APPLICATIONS OF COMPUTED TOMOGRAPHY TO FOSSIL CONSERVATION AND EDUCATION

GIRISH TEMBE[1,3] AND SHAMEEM SIDDIQUI[2,4]

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Abstract.—Computed tomography (CT) has been used for decades for paleontological research and fossil preparations. However, the benefits of CT scanning regarding conservation, exhibits, and education are rarely discussed. CT and rapid prototyping, although still prohibitively expensive on a large scale, are becoming cheaper and can provide another tool available to museums and educators teaching natural history.

Resumen.—Tomografía computarizada (TC) ha sido usada durante décadas en investigaciones paleontológicas y geológicas. A pesar de esto, la aplicación de esta tecnología, en conjunto con impresoras tridimensionales y la rápida producción de prototipos, apenas se utilizan para suplementar educación, conservación, y exhibición dentro de estos campos. El desarrollo de esta tecnología, la reducción de costos y la aumentada precisión de estos productos, los hace más accesibles para instituciones. Aunque predomina su uso en rubros investigativos también se puede extender a profesionales asociados con la historia natural. Este papel brevemente menciona los principios de TC y su rol investigativo, pero enfoca en desarrollar el uso de CT en conjunto con la rápida producción de prototipos para conservación de material geológico y el uso de tal como material educacional.

INTRODUCTION

Computed tomography (CT) is an imaging technique that uses X-ray technology and mathematical reconstruction algorithms to view a cross-sectional slice of an object. Although the CT scanning is still primarily used in the field of medical radiology, CT scanners have found use in various other disciplines. The nondestructive nature of the data collection as well as the very high resolution of the collected data have prompted their use in materials science, geotechnology, and petroleum engineering since the early 1980s. The use of radiography in archaeology, especially Egyptology, started in the late 19th century. CT applications in paleoanthropology began about a century later, after the advent of CT (Boni et al. 2004, Bruner and Manzi 2006).

CT scanning is frequently used to aid paleontological and geoscience research by providing internal views of samples as well as enabling the creation of internal volumes and serial images (Ketcham and Carlson 2001, Carlson et al. 2003, Witmer et al. 2003, Bruner and Manzi 2006, Carlson 2006, Witmer and Ridgely 2010, Rowe et al. 2011, Ni et al. 2012, Gee 2013). However, CT can also be an invaluable tool for conservation and education. CT produces digital data, such as tagged image file format (TIFF) or Joint Photographic Experts Group (JPEG) files. Data produced from CT scanning are easier to share than physical specimens. Not only does this increase scientific repeatability, it reduces potential damage from shipping or mishandling. CT data can also be used to produce educational animations (such as cut-away sequences) and three-

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dimensional models, which can be used in museum exhibits or educational settings. The use of three-dimensional models and CT movies can expand the educational value of rare or delicate specimens without increasing the strain on these specimens.

Principles of CT Scanning

Traditional X-rays have been used to create two-dimensional images, such as for medical imaging at least since the 19th century. The development of CT in the mid-20th century enhanced the use of X-rays to create three-dimensional data since the mid-20th century. While a brief explanation of different types of scanners and the principles of how they work are provided below, a thorough discussion of the technology can be found elsewhere (Vinegar 1986, Wellington and Vinegar 1987, Withjack 1988, Kantzas 1990, Akin and Kovscek 2001, Siddiqui 2001, Withjack et al. 2003).

Computed tomography data are collected using a variety of CT scanners, such as medical scanners, industrial scanners, synchrotrons, micro-CT, and more recently nano-CT—all varying in their power and resolution (Ketcham and Carlson 2001, Carlson 2006, Sobral et al. 2012). Using such devices, X-rays are transmitted through a sample into a detector and reconstructed as digital thin sections ("slices"). The attenuation of the energy in the X-ray beams is related to the electron density and atomic number of the materials present in the object being scanned. Each material possesses a distinct linear attenuation coefficient, and the total response received by the detectors is a combination of these coefficients. In order to simplify the complicated mathematics, the medical industry adopted the CT Number (CTN), which is based on an arbitrary scale proposed by Hounsfield, the inventor of the first CT scanner, which sets -1000 and 0 as the CT numbers for air and distilled water, respectively. At relatively high X-ray energies at which the Compton Scattering effect becomes predominant, the CTN becomes mainly a function of the electron density. The resulting quantitative statistical data (usually the mean CTN for each slice) are converted to bulk densities and porosities based on some conversion equations. The conversion equations, in turn, are based on the CT response of some known standards of known bulk densities.

The data are processed and saved on a computer and can be viewed and manipulated using various software. A subset of the data, representing just the actual material within a circular region-of-interest, may be used. Varying densities within the sample (such as mineralogy) or body parts can be filtered out or segmented (Vinegar 1986, Wellington and Vinegar 1987, Ketcham and Carlson 2001, Carlson 2006, Bruner and Manzi 2006, Ni et al. 2012). This may be a time-consuming process, depending on the complexity of the specimen. Adjacent slices can be digitally placed on top of each other to create a stack, or digital volume.

There are a variety of CT scanners, as well as generations. The term "generation" is used in CT to describe successively commercially available types of scanners using different modes of scanning motion and X-ray detection. Each generation is characterized by a particular geometry of scanning motion, scanning time, shape of the X-ray beam, and detector system. However, no single one of these features bestows a definite superiority on one generation in comparison with the others (Morgan 1983).

The first-generation CT scanners use a single pencil-beam X-ray source and a single crystal-photomultiplier tube-detector arrangement. The scan sequence used is both translational and rotational. After a single linear motion of the tube and the detector, during which time 160 X-ray readings are typically taken, the tube and detector are rotated through 1°, and another linear scan is performed. This is repeated typically 180 times. As the beams cross only a small part of the object scanned, it takes almost 20 minutes to take a scan.

The second-generation scanners use a modified fan beam in which multiple collimated X-ray beams (from 3 to 52, depending on the design) from the same source and an equal number of detectors are used in a rotational manner. This arrangement in the second-generation scanners reduces the number of rotations and allows gathering more data per translation, resulting in a significant drop in scanning time (typically about 2 minutes per slice).

The third-generation CT scanners eliminate the complex translational–rotational motion of the first two generations. They use a rotational fan-beam geometry with a much wider fan beam, potentially covering the entire object to be scanned. In this arrangement, the detectors and the source are both aligned rigidly to one another, and they both rotate around the object. Because there is no linear translation in the third-generation scanners, the scanning time is reduced significantly (typically 2–3 seconds per slice), with improved spatial and density resolutions.

The fourth-generation CT scanners also feature a wide fan-beam geometry. However in the fourth-generation scanners, the detectors remain fixed within a ring, while the X-ray source rotates around the object. In this arrangement, the detectors are not aligned rigidly relative to the X-ray beam and, because only the source is rotated, the scanning time is potentially slightly less than that of a typical third-generation scanner.

The fifth-generation scanners use a stationary-geometry method in which both the source and the detectors are fixed. Thus, data are collected without any physical movement. This greatly reduces the scanning time to the millisecond range, which is fast enough to image the beating of a heart. The third- and fourth-generations both represent units with purely rotational geometries designed to gather the maximum amount of X-ray transmission data in the shortest possible time. Since the fifth-generation scanners did not become successful commercially, the third and the fourth-generation scanners remain the most popular CT scanners used.

Current focus in CT development is in multislice technology in which each rotation results in 4, 8, 16, 32, or 64 slices, which improves the axial resolution of the scanner. Rather than pencil beams, CT flux is used (cone beam technology) while most scanners use the third-generation geometry.

Micro-CT scanners, which belong to the industrial CT scanner group, have been in existence since the early 1980s (Elliott and Dover 1982). They are used mostly in materials evaluation and inspection and have typical resolutions in the 1–50 micron range. Microtomography, like tomography, uses X-rays to create cross-sections of a three-dimensional (3D) object that later can be used to recreate virtual models nondestructively. Micro-CT scanners are usually smaller in design compared with the medical version and are ideally suited for scanning smaller objects ranging from microfossils and small hand samples to reservoir rocks (i.e., sandstone and carbonates). Table 1 shows some of the differences between medical and micro-CT scanners.

In petrophysics and petroleum engineering, CT has proved to be a valuable tool to look at core mineralogy, porosity, and fluid movement without destroying the sample. A series of closely spaced CT scans from a core can create a three-dimensional representation of the core and internal volumes (Siddiqui 2001), similar to what is done with medical and paleontological scans. The digital data of the intact core sample stay preserved even after the sample is physically altered due to extensive plugging for conventional and special core analysis tests. Reviews of the various applications of CT scanning in petrophysics can be

Table 1. Differences between medical and micro-CT scanners.

	Medical X-ray CT	Microfocus X-ray CT
Geometry	Mostly 3rd (fixed object, rotating source and rotating detector) and 4th generation (fixed object, rotating source, and fixed detector) geometry	Mostly modified 3rd generation (rotating object, fixed source, and fixed detector) geometry
Volume imaging	By moving the scanning table toward or away from the source and detectors housed inside the gantry, with the stationary sample staying in a horizontal position	By moving both the source and detectors up or down while the sample mounted on the rotating stage rotates in a vertical position
Data capturing	Fan beam	Cone beam (volume)
X-ray source	High output (80–140 kV, 200–100 mA), rotating anode type	Low output (30–130 kV, up to 2 mA)
Focal spot (mm)	0.5–2	1–10
X-ray interaction with matter	Mostly Compton scattering, some photoelectric effect especially below 90 kV	Mostly photoelectric effect, some Compton scattering
Resolution (mm)	0.3–0.5	1–50
Detector	Mostly solid state detectors	Image intensifier and camera combination, or flat panel detectors
Output	Attenuation data converted to Hounsfield units, HU (air = −1000 HU, water = 0 HU)	Attenuation data given as 8-, 12- or 16-bit grayscale images, e.g., jpg, tiff)
Footprint	Have a large footprint, need separate shielding of room	Have a small footprint, typically available with own shielding
Common artifacts	Positioning, beam hardening	Ring, beam hardening
Data grid	512 × 512	1024 × 1024 and 2048 × 2048

found in the literature (Vinegar 1986, Wellington and Vinegar 1987, Withjack 1988, Kantzas 1990, Akin and Kovscek 2001, Siddiqui 2001, Withjack et al. 2003). CT is a powerful tool in the manufacturing industry. Automobile manufacturers use the industrial type of CT scanners for scanning large size objects such as engine blocks, for scanning sensitive parts, for measuring distances, for checking for flaws, and for rapid prototyping and quality control.

RESEARCH

Dissection and mechanical grinding can be time consuming, destructive, and may distort data from specimens. Illustrating or molding specimens may lengthen the process. Images derived from dissection may be placed in an article or online supplementary data, depending on limits on article length or amount of supplementary data (Ketcham and Carlson 2001, Carlson et al. 2003, Gee 2013).

However, CT can provide most of these benefits without the resulting damage. CT shortens the data acquisition time to a few hours, although data processing can be time intensive. By virtual reconstruction of internal volumes, researchers can digitally see otherwise hidden details of geological specimens (like fossils or cores) that were previously available only by mechanical dissection. This includes endocasts and histology in fossils and porosity and mineralogy in geological samples (Vinegar 1986, Wellington and Vinegar 1987, Brochu 2000, Ketcham and Carlson 2001, Siddiqui 2001, Siddiqui and Khamees 2004, Gunz et al. 2010, Curtin et al. 2012, Ni et al. 2012, Sobral et al. 2012, Gee 2013). Like dissection, these data may also be published in a journal's supplementary information, allowing wide access. This virtual and physical specimen can be reanalyzed at a later time if needed. This reanalysis is not an option once a specimen is lost to destructive analysis.

CT can also be used to reconstruct missing elements, such as pelvis and skull fragments (Zollikofer et al. 1998, Zollikofer et al. 2005, Berge and Goularas 2010). The fossil record is frequently incomplete and rarely preserves a whole skeleton. Even when a fairly complete skeleton is preserved, it typically is heavily damaged. As such, specimens—especially rare and incomplete specimens—may need reconstructions based on mirroring remains to create a whole specimen. Reconstructions have frequently involved materials such as plaster, glues, and other materials, many of which are irreversible and can lead to object deterioration. This causes problems not only for object stability, but also when new data bring about new interpretations (Zollikofer et al. 1998, Shelton and Chaney 2005, Zollikofer et al. 2005, Bruner and Manzi 2006). If a specimen has elements embedded in a nonreversible medium, they cannot be removed or reoriented with new interpretations, essentially making the physical specimen lost to reinterpretation. While modern reconstruction techniques aim to be reversible and stable, past reconstructions typically cannot be undone.

Zollikofer et al. (1998) provide a good case study of digital reconstruction using the Gibraltar 1 specimen, an adult *Homo* skull. This specimen lacks its "skull roof…along with a large part of the left side of the brain case…[and] the upper jaws had been bent out of shape and internal structures crushed" (Zollikofer et al. 1998:47) because of taphonomy. Zollikofer et al. (1998) used CT and 3D reconstructions to remove plaster applied in previous reconstructions. They mirrored the right side of the face onto the missing left side of the face. The missing portion of the braincase was also digitally reconstructed, allowing the authors to create a virtual endocast and reconstruct the right bony labyrinth and paranasal sinuses (Zollikofer et al. 1998).

Distorted and fragmented specimens can also be digitally restored and reconstructed using CT data. Zollikofer et al. (2005) looked at the skull of a fractured *Sahelanthropus tchadensis* skull (TM 266-01-60-1). They were able to digitally remove the matrix and reconstruct the specimen. Their study found that the specimen was not as originally described and that it was closer to later hominids than previously suggested (Zollikofer et al. 2005). Similarly, Ni et al. (2012) looked at the ear structure of the fossil primate *Chelicebus carrascoensis*. While the structures had been offset from each other during fossilization, the authors were able to digitally restore them close to their original position (Ni et al. 2012). There is an abundance of published literature indicating significant reappraisals of anatomy and phylogeny based on CT data, even outside of paleoanthropology.

In petrophysics and the petroleum engineering, CT is valuable to look at core mineralogy, porosity, and fluid movement without destroying a core (Siddiqui 2001). A series of closely spaced CT scans from a core can create a three-dimensional representation of the core and internal volumes (Siddiqui 2001), similar to what is done with paleontological and medical scans. The digital data of the intact core sample stay preserved even after the sample is physically altered due to extensive plugging for conventional and special core analysis tests.

CONSERVATION

Many fossils are in fragile condition or hold special importance (i.e., type specimens or lagerstatten). In these situations, museums are, legitimately, restrictive in allowing excessive access or destructive analysis to these specimens. Certain analytical techniques, such as grinding specimens to look at internal anatomy, destroy specimens. CT scanning is generally considered nondestructive because the original specimen remains intact, while most of the same data are retrieved (Carlson et al. 2003, Bruner and Manzi 2006, Carlson 2006, Rowe et al. 2011, Ni et al. 2012, Gee 2013).

CT data are recorded as digital files. Digital files must be saved with appropriate backups (Chiorenau et al. 2008, Rowe and Frank 2011), such as in multiple formats and at multiple locations, to ensure they are not lost nor corrupted. One immediately clear benefit is that these images can be used as backup, much like photographs, in case the original specimen is damaged or lost. These data also have the benefit of being reusable without loss of data, if they are properly archived. One method is to save files in multiple formats and locations (Rowe and Frank 2011). However, the longevity of electronic data and their respective formats is uncertain. A solution is to print individual slices onto archival photographic media or paper. Since CT scan images are gray scale, the printed copies are more stable than color photographs (CCI 2013). In the event that both an original object and the CT data are lost, these printed copies can provide an archive of these digital slices and may potentially redigitized in the future.

Images from CT scans can provide accurate measurements, making them useful for collecting metric data. Measurements (such as linear and volumetric) can be collected using software applications once an accurate reference measurement is set. Since CT can also be used to generate volumes such as surface models and endocasts (Bushwick 2011a, Ni et al 2012, Rowe and Frank 2011), these data can be an alternative to using actual specimens. This potentially leads to less handling of a physical specimen, since data can be collected from a digital model.

Also, these datasets and models can be shared, rather than shipping actual specimens. The reduced strain and handling of specimens reduces the potential damage from mishandling of specimens. Whenever a specimen is handled or placed in a container to ship, even with the greatest precautions, there is an increased chance of the specimen being damaged or lost. For rare and type specimens, the loss of information is even more significant. An added benefit is cost savings. Sending data via disk results in lower shipping and insurance cost than sending a specimen. Sending data electronically (i.e., file transfer protocol or email) further reduces cost (Chiorenau et al. 2008, Rowe and Frank 2011). Another advantage of the digital format is that, with the help of appropriate software, the end user can process the raw data to generate new and different renderings in two or three dimensions, thus allowing new interpretations to be made (Ni et al. 2012). This repeatability is essential to science.

CT can also be used to detect past conservation treatments, to detect reconstructions, and to detect fraud. This knowledge can help determine the stability of specimens and may dictate future treatments, such as support systems or the types of adhesives to apply. Ideally, past conservation and mounting treatments should be fully documented. However, the lack of proper documentation can leave future museum staff in the dark about what has happened to a specimen and why it is deteriorating (Fitzgerald 1988, Lindsey 1991).

Plaster has a negative long-term impact on museum objects (Lindsay 1991, Shelton and Chaney 2005, Lee 2013). Plaster has a similar chemistry to bone. In CT scans, this may make it difficult to separate (Zollikofer et al. 1998); however, this may be overcome depending on X-ray energy and density distribution (Bruner and Manzi 2005, Schoenemann et al. 2005). This principle can also apply to other materials used in past

Figure 1. *Equus simplicidens* (JWT 774) maxilla, ventral view. Top image: original specimen. Bottom image: CT reconstruction with plaster digitally removed. Arrow shows wire lattice used in reconstruction.

restorations, such as epoxy or wood. If the material used has different phases, they may be detected using CT and show the extent of restoration, the material used, and the long-term stability of the specimen.

A good case study is the paleontological specimen JWT 744, the maxilla of the Pliocene–Pleistocene horse *Equus simplicidens* from Cita Canyon, Texas. In the past, plaster was used to reconstruct the palate and hold the left and right cheek teeth together. In the specimen, the plaster is visually distinguishable from the original material. The specimen underwent a CT scan in part to determine the extent of plaster reconstruction. Data were collected using a medical scanner at the Bob L. Herd Department of Petroleum Engineering at Texas Tech University. The scan data showed different density peaks, or phases, for the fossil and plaster. This revealed the extent of plaster reconstruction and also revealed that a wire mesh was embedded in the plaster during the reconstruction (Fig. 1). The presence of the plaster and wire mesh may lead to the deterioration of the specimen, such as cracking, if not properly conserved.

A similar process was carried out for the holotype of *Equus simplicidens* (TMM 40287-92), an upper molar from the Blanco Formation of Texas. E.D. Cope first described it in

Figure 2. *Equus simplicidens* (TMM 40287-92) upper left cheek tooth. Top image: original specimen. Bottom image: CT reconstruction with plaster removed.

1892; however, plaster was used to reconstruct a portion of the holotype, including the protocone. The plaster is well cemented to the specimen, and removing it will likely cause significant damage. However, the original fossil underwent a CT scan and was digitally reconstructed by digitally subtracting the plaster (Fig. 2) at the University of Texas' High-Resolution X-Ray CT Facility. This is scientifically valuable for type specimens, where damage can cause significant scientific loss. This is also scientifically valuable with regard to horses. The morphology of horse teeth is variable within and between species, even varying within an individual with tooth wear. The cusp pattern can be distinguished in CT; this digital data set can be shared, sparing the holotype from the mechanical grinding.

A well-known example of uncovering past reconstructions is a specimen of the plesiosaur *Kronosaurus*, nicknamed "Plasterosaurus" because of the extent of plaster reconstruction. The specimen was originally incomplete, and approximately one-third of it was reconstructed in the early and mid-20th century, with at least some fossil material embedded in plaster (Switek 2011). While large portions may not be removable from plaster, CT scans may be useful in digitally separating the original fossil material from plaster and creating a more accurate reconstruction. There are several good case studies of using CT to look at fossil specimens before, or in lieu of, preparing them. CT can also be used to scan a specimen before preparation in situations where the specimen is not visible (such as in a field jacket or matrix), allowing staff to determine the safest way to prepare a specimen. However, this depends on a reliable and significant contrast between fossil and matrix. Brochu (2000) looked at the skull of a mature *Tyrannosaurus rex* ("Sue") at the Field Museum of Natural History to reconstruct its endocast before preparation. This virtual endocast provided information on the specimen without damaging it; this is valuable because of the completeness and preservation of the specimen. The information derived from the specimen is useful for taxonomic comparisons between therapods and birds, as well as acting as a guide for fossil preparations.

Neoceratopsians are very common Cretaceous dinosaurs; however, there is limited knowledge of their embryonic stages because of small samples. Balanoff et al. (2008) looked at the first embryo of a neoceratopsian preserved within an egg. On account of the specimen's uniqueness and fragility, it could not be physically prepared. In lieu of traditional preparation, Balanoff et al. (2008) CT scanned the specimen. The resulting dataset provided some taxonomic information, as well as ontogenetic transformations that occur in Neoceratopsia. While the condition of the specimen did not allow a very precise taxonomic determination, the study demonstrates how CT can be used to get invaluable data without damaging or destroying a priceless specimen.

Gee (2013) looked at the preservation of conifer pine cones from the Jurassic-aged Morrison formation. While several have been found, the overall number of fossilized plant specimens is low. Furthermore, there is limited information that can be gained without destructive dissection. However, Gee (2013) was able to determine the number of seeds, chiralty (the direction of spiral), and the number of spirals, allowing family level determination without destruction of rare specimens.

Fossils, especially complete and rare fossils, tend to hold high value, not just in publicity but also commercially. This is driven, at least in part, by the publication in popular articles discussing fossils and their financial value (cf. Osborne 2009, among others). One unfortunate side effect is that fossil forgeries are made to satisfy and profit from the demand for complete fossils. Frauds range from complete forgeries to real fossil specimens "enhanced" to look more complete and have fooled people from amateurs to professional collectors and paleontologists (Rowe et al. 2001, Mateus et al. 2008, Zipfel et al. 2010). Well-known fossil forgeries include the Piltdown Man and *Archaeoraptor*. There are several ways to distinguish frauds from real, unadulterated fossils, depending on the extent of forgery. This includes visual inspection (by eye or under microscope) to observe unusual color differences, poorly set waxes or glues, and texture. Tests with chemicals, such as acids or solvents, may also be useful (Mateus et al. 2008).

Computed tomography can provide one major tool for distinguishing forgeries from real fossils. As mentioned earlier, CT (and traditional radiographs and X-rays) can differentiate densities in scanned materials, such as original fossil from glues (Mateus et al. 2008). Rowe et al. (2001) looked at the specimen of *Archaeoraptor* from China, which had been proposed as an intermediary between dinosaurs and birds. However, after undergoing a CT scan, the specimen was shown to be a forgery. The slab contained real fossils from at least two different species, a layer of grout, and a single bottom piece of shale (Rowe et al. 2001). CT can be used to determine the authenticity of future potential acquisitions. Depending on the size of the specimen and the potential cost of CT scan, it may be more appropriate to use other tests first. Regardless, CT and other tests for forgeries cannot replace proper provenance research.

CT has frequently been touted as a nondestructive alternative to past research and conservation techniques. However, one area of concern is the amount of radiation fossils are exposed to. Some institutions use medical scanners, which typically emit X-rays below 125 keV, although some may go up to 140 keV. High-energy X-rays, such as those used by industrial scanners, can give better resolution (Ketcham and Carlson 2001, Curtin et al. 2012), but they also expose fossils to greater radiation. One question regarding further study is how X-ray radiation, even on short time scales, affects the object scanned.

It has been observed that exposure to visible and ultraviolet light can have various detrimental effects on museum objects, including discoloration, embrittlement, and other chemical changes (NPS 2000, 2006, 2012). Richards et al. (2012) have found that, when exposed to X-rays during synchrotron microtomography, modern and fossil bones show bands of discoloration. It has yet to be shown whether this is a purely aesthetic change, or whether it can potentially affect the long-term stability of specimens. Ravelli and McSweeny (2000) found that X-rays could change the molecular structures in modern (nonfossil) specimens when used for protein crystallography. While fossils have lost their protein structure, the results from Richards et al. (2012) and Ravelli and McSweeny (2000) bring up an important question: if X-rays from CT can change the structure of the object under study, how safe are the long term? While it seems a better tool than more destructive analysis, much more work is needed to determine how CT affects overall stability of specimens.

Education

Handmade casts are commonly used in paleontological exhibits to show rare or missing parts. However, these can be time consuming and difficult to make, and they require skilled workers to not damage the original fossil. Also, handmade casts are likely to carry some form of "artistic error," even unintentional. Accurate models can be printed without touching or damaging the original specimen (Allard et al. 2005, Bushwick 2011a). Rare specimens, by definition, do not exist in sufficient numbers for a large group of people (such as in a classroom) to use. As such, they typically are not used in labs or classrooms because they cannot be easily repaired or replaced. Rapid prototyping/3D printers can potentially print enough models for students (or at least groups) in classrooms to use in the place of delicate specimens that will break with mishandling.

CT data, as well as laser surface scanning data, can be used to create virtual surface models. One example of a virtual exhibit is the Northwest Palace at Nimrud, in modern day Iraq. Portions of the temple were photographed, and a digital and 3D model was created at the Metropolitan Museum of Art in New York City (Bawaya 2010). Chiorenau et al. (2008) similarly use a series of panoramic images to create a 360° mosaic, which can be set in a series to create a virtual tour of locations. Data collected from three-dimensional maps (including geographic information system data) and computer aided design (CAD) can be used to create virtual sites, such as excavations. These virtual

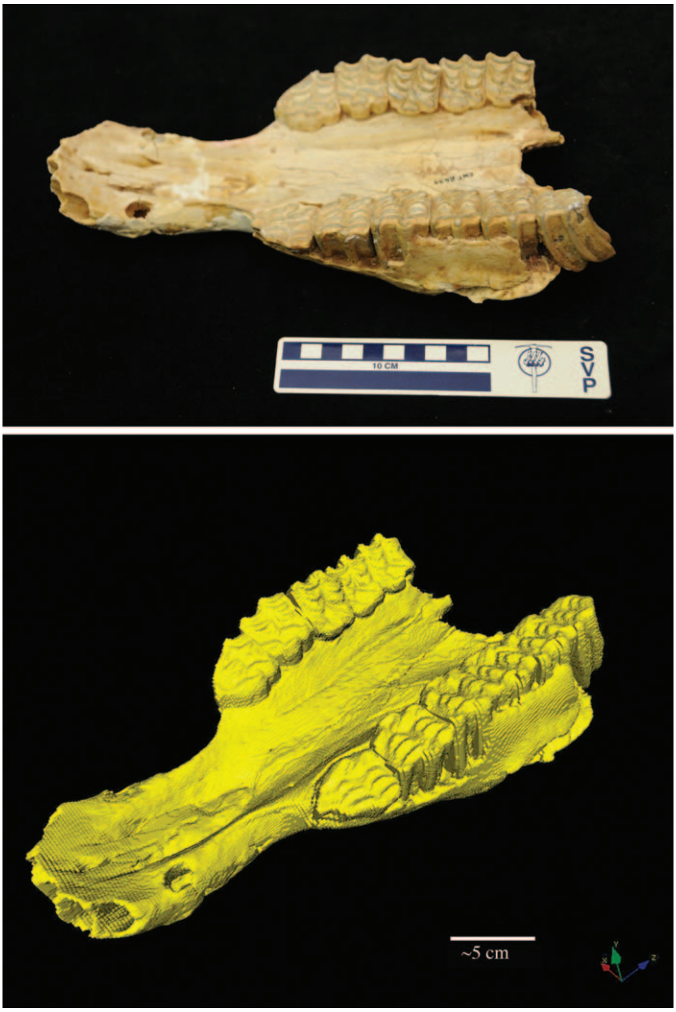

Figure 3. *Equus simplicidens* (CWT 2639) maxilla, ventral view. Top image: original specimen. Bottom Image: CT reconstruction.

excavations can be used in exhibits, or displayed in classrooms to illustrate methodology. They can also be used to show an artifact or fossil *in situ* (Carson 1997).

While Bawaya (2010), Carson (1997), and Chiorenau et al. (2008) created virtual models using photographs, 3D virtual models can be created for natural history collections using CT (Figs. 3 and 4). These models and animations can be made publicly accessible, such as on Web sites. Examples include Digimorph (www.digimorph.org) and WitmerLab's 3D Visualizations (http://www.oucom.ohiou.edu/dbms-witmer/3D-Visualization.htm). Not only do these sites act as digital repositories for CT data, virtual models (i.e., movies and animations) are publicly accessible. This allows a form of access for the general public, students, and educational groups who would not be able to physically see a specimen. This may lead to issues of intellectual protection and copyright of data, discussed below. Depending on the quality of the virtual model, these models may also be used for research purposes.

Figure 4. *Equus simplicidens* (TTU-P06364) partial mandible, dorsal view. Top image: original specimen. Bottom image: CT reconstruction.

Data from CT and laser scanners can also be used to print models, which can be scaled in size to fit various needs, such as exhibits or classes (Allard et al. 2005, Bawaya 2010, Bushwick 2011a,b). These virtual surface models can be saved as a surface image (i.e., stereolithography) and sent to a digital printer to create accurate physical models. Three-dimensional printers can work using either additive or subtractive manufacturing and use materials such as resins, plaster, and metals (Sachs et al. 1994, Allard et al. 2005, Silva et al. 2008, Bradshaw et al. 2010, Dickey 2013, Echenberg 2013). The printing material will typically be determined by cost and the planned use of an object. A plaster print might be appropriate for a lab course, while a resin printout would be more appropriate for an exhibit because of its lower weight. The printout of a specimen could also be printed in parts. This is very useful in anatomy course elements that are made up of smaller bones, such as the skull. Having a puzzle will allow students to see how the internal anatomy fits together without breaking apart the original fossil. While initially expensive, 3D printers, rapid prototyping, and stereolithography have been becoming more affordable while providing better print qualities (Bradshaw et al. 2010, Dickey 2013, Echenberg 2013).

Allard et al. (2005) used a laser surface scanner to scan a human skeleton to create a surface image and created a 3D printout using plaster for exhibits. The remains were from an archaeological site containing remains of the Mennonite community; the original remains were not displayed to respect the group's cultural wishes. While some detail and resolution were lost during the surface smoothing and printing processes, they found the loss was not significant enough to impact the exhibit. Every step from data acquisition to printing, as well as data protocols, should be reviewed to reduce errors. Accuracy and quality most likely improve with faster, cheaper, and more precise printers. The degree of desired accuracy will also vary depending on the purpose of the end result, such as exhibit versus research (Allard et al. 2005, Silva et al. 2008). Lee (2013) also describe using a surface scanner to scan fossilized whale remains from Chile, with plans to create 3D printouts for exhibit in the Smithsonian, while the original remains stay in Chile. Not only does this protect specimens from the dangers of transport, it provides access for visitors who would not be able to visit South America or access museum collections.

For engineering drawings, a combination of CT and 3D printing can help students visualize complex objects such as engine blocks and pumps by looking at different sections made from original CT scan images and CAD. Three-dimensional printouts can similarly be used in conjunction with museum exhibits. Rather than just having "see but do not touch" exhibits, museums can have printouts of selected specimens that visitors can touch, expanding their experience. A movie from CT scans, such as rotating movies or cut-away sequences, can also show different features (e.g., brain cases) that visitors and students will miss from just seeing a fossils' external anatomy.

One significant drawback in sharing virtual models is that they may be used in making unauthorized reproductions. While sharing data is invaluable in the sciences, unauthorized reproductions of virtual models can potentially be used for commercial or nonacademic/noneducational uses or violate intellectual property (IP) rights (Bradshaw et al. 2010, Farke 2013). While an exhaustive discussion of all applications of IP/copyright law is beyond the scope of this paper, there are some questions regarding how publicly available CT data affects research. Who receives priority in publications based on CT—the individual who funded/collected the data, or the individual who downloaded the data from a public Web site and finished the analysis first? If an institution makes CT data available for academic use, what recourse do they have for an individual/group who uses the data for commercial use?

The most common solution to this issue is for museums to require researchers and educators requesting digital images to sign agreements explicitly stating permitted uses for data and reproductions of images. The institution housing the fossil may charge fees for image usage, generally depending on level of staff involvement. Although this will not protect against unscrupulous users who will violate an agreement, it provides formal guidelines for ethical researchers. This process is already in place at many institutions for photography and data, so it could readily be extended to CT data (for data that are and are not publicly accessible online). Institutions could also state, *a priori*, on Web sites and portals that data are for educational and/or personal use, not for commercial use. This potentially can afford legal protection, depending on jurisdiction. Carson (1997) and Bradshaw et al. (2010) give discussions on copyright and IP law protecting research data and printouts in the USA and UK, respectively; however, as these types of data and objects become more common, such laws are likely to change.

Another solution is to either delay/embargo data from being posted online until after publication or to place low-resolution images online. The former is feasible. The latter is technologically feasible. However, this process may increase cost, since time and computer resources must be spent in creating two models: a high-quality research version and a low-quality public version. These options can protect the researcher who funded/collected the data for publication until the researcher has published the work. The Web sites/portals can still provide a statement limiting usage as stated above. Depending on local copyright and intellectual property laws, researchers and CT portals may have varying options.

Conclusions

Computed tomography is a powerful tool with several applications in the Earth sciences. While its primary use for several decades has been in research applications, a recent focus has been to use it in conservation, archiving, and education; however, these areas are still underutilized. While it may be difficult to finance CT, the costs for scans and 3D printing/rapid prototype are decreasing, making them more accessible for a variety of institutions. This paper elaborated on some of the current nonresearch uses of computed tomography that can be further developed to allow greater access to objects, as well as their archival purposes. Whenever possible, museum objects should be scanned, not just as a research tool, but also to complement current conservation and education techniques.

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