanded into medical and dental applications. In clinical contexts, physicians and dentists use image capture devices such as infrared imaging, laser scanning, and CT scanning in the CAD stage to image the patient's body, and then use CAM technologies to produce medical and dental prostheses, appliances and restorations (Beuer et al. 2008; Ciocca and Scotti 2004; Eufinger et al. 1995; Fasbinder 2010; Mercuri et al. 2002, 2004; Tinschert et al. 2004).

CAD-CAM technologies also have a long history of use in archaeology and historic preservation. However, they are typically used on a site-level or even larger scale in landscape archaeology, archaeological surveys, and other macro-scale archaeological applications, in which case CAD-CAM technologies are typically conflated with other documentation / data capture / information management / analysis tools including GIS, remote sensing, and geophysical survey. Results of such studies are translated into virtual representations of excavation units and site-level reconstructions, which are useful tools for archaeological inference (CAD CAM News 2010; Patias et al. 2006). Other CAD-CAM technologies are used to record, measure, and collect data on artifacts and antiquities, for the purpose of study, restoration, and preservation (Boehler and Marbs 2004; Cooper et al. 1992; Ioannides et al. 2003; Ioannides and Wehr 2002; Pieraccini 2001). Regional, site-level, and artifact-specific data collected in digital format can streamline data sharing and collaboration (Ioannides et al. 2003). Often these results are used in the service of public archaeology, to create 3-D interactive web

pages, cultural heritage virtual tours, and active/interactive museum exhibits (Allard et al. 2005, Koutsoudis et al. 2007; Patias and Peipe 2000).

In the present research, I use both approaches to apply existing CAD-CAM dental technology in a novel archaeological and cultural heritage management application, to digitize and replicate microscopic surface features from archaeological human teeth destined for re-burial. The application of CAD-CAM to specimens from archaeological contexts has the potential to provide future researchers with access to data and specimens otherwise lost to re-burial, enhancing research and replicability of results. These data can be stored as digital image files or as physical replica teeth. Data files can be transmitted electronically, allowing researchers to instantly share data across the globe. It is an added benefit that CAD-CAM technology is widely available, comparatively inexpensive, and non-destructive.

Methods and Materials

CAD-CAM technologies are used daily in dental offices to produce crowns and other dental appliances that are identical to a patient's original tooth morphology. In practice, the patient's tooth is sprayed with a food grade antireflective contrast medium which produces a matte finish and ensures uniform digitizing of tooth enamel and dentine, which otherwise have different infrared bounce-back rates. This powder coating is considered reversible, though we discovered that at the microscopic level some traces of residue will remain. The coated tooth is then imaged with an infrared digitizer wand to create a three-dimensional image.

The digital model of the tooth is wirelessly uploaded to an on-site milling system, which fabricates a replica from a block of porcelain. The porcelain from which the replica is cut is

manufactured to specific tolerances to produce a material as close as possible to human tooth dentine and enamel, in order to accommodate the need for proper heat-cold tolerance and resistance to bite stress. In clinical practice, the resulting replica is then used as a crown or restoration in the patient's mouth, duplicating the original tooth surface.

Using these CAD-CAM procedures and dental-grade porcelain, dental surface features, or what I have termed "dental micro-topography", can be reproduced to a resolution of 7.5 microns. The resulting replica tooth is amenable to scanning electron microscopy (SEM), which can be used to investigate surface features of the tooth in fine detail.

The procedures for this project were simple and straightforward, designed to test the research question, and assess the feasibility of using this technique for bioarchaeological data collection and preservation on a larger scale. My plan was to proceed in five steps towards evaluating this technique:

1. Prepare and scan sample archaeological teeth with the scanning electron microscope to establish a "control" set of micrographs.
2. Collect three-dimensional surface data from sample teeth using a dental-grade CAD digitizer wand.
3. Employ CAM technology to mill a physical three-dimensional replica of each sample tooth, using the CAD data collected in the preceding step.
4. Scan the resulting replica teeth with the SEM to create a "test" set of micrographs.
5. Compare control and test micrographs by gross visual examination.

Scanning electron microscopy for this project was conducted at the MTSU Interdisciplinary Microanalysis and Imaging Center (MIMIC) by microimaging technician Alison Jordan, using a Hitachi S-3400 Scanning Electron Microscope with Oxford INCA Energy 200 Dispersive X-Ray Analyzer. Tooth imaging and replication were done on a CEREC chairside acquisition center for imaging and data capture, and the accompanying CEREC MC XL in-lab milling unit was used to produce the replica teeth. The milling unit was equipped with diamond-tipped burs, and the material selected for the replicas was Sirona CEREC feldspathic porcelain. Tooth imaging and replication were performed by Dr. Aaron Pryor, D.D.S. of Pryor Family Dentistry.

Following the protocol established above, three unprovenienced teeth from archaeological contexts were selected for replication. They were imaged in the SEM, digitized using the CEREC system, and porcelain replicas were milled. The replicas were then also imaged with the SEM, and the resulting micrographs were compared with the original micrographs of the natural teeth in side-by-side gross examination of the resulting images, viewed on a single flat panel computer monitor. No attempt was made to quantify the results of these tests. For the results to be useful, the digital model needed to be precisely detailed enough to faithfully reproduce microscopic patterns of dental wear, pathology, and other topography on the surface of teeth.

Results and Discussion

Our results of this small test were positive. We found that the CAD-CAM replicas did faithfully reproduce the surface topography of the archaeological tooth specimens, down to a

level of detail of about 4 to 12 microns. Given that pathological or cultural alterations to the tooth crown can typically be measured in tens or even hundreds of microns, this resolution is more than sufficient for the purposes of this study. In general, our expectation was that surface micro-topographic features would be accurately replicated in size and morphology, including dental chipping, masticatory dental wear, occupational or lifestyle-related wear (e.g., toothpick wear, labret wear), cultural modifications (e.g., dental filing, inlays), nonmetric traits, linear enamel hypoplasia, shallow caries, and other pathological or cultural alterations.

We did discover that the laser milling technique left an allover pattern of linear furrows in the surface of the replica tooth, which conveniently make the micrographs of the original and replica teeth easily distinguishable from one another. Because of the scale of these furrows in relation to any possible pathological or cultural features on the tooth, we consider them little more than background noise.

Research question – did it work?

"Can existing computer-aided design and manufacturing technologies (CAD-CAM) create digitally and physically accurate models of human dental micro-topography precise enough to serve as a research grade replica for use after the original specimen has been reburied?"

The answer to this question is YES, with some limitations.

What this technique can do:

- The CAD-CAM replicas faithfully reproduced the surface micro-topography of the archaeological tooth specimens, down to a level of detail of about 4 to 12 microns.
    - *Note that a red blood cell averages 8 microns in diameter, and a human hair ranges between 20 and 180 microns in thickness.*
- Pathological or cultural alterations to the tooth crown typically range in size from tens or hundreds of microns (including microwear) up to fractions of millimeters, so this degree of resolution is more than sufficient for the purposes of paleopathological study.

What this technique can't do:

- This level of resolution is useful for study of most pathological or cultural alterations.
- We don't yet know if it is appropriate for looking at perikymata (30-50 microns) or other incremental structures of the tooth (Hillson 1992).
- None of the inner features of the tooth are preserved in the replica.
    - Although thin-sectioning of the ceramic material would be similar to thin-sectioning a natural tooth due to the manufacturing tolerances of the material, there would be no purpose other than for counting and measuring surface features in cross-section.
- The biggest drawback of this technique is that very deep tooth features, such as large carious lesions are not faithfully reproduced. Because of the nature of the imaging process, in areas where the infrared beam does not reach, the software smooths over the gap in the data, producing a plain flat surface. This discrepancy is easily

distinguished from tooth surfaces which are accurately reproduced, but results in a less-than-exact replica of the tooth.

Other technical concerns:

Charging

One of the concerns of this project was that items to be imaged in the scanning electron microscope typically are coated with gold or another material which acts to prevent the accumulation of static electric charge on the item being scanned as it is bombarded with the electron stream in the imaging process. In general, this gold coating is irreversible, which might not be acceptable to either concerned Native American parties, or to museums or other curation facilities from whom specimens might be borrowed. There are processes for removing the coating, but it is unclear whether or not the delicate archaeological specimens would stand up to the removal treatment. Therefore, we found it preferable to test the idea of scanning uncoated teeth. We were pleasantly surprised by the results; because dental pathologies and cultural modifications to teeth are of relatively large size, it was not necessary to image them at higher resolutions which typically create greater electrical charge. In addition, because truly high-resolution magnification was not required, navigation of the tooth surface in the SEM was less complicated and required less scope time, which again reduced the degree of electrical charging of the specimen.

Powder coat

The CAD imaging process requires coating the original tooth with food-grade antireflective contrast medium, in order to standardize the infrared bounce-back rate, which

differs between enamel and dentine. This coating is completely reversible to the naked eye with plain water. However, we found it preferable to produce SEM images of the natural teeth prior to powder-coating them, because microscopic traces of the powder did remain, which were visible on the SEM.

Cutting head marks

The milling process involves cutting the ceramic material with a pair of diamond-tipped cutting heads. This results in an allover pattern of tiny striations, though these appear to be at a scale that would not be easily confused with cultural or pathological modifications.

Conclusions

So again, we ask: "Can existing computer-aided design and manufacturing technologies (CAD-CAM) create digitally and physically accurate models of human dental micro-topography precise enough to serve as a research-grade replica for use after the original specimen has been reburied?" The answer is, "YES", with some limitations. This technique is able to capture surface details of the teeth to a resolution of 4 to 12 microns. This degree of precision is far finer than is necessary to capture the details of most pathological and cultural alterations to human teeth. We don't yet know if these replicas are appropriate for looking at perikymata or other incremental structures of the surface of the tooth. We do know that no internal features, damage, or pathologies are preserved in the replica, because this technique is intended to reproduce only surface detail.

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Acknowledgments

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Appendix A: Images

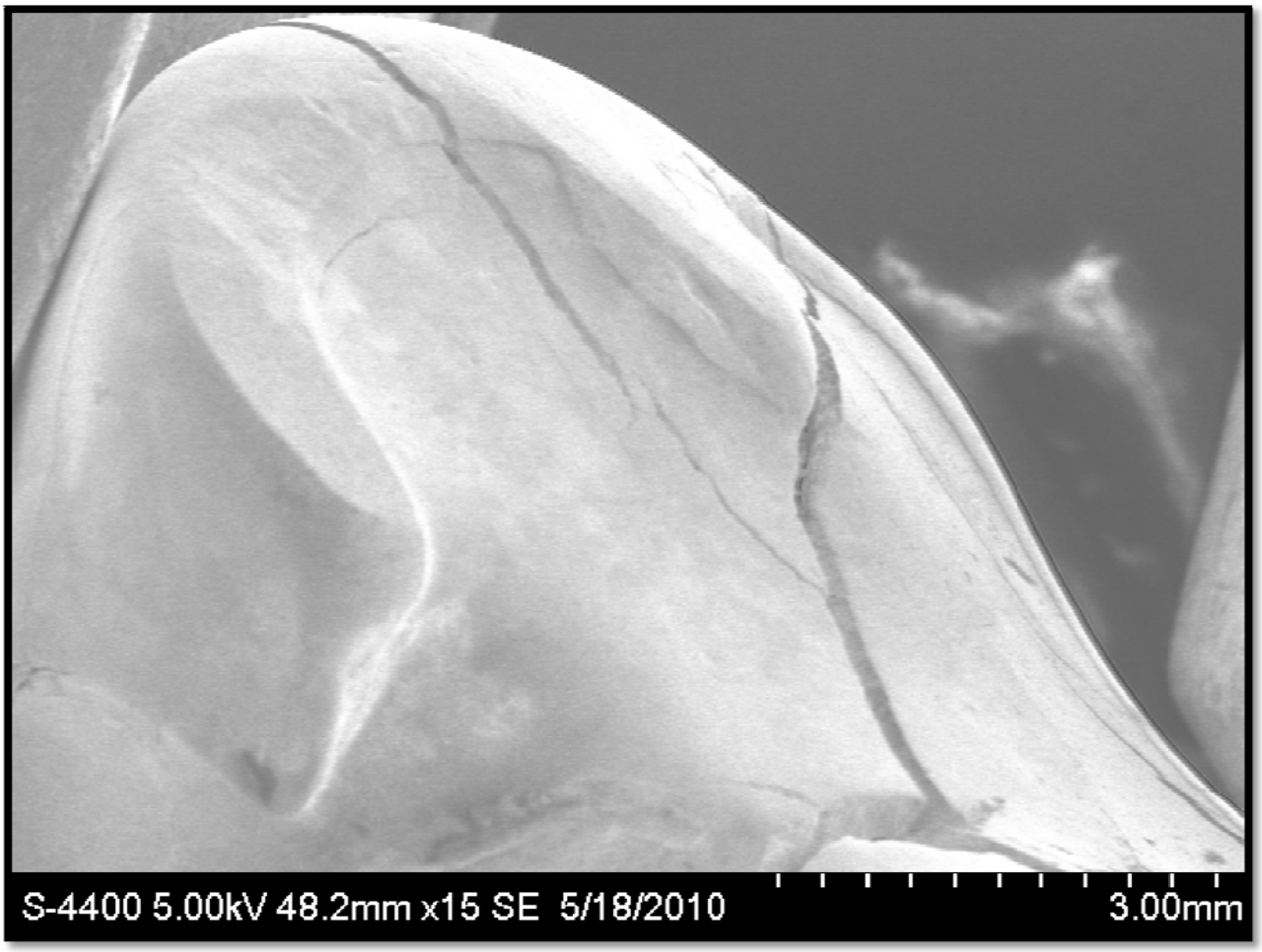

Figure 1: SEM image of the occlusal surface of a worn natural human tooth, showing the contrast between worn enamel and dentine, taphonomic surface cracks, and some small pits and striations associated with dental wear.

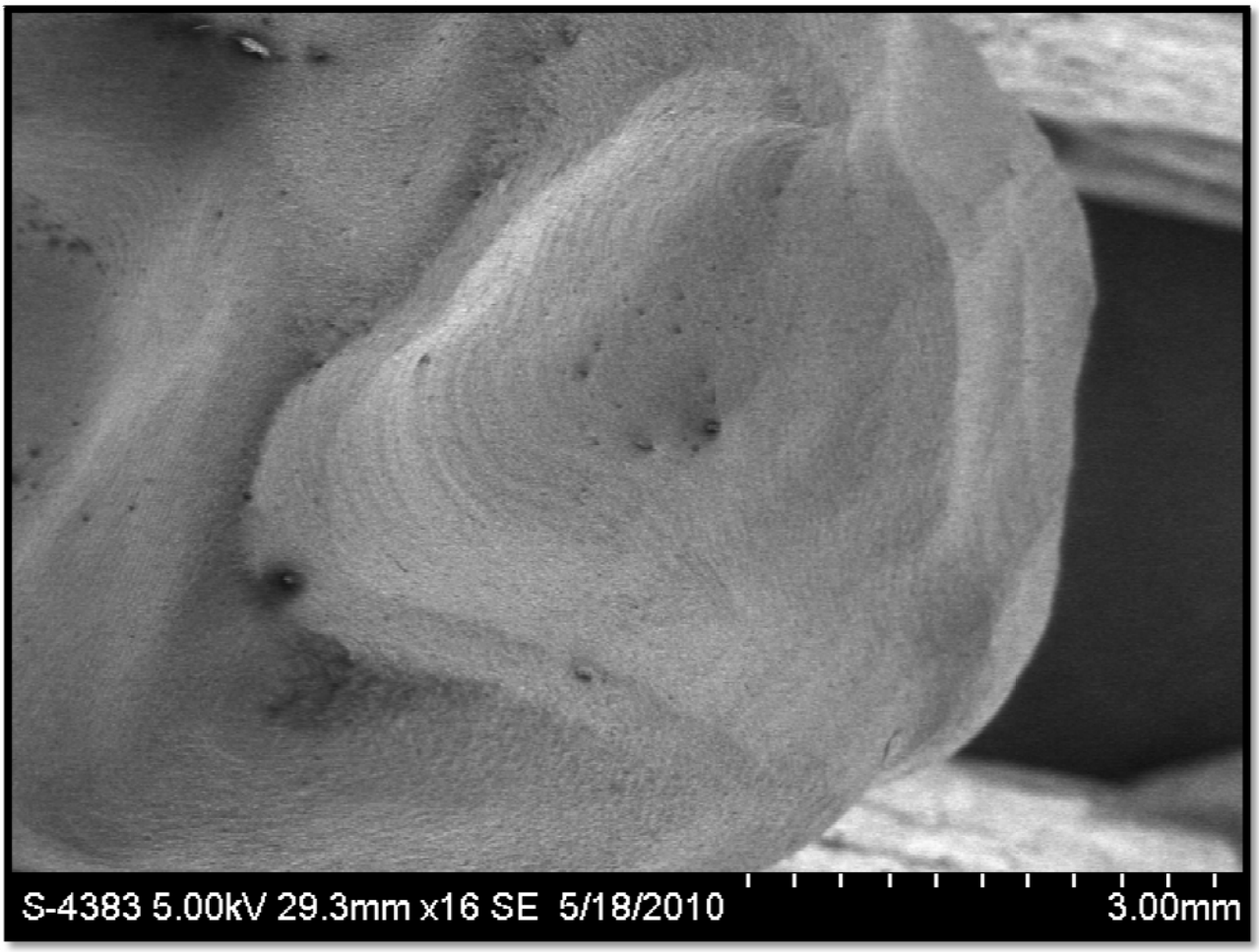

Figure 2: SEM image of the occlusal surface of a replica tooth, showing the contrast between worn enamel and dentine, surface wear, and some small pits and striations associated with dental wear. Note also the linear pattern of surface striations, associated with milling the dental ceramic material.

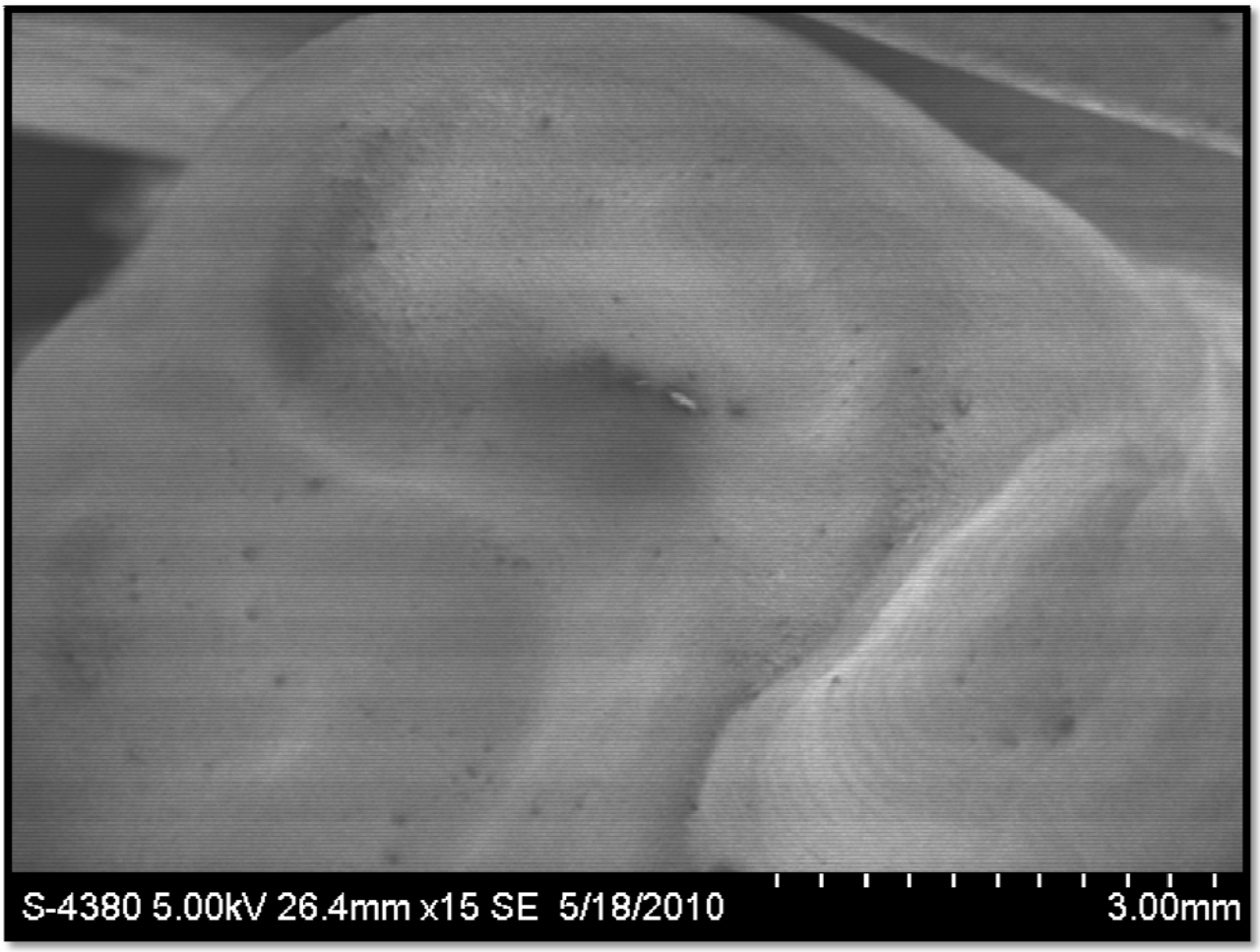

Figure 3: Cutting head marks on a replica tooth.

Figure 4: Mounting the replica tooth in a spring-type scope mount in preparation for SEM imaging.

Figure 5: SEM micrograph of surface details of a natural tooth.

Figure 6: coating a mock specimen with antireflective contrast medium prior to infrared data capture.