Journal of Paleontological Techniques

Number 21 - Dec 2018

EFFICIENCY, WORKFLOW AND IMAGE QUALITY OF CLINICAL COMPUTED TOMOGRAPHY SCANNING COMPARED TO PHOTO-GRAMMETRY ON THE EXAMPLE OF A *TYRANNOSAURUS REX* SKULL FROM THE MAASTRICHTIAN OF MONTANA, U.S.A.

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ABSTRACT

Imaging is crucial to gather scientific data in paleontology. Photogrammetry is currently a frequently used technique for surface imaging, producing high-quality 3D surface data. Clinical computed tomography (CT) scanners are interesting for paleontological research because of their high availability and the potential to image internal structures in addition to the surface. In this study we report the technical effort, workflow and image quality of clinical CT compared to photogrammetry for a large fossil. The fossil investigated in this study is the skull of a *Tyrannosaurus rex* (MB.R.91216) from the Maastrichtian of Montana, U.S.A., of which 47 bone elements are preserved. CT scanning was technically feasible in all bone elements and 3D models were generated from CT data and photogrammetry. The overall scanning procedure time measured 83 min 51 sec. The overall CT data volume measured 36,265 GB. The overall radiation exposure (DLP) measured 62,313.6 mGy*cm. The total costs were calculated with 243.17€ and 408.18€ for CT and photogrammetry, respectively. This study shows that a clinical CT scanner can be used for imaging even large paleontological objects with high density. In comparison to CT scanning, the data-capture effort of photogrammetry is directly linked to the size and color of the specimen and to the complexity of its shape. While those factors influence the photogrammetry-based 3D model and the quality of its details, the CT scan is mostly free of these variables. Unlike the acquisition and calculation time in photogrammetry the CT scanning time for large and small objects measures roughly the same, as this method is independent of the specimen's shape and complexity.

Keywords: cranium, dentary, Theropoda, 3D imaging, methodology

RESUMO [in Portuguese]

A geração de imagens é crucial para reunir dados científicos em paleontologia. A fotogrametria é atualmente uma técnica frequentemente usada para obter imagens de superfície, produzindo dados de superfície 3D de alta qualidade. Os scanners de tomografia computadorizada clínica (TC) são interessantes para a investigação paleontológica devido ao facto de estarem acessíveis e ao potencial para visualizar estruturas internas e de superfície. Neste estudo debruçamo-nos sobre o esforço técnico, fluxo de trabalho e qualidade de imagem da TC clínica em comparação com a fotogrametria no estudo de um fóssil de grandes dimensões. O fóssil investigado neste estudo é o crânio de um *Tyrannosaurus rex* (MB.R.91216) do Maastrichtiano de Montana, EUA, que contém 47 elementos ósseos preservados. A tomografia computadorizada foi tecnicamente viável em todos os elementos ósseos e foram gerados modelos 3D a partir de dados de TC e fotogrametria. O tempo total do procedimento de TC durou 83 min 51 seg. O volume total de dados de TC atingiu os 36.265 GB. A exposição global à radiação foi de 62313,6 mGy*cm. Os custos totais foram calculados em 243,17€ e 408,18€ para a TC e fotogrametria, respectivamente. Este estudo mostra que uma tomografia computadorizada clínica pode ser usada para gerar imagens de objetos paleontológicos grandes com alta densidade. Em comparação com a tomografia computadorizada, o esforço de captura de dados da fotogrametria está diretamente relacionado com o tamanho e cor da amostra, bem como à complexidade da sua forma. Embora esses fatores influenciem o modelo 3D gerado com base na fotogrametria bem como a qualidade de seus detalhes, a tomografia computadorizada é praticamente imune a essas variáveis. Ao contrário do tempo de aquisição e cálculo na fotogrametria, o tempo da TC para objetos grandes e pequenos é aproximadamente o mesmo já que esse método é independente da forma e complexidade da amostra.

How to cite this paper: **Hamm, C. A., H. Mallison, O. Hampe, D. Schwarz, J. Mews, J. Blobel, A. S. Issever, and P. Asbach. 2018.** Efficiency, workflow and image quality of clinical Computed Tomography scanning compared to photogrammetry on the example of a *Tyrannosaurus rex* skull from the Maastrichtian of Montana, U.S.A. Journal of Paleontological Techniques 21: 1-13**.**

INTRODUCTION

Tyrannosaurus rex, the embodiment of a terrestrial top-predator, is probably the most stunning dinosaur, recognized by every child and adult, and still stimulates the imagination of the public. After more than 100 years of research, *Tyrannosaurus rex* is still a welcome subject of research for paleontologists. The earliest documented remains of the theropod dinosaur *Tyrannosaurus rex* are teeth from the Denver Formation near Golden, Colorado, found in 1874 (Breithaupt et al., 2005). Since then, around fifty skeletons of *Tyrannosaurus rex* have been found since Barnum Brown excavated the first partially preserved specimen in Wyoming in 1900 (Larson, 2008), today stored in the Natural History Museum in London. The North American dinosaur species is considered to have been one of the largest theropod dinosaurs – only the North African *Spinosaurus* and the Argentinian carcharodontosaurid *Giganotosaurus*, both from the Early Cretaceous period, were bigger (Coria and Salgado, 1995; Calvo and Coria, 2000; Dal Sasso et al., 2005; Ibrahim et al., 2014). The here investigated *Tyrannosaurus rex* was found in 2012, a skeleton unearthed from the Hell Creek Formation in Carter County, the southeast corner of Montana. This individual is well preserved, with 170 fossilized bones present, including a nearly complete skull. That skull therefore ranks as one of the top three, following "Stan" (BHI-3033) from Harding County, South Dakota, which has the so far most complete skull ever found, only lacking right articular and left coronoid of the lower jaw (Larson, 2008), and "Sue" (FMNH PR2081) from Ziebach County, also South Dakota, with a damaged left temporal region and broken-off left postorbital (Brochu, 2003). Since the new *Tyrannosaurus rex* is a subject of great interest for research, imaging is a crucial tool for acquiring scientific data.

Computed tomography (CT) is of irreplaceable value in clinical medicine, and continued research is still leading to increasing imaging capabilities for nearly all organs and medical conditions. The steadily improving CT technique is also useful in the field of paleontology. In recent years several computed-tomographic analyses of the braincases of fossil tetrapods and other fossil specimens have been performed with the aim of investigating anatomical structures and evolutionary development (Cruzado-Caballero et al., 2015; Knoll et al., 2015; Benoit et al., 2016; Paulina-Carabajal et al., 2016). CT scans provide insight into the internal 3D anatomy of the investigated specimen, which can be used as a basis for the reconstruction of otherwise obscured anatomical structures. Additionally, the information gathered from CT scans provides a basis for higher-level scientific questions such as simulations of biomechanics, animal behavior and physiology (Snively and Theodor, 2011; Cuff and Rayfield, 2013; Bourke et al., 2014; Racicot et al., 2014; Sharp, 2014). Although CT is commonly used in paleontology, only little technical information is available about the CT scan procedures and technical parameters (Cox, 2015). During the last few decades, the spatial resolution of clinical CT scanners has improved from 3 mm (1990) to 1 mm (2000) and 0.35 mm (2010) edge length of isotropic voxels. The wide availability of clinical CT scanners and their high spatial resolution, allowing surface rendering in addition to obtaining information from the inside of the fossil specimens, makes this technique particularly interesting for paleontological research (Schilling et al., 2014).

The best-established 3D imaging technique in paleontology is photogrammetry, since it can be applied to specimens of any size, provides the highest spatial resolution of all imaging modalities and can illustrate the specimen's actual color. Within paleontological research, there is a vast range of applications for photogrammetry (Mallison and Wings, 2014). Being the primary method of choice for all surface-only 3D visualizations (Sutton et al., 2014), photogrammetry facilitates studies that rely on the 3D surface architecture and 3D modeling of specimens, as for example body mass estimations or studies using Finite-Elements-Analysis (Rayfield, 2004). Its combination of versatility, movability and relative ease of use makes this high resolution method a universal tool for digitization of paleontological specimens.

The fundamental difference between CT and photogrammetry is the CT's ability to depict internal structures, while photogrammetry is a purely line-of-sight method for capturing outside shape, with a highly variable resolution from meters to microns (satellite images to electron microscope images) for one uniform workflow.

The purpose of this study was to analyze the technical efforts, workflow, and image quality of computed tomography using a clinical CT scanner for a large fossil specimen, the skull of a *Tyrannosaurus rex*, and to compare clinical CT with 3D digitizing by photogrammetry.

Institutional Abbreviations

BHI, Black Hills Institute of Geological Research, Hill City, SD, USA

FMNH, Field Museum of Natural History, Chicago, IL, USA

MB, Museum für Naturkunde Berlin, Germany

METHODS

Computed tomography (CT)

Acquisition technique

Owing to the large size of the skull, in particular the maxillary bones, a clinical CT scanner was used for imaging (Aquilion ONE- Vision Edition, Toshiba Medical Systems, Tochigi, Japan), which is housed at a university hospital in close proximity to the museum. This CT scanner is a 320-slice volume scanner with a gantry opening of 78 cm and a field-of-view of 50 cm in the x-y direction and 200 cm in the z direction. The following scanning protocol was used: collimation 80 x 0.5 mm, 135 kVp, tube current 700 mA. For reconstruction, we used a soft-tissue kernel with an image thickness of 0.5 mm and a reconstruction interval of 0.3 mm, which leads to 0.35 mm spatial resolution. In dense objects the highest voltage assures the best image quality by minimizing starvation of the X-rays by the object.

CT workflow analysis

The overall CT scanning procedure was assessed by measuring the acquisition time and adding up the positioning and post-scanning preparation times for each object. The smaller bone elements were scanned in the plastic safety-boxes used for transport (accounting for approximately 60 sec preparation time), whereas the larger bone-elements had to be removed from the boxes for precise positioning and were directly placed on the CT table (accounting for approximately 120 sec preparation time). The number of CT images (data volumes in gigabytes) and the radiation exposure (dose length product, DLP; measured in mGy*cm) were documented for each bone element. Also, the time to generate the 3D surface reconstruction, using dedicated commercially available radiological reconstruction software (Vitrea Enterprise Suite, version 6.7.2, Vital Images Inc. Minnetonka, Minnesota) was measured for the bones, which were also assessed by photogrammetry. The 3D reconstruction was performed on a Hewlett Packard desktop computer with the following specifications: 64-bit operating system, 3.5 GHz Intel Xeon CPU, 16 GB RAM, SSD hard drive, Windows 7 system platform. A CT scanning-process cost analysis was performed by calculating costs for human resources and technical costs (direct costs) as follows: binding of human resources is based on one radiological technologist, with costs of € 0.46 per minute (Huppertz et al., 2011). The total direct costs for CT scanning was set to € 2.44 per minute of scan time, assuming use of a CT scanner at a general hospital (Huppertz et al., 2011).

CT image-quality analysis

The beam-hardening artifacts at the surface and within each bone element were assessed on a 4-point scale (0 = no artifact, 1 = minor artifact, 2 = major artifact, 3 = non-diagnostic image) by a radiologist with more than 10 years of experience with CT scanning of paleontological objects. The presence of any metallic structures added during the process of preparation of the fossil (e.g. metallic mesh or nails) was recorded. For analyzing the quality of the 3D surface reconstructions, dense point clouds were generated from the CT data from which true 3D meshes were extracted by one of the authors, using the program suite AMIRA 6. Segmentation was performed by using a threshold, as any other method would have been too time-consuming.

All CT scan data regarding the here investigated specimen are deposited and available through the Department of Science Data Management of the Museum für Naturkunde, Berlin under https://dx.doi.org/10.7479/hyek-4pt0 (Asbach et al., 2018; Clinical CT dataset *Tyrannosaurus rex* MB.R.91316. [Dataset]. Data Publisher: Museum für Naturkunde Berlin (MfN) Leibniz Institute for Research on Evolution and Biodiversity), shared under a CreativeCommons CC-BY-NC 4.0 international license.

Photogrammetry

Acquisition technique

Manual photogrammetry is considered the gold standard for surface analysis of fossil structures (Breithaupt and Matthews, 2001; Matthews et al., 2006; Falkingham, 2012; Mallison and

Wings, 2014). Here we report details of the process of photogrammetry for three bones of MB.R.91316 (right articular, T-36), representing a small bone; right lacrimal (T-10), representing a medium size bone; left dentary (T-28), representing a large bone with teeth) performed by a paleontologist with several years of experience in the field of photogrammetry research. The manual photogrammetry was performed on the basis of methods previously published (Mallison and Wings, 2014); therefore, this description is concise. In order to compare the CT scanning with photogrammetry, an optimum laboratory set-up was arranged (Figure 1). Its basic tools included a high-end digital single-lens reflex (DSLR) camera with additional equipment (lenses, camera stand, remote shutter release, LED ring flash, polarizing filters). Two separate photography stations with all around accessibility and a makeshift third station accessible from one side only were set up, so that the fossils could be photographed in different orientations without any overlap in the background between the image sets. This approach allowed the images to be used without background masking. As these stations can be used for a multitude of specimens in sequence, the added effort required to set up several is practically negligible. Each fossil was placed on the stations on cut-to-fit Ethafoam, as this is a soft but firm support material that can be easily cut with any knife. Several non-reflective scale bars were placed alongside the specimens for scaling the model during post-processing. Specimens were photographed in overview images for scaling, and in close-up views roughly perpendicular to the surface all around for model creation. Additionally, images were taken with the camera pointed into all recesses of the bones at many angles, as photogrammetry is line-of-sight and requires any feature to be depicted in several images in order to model it. The camera settings were selected as follows: ISO 100 to 400 (light sensitivity of camera sensor), autofocus single shot with center-point focus, aperture variable mode (aperture 7.1 to 11). The use of a LED ring flash allowed capturing images practically devoid of shadows.

Photogrammetry workflow analysis

The time required for the different steps of preparation of the photogrammetry set-up (including deconstruction), object-positioning (including repositioning for different perspectives), recording photographs, and post-preparation (storing of the object) was measured. Additionally, the process of converting the pictures into a 3D model was measured. The photogrammetry process cost analysis was calculated as a combination of costs for human resources and technical costs (direct costs) as follows: The binding of human resources is based on one paleontologist, estimated with the same costs (€ 0.46 per minute) as for one radiological technologist (to allow comparison). The total technical costs for the process of photogrammetry was based on a previously published study in which the authors estimated € 0.01 per photograph (Fahlke and Autenrieth, 2016), taking the total photogrammetry equipment cost of approximately € 1800 into account. Finally, the photogrammetry process-cost analysis per bone was calculated by multiplying the number of pictures by the cost per photograph plus the costs for bound human resources. This calculation is therefore only a rough estimate, as the actual number of images that can be taken with a camera before it breaks varies highly, and the costs for human resources are estimated by assuming those of a radiological technologist. The 3D models were generated by using Agisoft Photoscan Pro 1.2.6 (www.agisoft.com). The process of model creation consists of two main computationally expensive steps, alignment of the cameras (including feature detection and matching) and dense cloud generation (including image undistortion and depth map generation). The time required for each depends directly on the available CPU and GPU, and on typical high-power desktop PCs with high-quality graphics cards this typically takes several hours for a data set that consists of several hundred images. The time required to start each modeling step is in the order of under a minute, whereas scaling a model based on the scale bars included in the images typically takes two minutes. However, additional clean-up work on the dense point cloud, including removal of the background and of erroneous points, requires manual interference, the amount of which varies greatly and depends upon the initial set-up during photography. Here, we used a simple set-up without a complex lighting system, without the use of a turntable or color-controlled background, which resulted in a fairly high requirement for editing. The times given would probably vary significantly for other operators and for slightly different set-ups.

Figure 1: Photogrammetry setup with an example bone of *Tyrannosaurus rex*, MB.R. 91216 (nasal).

The photogrammetry data of the herein studied bones are deposited and available through the Department of Science Data Management of the Museum für Naturkunde, Berlin under https://dx.doi.org/10.7479/4b6c-n9rn (Mallison, 2018; Photogrammetry data *Tyrannosaurus rex* MB.R.91216. [Dataset]. Data Publisher: Museum für Naturkunde Berlin (MfN) Leibniz Institute for Research on Evolution and Biodiversity), shared under a CreativeCommons CC-BY-NC 4.0 international license.

RESULTS

The fossil

The specimen investigated here is a *Tyrannosaurus rex* (MB.R.91216), nicknamed "Tristan Otto", from the Maastrichtian (Late Cretaceous; approximately 68 Ma old) of Montana, USA. Most of the preparation of the fossil was performed by the company 'Prehistoric Journeys' in Sunbury, Pennsylvania. The fossil is privately owned (see data availability statement) and since December 2015 the entire skeleton is on display in the *Museum für Naturkunde*, Berlin, Germany.

The subject of investigation of this study was the skull. Anatomically, the entire skull of *Tyrannosaurus rex* comprises 1 fused braincase, 31 skull bones, and 14 mandible bones, amounting to a total of 46 bones (Brochu, 2003). The skull consists of 15 paired bones and the single vomer, of which 25 are preserved in "Tristan Otto". The mandible consists of 7 paired bones, of which 11 bones are preserved in "Tristan Otto" (see table in the supplementary material). The following bones are not preserved: the frontal (bilateral), parietal (bilateral), epipterygoid (bilateral), coronoid (bilateral), and left splenial bones. The preserved skull of "Tristan Otto", including the braincase and mandible presents 47 separately scanned bone elements, of which 4 are replicated parts of polyurethane resin (see table in the supplementary material).

The reassembled skull has a maximum length of 144.4 cm (right quadrate to premaxilla) and weighs approximately 180 kg. Therefore, "Tristan Otto" apparently is the current record-holder regarding skull length. "Stan" (BHI-3033) reaches a maximum anteroposterior length of roughly 140 cm (Hurum and Sabath, 2003) and "Sue" (FMNH PR2081) measures a maximum of 140.7 cm from the tip of the snout to the back of the left quadratojugal (Brochu, 2003).

Computed tomography (CT)

Applying the method of CT scanning and photogrammetry as a digitization tool, we were able to generate detailed 3D models of the head bones of the *Tyrannosaurus rex* (Figures 2, 3, and 4). Each technique presents with distinctive characteristics.

Figure 2: *Tyrannosaurus rex*, MB.R. 91216, Maastrichtian of Carter Co., Montana. Anterolateral view of the 3D model of the skull obtained by photogrammetry, the gold standard for 3D surface imaging in paleontology.

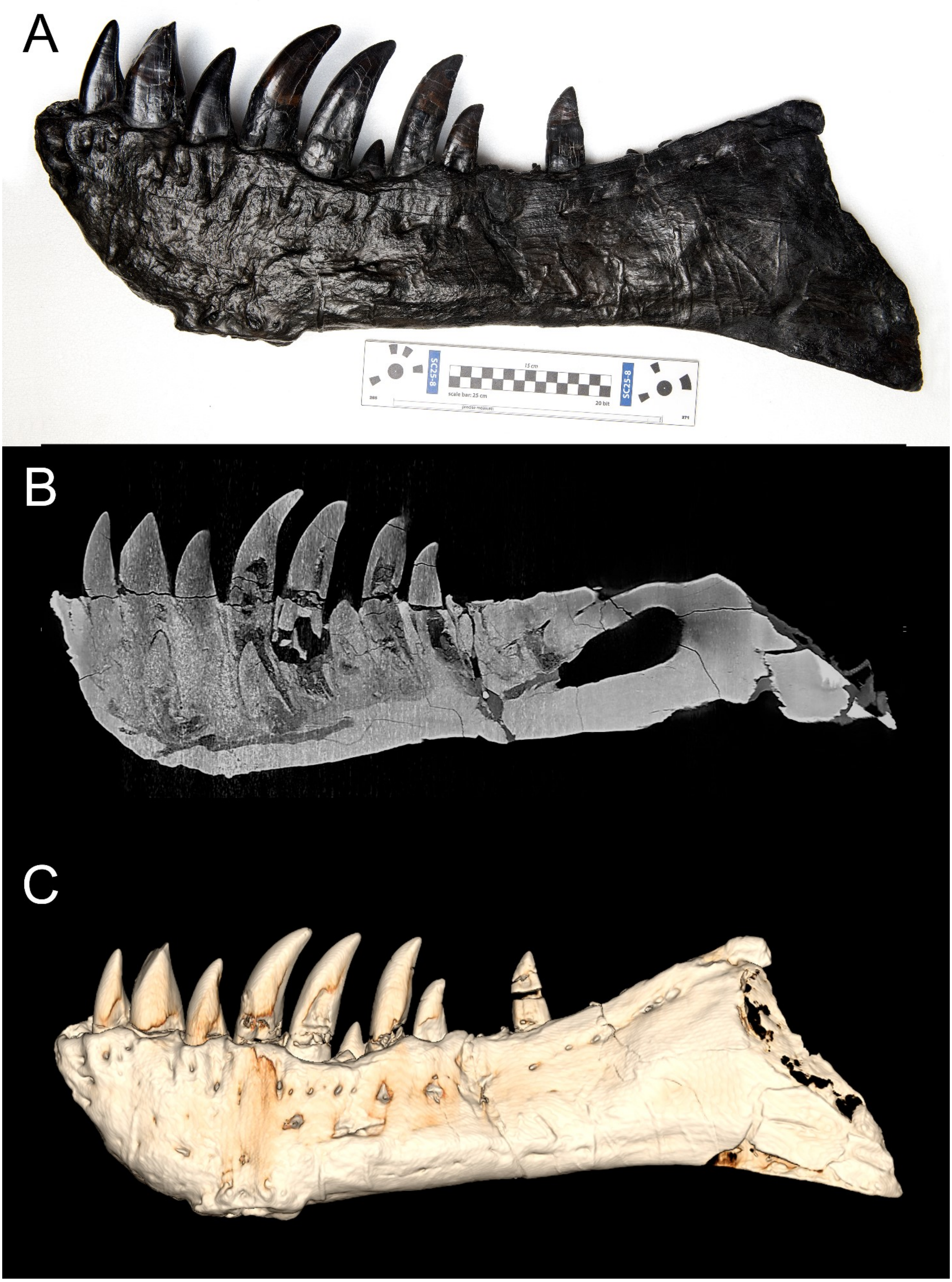

Figure 3: *Tyrannosaurus rex*, MB.R. 91216, Maastrichtian of Carter Co., Montana. A) Photograph of the left dentary in lateral view. B) sagittal CT reconstruction. C) 3D surface reconstruction (visualization) of the left dentary based on data from a clinical CT scanner.

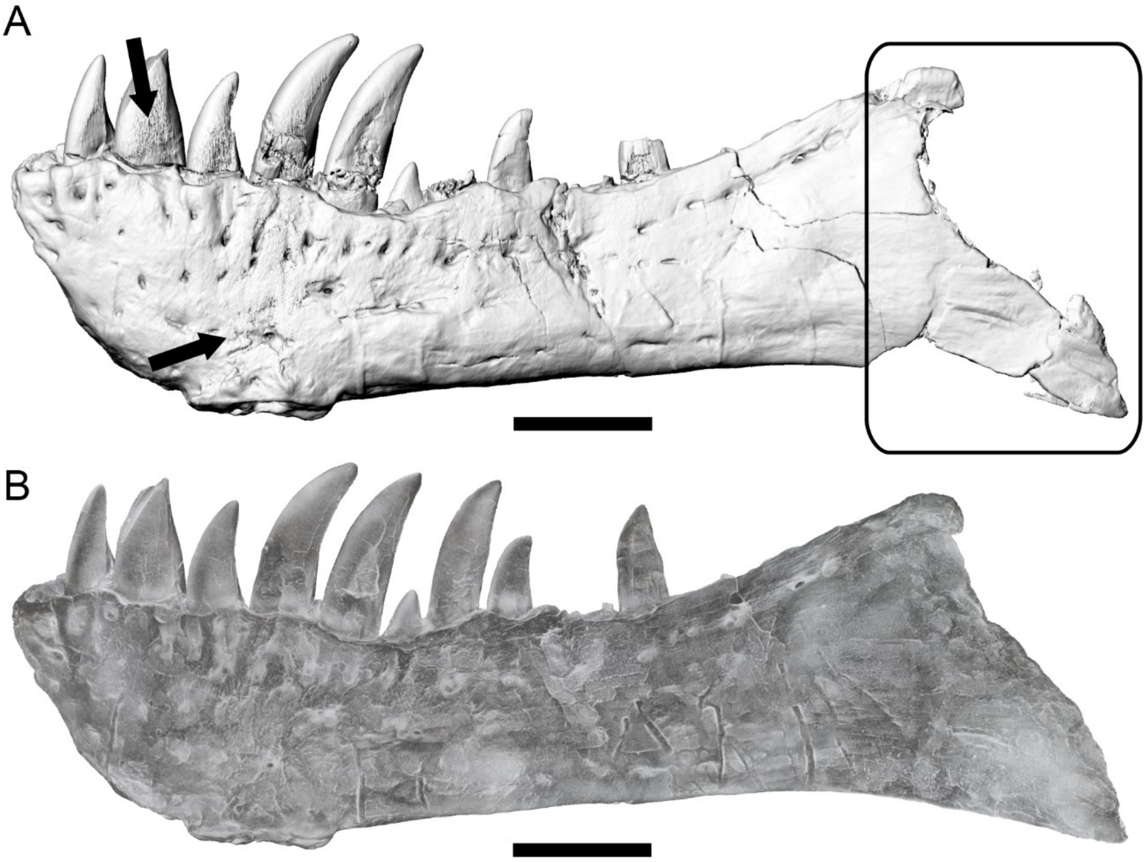

Figure 4: *Tyrannosaurus rex*, MB.R. 91216, Maastrichtian of Carter Co., Montana. Polygon meshes of the left dentary created from CT data (A) and through photogrammetry (B). Note: In (A), there are surface artefacts visible (arrows) which mandated the use of a segmentation threshold too high to capture the repair material especially at the distal end of bone (box – see also Figure 3C), at the base and in many teeth. Scale bar 10 cm.

CT workflow analysis

Despite the high density of the fossil, CT scanning was technically feasible in all the 43 bone elements investigated and in the 4 replicated bone elements (no non-diagnostic scans). 21 delicate, smaller bone elements were scanned directly in their safety-boxes, and 26 larger and sturdier bone elements were removed from the boxes and positioned on the patient table. The overall scanning procedure time was calculated by adding the acquisition times and the pre- and post-scan preparation times. The total acquisition time for the 47 bone elements was found to be 651 seconds (see table in the supplementary material). Therefore, the overall scanning procedure time was 651 sec + (21 x 60 sec) + (26 x 120 sec) = 83 minutes 51 seconds.

The overall data volume for the *Tyrannosaurus rex* skull measured 36,265 GB, and the overall number of slices was 62,328. The overall DLP measured 62,313.6 mGy*cm. The data volumes and the number of slices taken for each bone element are given in the table in the supplementary material. Using the dedicated radiological reconstruction software, the reconstruction time for each of the three abovementioned bones are listed in Table 1. An example of 3D surface reconstructions is shown in Figure 3.

With a total overall scanning procedure time of 83 minutes and 51 seconds the total costs are calculated as follows: (83 min 51 sec x human resources costs at € 0.46/min) + (83 min 51 sec x total direct costs for scanning at € 2.44/min) = € 243.17.

CT image-quality analysis

Beam-hardening artifacts at the surface were absent in 11 bone elements (as well as in 4 replicated bone elements), minor in 25 bone elements and major in 7 bone elements. Beam-hardening artifacts of the internal structures were absent in 26 bone elements (as well as in 3 replicated bone elements), minor in 16 bone elements (as well as in 1 replicated bone element), and major in 1 bone element (see supplementary information).

Table 1 **:** 3D surface reconstruction times

Bone element	**Time**		
	CT-based 3D reconstruction	CT Mesh	Photogrammetry (operator work time only)
T-10 (right lacrimal)	14 sec	2 min 35 sec	5 min 47 sec
T-28 (left dentary)	15 sec	~ 7 minutes	39 min 44 sec
T-36 (right articular)	14 sec	3 min 13 sec	9 min 31 sec

CT quality of 3D surface reconstructions – mesh generation

The segmentation and surface mesh generation in Amira 6 took 13 minutes for the three specimens together, of which the data load time consumed 7 minutes. The extracted polygon meshes consisted of 1,014,664 polygons for a file size of 8.5 MB for the right lacrimal (T-10), 2,973,652 polygons and 55.3 MB for the left dentary (T-28), and 584,173 polygons and 10.8 MB for the right articular (T-36) (Figures 4 and 5). The extracted polygon mesh of the left dentary (T-28) has a plethora of holes, because the threshold used for segmentation was too high to capture the repairs made to the damaged regions of the bone (Figure 5). A repeat extraction using a higher threshold captured these regions better, but suffered from massive surface artifacts on the anterior region of the bone, where the natural variation in mineral density and natural metallic content are high enough to cause the extracted surface to have a significantly different morphology from the physical specimen. Although the initial extraction was the less useful file for many potential uses (such as 3D printing) and gave the less accurate representation of the physical object, it gave a better representation of the real fossil, and was thus used for the comparative aspect of this study. More refined extraction techniques exist that are only marginally more time intensive, however, these techniques were not applied in this study.

Photogrammetry

The initial preparation and final removal after data capture of the work stations took 4 minutes 54 seconds. Specimen positioning took 3 min 42 sec (3 perspectives) for the right lacrimal (T-10), 7 min 32 sec (3 perspectives) for the left dentary (T-28), and 2 min 50 sec (2 perspectives) for the right articular (T-36). The post-preparation times were 30 sec for the right lacrimal (T-10), 1 min 12 sec for the left dentary (T-28), and 30 sec for the right articular (T-36), respectively. Additionally, the left dentary (T-28) was covered with a thin layer of cyclododecane spray to reduce shininess. Image capture took 4 min 58 sec for the right lacrimal (T-10) (224 images), 12 min 54 sec for the left dentary (T-28) (493 images), and 2 min 23 sec for the right articular (T-36) (197 images). In total, the process of photogrammetry data capture of the three bones took 41 min 25 sec, including the application of cyclododecane. Creation of the necessary project files in Agisoft Photoscan Pro required 60 seconds per specimen. In-program handling (starting the various calculation steps, scaling, alignment optimization) except for dense cloud cleaning took 2 min 33 sec for the right lacrimal (T-10), 2 min 41 sec for the left dentary (T-28), and 1 min 58 sec for the right articular (T-36). Manual cleaning of the dense point clouds took 3 min 14 sec for the right lacrimal (T-10), 17 min 3 sec for the left dentary (T-28), and 7 min 33 sec for the right articular (T-36). The resulting files are shown in Figures 4 and 5. The model of the right lacrimal (T-10) had 21,315,420 polygons and a file size of 427 MB as a PLY (polygon file format). The model of the left dentary (T-28) had 102,094,869 polygons and 2,044 MB, and the right articular (T-36) had 27,308,462 polygons and 547 MB.

Photogrammetry cost analysis

With a procedure time of 41 minutes and 25 seconds for the 3 represented bones the overall procedure is calculated as follows: (41 min 25 sec x human resources costs of € 0.46/min) + (914 pictures x € 0.01 per photograph) = € 28.19. Taking the average procedure time per bone element (positioning time of 4 min 41 sec, data capture time of 6 min 45 sec and post-preparation time of 44 sec = 12 min 10 sec), an average number of pictures per bone element (approximately 304 pictures) and the workstation preparation time (4 min 54 sec) into account, the total overall procedure costs are calculated as follows: 47 bone elements x ((12 min 10 sec per bone element x human resources costs of € 0.46/min) + (304 pictures per bone element x € 0.01 per photograph) + 4 min 54 sec x human resources costs of € 0.46/min)) = € 408.18. The 3D surface reconstruction times varied distinctly between the three bones investigated (Table 1).

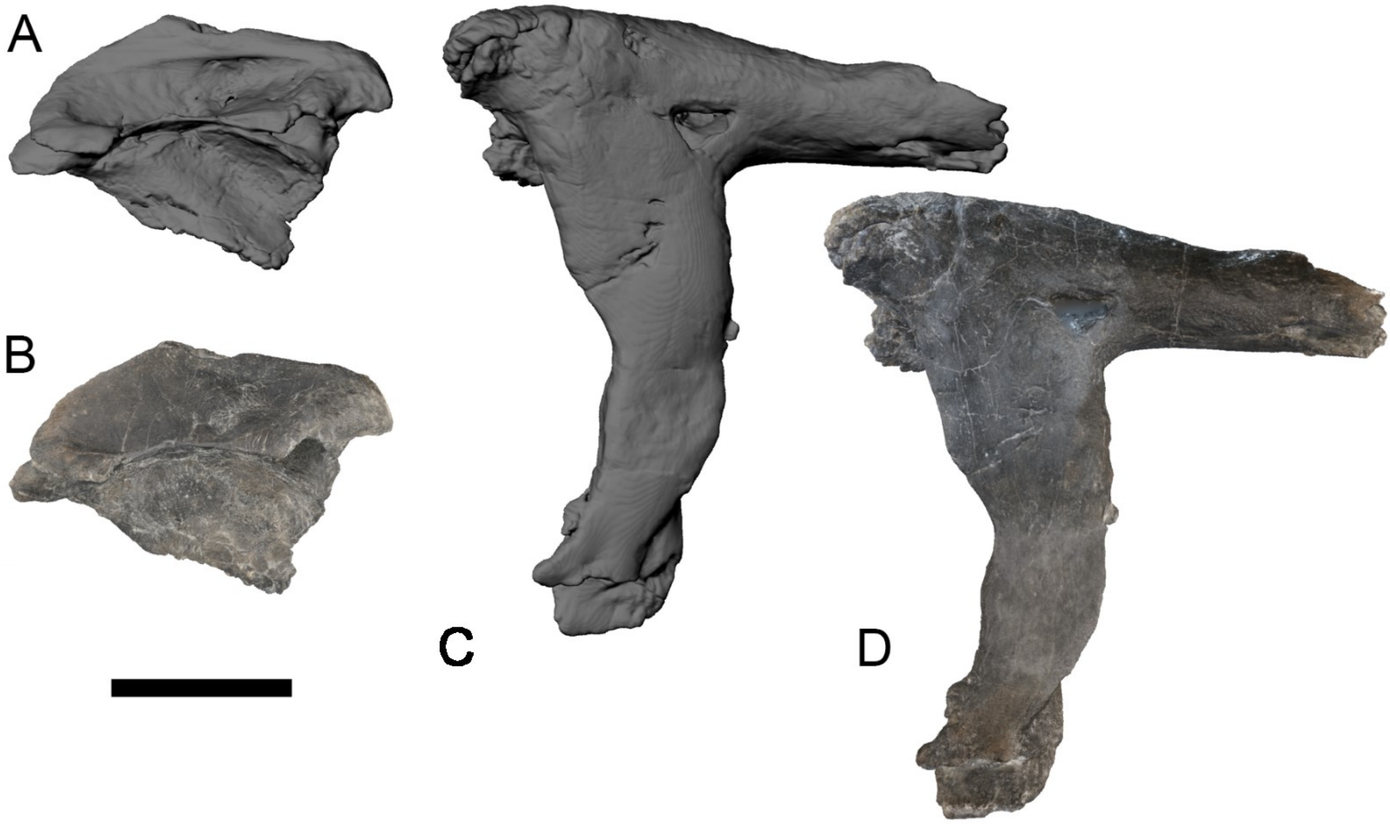

Figure 5: *Tyrannosaurus rex*, MB.R. 91216, Maastrichtian of Carter Co., Montana. Polygon meshes created from CT data and through photogrammetry (10 cm scale bar). A) right articular bone from CT. B) right articular bone from photogrammetry. C) right lacrymal bone from CT. D) right lacrymal bone from photogrammetry. Note: The deep recess in the right lacrymal is faithfully represented in (C), but is only seen as a shallow groove in (D). (A) and (especially) (C) show steps in the model caused by the relatively thick slicing in the CT, whereas the photogrammetry models' greater resolution creates much smoother surfaces.

DISCUSSION

From the perspective of three-dimensional digitization of fossil specimens, photogrammetry has become the gold standard for rapid surface capture in paleontological research (Sutton et al., 2014). Its striking features are its versatile applicability and relative ease of data capture. Furthermore, the possibility of obtaining images with sub-pixel resolution makes this method exceptionally accurate. A 3D model created by photogrammetry is based on actual pictures and hence is able to display the actual color of the fossil, although this is of minor scientific significance (Fahlke and Autenrieth, 2016). These features have even led to the use of photogrammetry in clinical medicine in certain instances, e.g. auricle reconstruction (Chen et al., 2015), lymphedema evaluation (Hameeteman et al., 2016), or 3D hand-imaging (Hoevenaren et al., 2015).

The focus of this study has been to analyze the technical effort, workflow, costs and image quality of using a clinical CT scanner for paleontological studies, performed on the skull of *Tyrannosaurus rex.* For a subset of bones, the clinical CT was compared head-to-head with the established standard method of manual photogrammetry. We considered giving special attention to acquisition time, costs, data volume, safety aspects and image quality. Despite the high density of the fossil (representing fossilized bone), CT scanning was feasible. As known from CT imaging of vertebral bodies after cement-augmented vertebroplasty, meaningful cross-sectional images could be obtained. In a total of 152.5 seconds (including scanning and preparation time) it was possible to obtain the basic information needed to produce a 3D model of the left dentary, one of the largest bones of the skull, based on clinical-CT imaging data. The same bone required a preparation and recording time of 20 minutes and 26 seconds to acquire the necessary pictures by manual photogrammetry. In direct comparison with photogrammetry, the CT scanning was therefore nearly 8 times faster in this example. This needs to be taken into particular account when one is using photogrammetry in clinical medicine, since the longer acquisition time has to be tolerated by the patient. Patient compliance and – especially – keeping still during the entire acquisition time is crucial for picture quality. Therefore, photogrammetric human face or whole-person capture is typically performed with expensive multi-camera rigs that take many images simultaneously, negating the relatively low acquisition price of the approach that we tested.

The 3D surface reconstruction time of the dentary bone was 15 seconds for the clinical CT data and nearly 20 minutes actual human work for manual photogrammetry. However, given the dependence of the photogrammetric modeling process on the available CPU and GPU of the used computer as well as the unpredictable necessity of additional cleaning of the models, 3D surface reconstruction in photogrammetry can require even more working time than recorded here. However, the spatial resolution is distinctly higher in photogrammetry (approximately 0.11 mm) compared with clinical CT (0.35 mm; Figures 4 and 5), which needs to be considered when one is comparing acquisition and 3D reconstruction times of the two imaging methods. A photogrammetric model at identical resolution could be produced in a much shorter time than by the approach taken here, although under no circumstances with the same speed as a CT scan. Bone handling and workplace set-up times are fixed, irrespective of the number of images captured. On the other hand, CT scanning provides cross-sectional information, which allows one to analyze the internal structure of the specimen, potentially yielding additional important knowledge. For this reason, CT scanning has become a prime method for the detection of fake fossils (Mateus et al., 2008).

When clinical CT and photogrammetry are compared, an important point to consider is the financial aspect. A direct comparison is barely possible, since the equipment for photogrammetry is commonly owned by the paleontologist, whereas access to a clinical CT scanner usually has to be obtained in a hospital or radiology practice. We attempted the best possible cost comparison between the two methods for scanning the entire skull, which revealed costs of € 243.17 for clinical CT scanning and approximately € 408.18 for photogrammetry. With this cost comparison we conclude that CT scanning is distinctly less expensive than photogrammetry, and is furthermore significantly less expensive compared with micro-CT scanning, which was previously stated to cost € 714 per specimen (Fahlke and Autenrieth, 2016).

Also, the 3D reconstruction for the CT images is much less time-consuming than photogrammetry. Note that this comparison omits the cost of the software and computers required for the two methods, as well as personnel costs incurred by post-processing; they can therefore only serve as very rough guidance.

To gain a full 3D surface model by manual photogrammetry, it is essential to take pictures from all sides and from various angles, which requires moving and repositioning the specimen several times, depending on its size and shape. In clinical medicine this demands a high level of compliance by the patient. Also, any handling of a fossil increases the risk of damage. That issue of safety is clearly minimized in the procedures for CT scanning, in which the specimen has to be placed on the CT table but in many instances can remain in its safety box (depending on the material and size of the box in relation to the gantry opening of the CT scanner). Also, it is normally not necessary to scan the fossil in several orientations, whereas a complete line-of-sight capture requires a minimum of two positions, doubling the need for handling. On the other hand it must be taken into account that the specimen has to be transported to the CT unit, whereas photogrammetry can easily be performed at the storage location of the specimen, minimizing the risk of damage during transport.

Furthermore, since the CT scans obtain multiplanar and volume information about the specimen, an analysis of internal structures in various planes is also possible. In this context, we discovered a hollow space in the right premaxilla, not visible from the surface observation, which makes this segment of bone prone to fracture. This finding was of significant importance for the paleontologists in relation to handling and storage. Additionally, some of the skull bones, in particular maxilla, lacrimal and postorbital, revealed internal sinuses and canals for blood vessels or the nasolacrimal duct. Tooth replacement can be studied by direct observation of the internal structures of the tooth-bearing bones premaxilla, maxilla, and dentary. Studies of the brain cavity and potentially even the reconstruction of an endocast from the braincase are made possible by the CT data. Therefore, a variety of future research questions can be addressed by clinical CT.

A further aspect in this comparison, which needs to be considered, is that not every photogrammetric data capture delivers a sufficiently detailed and complete model. The bones of "Tristan Otto" are especially difficult to photogrammetrize, as their color hardly varies, from "nearly black" to black, they are shiny (so that their brightness varies more with camera angle than does that of dull substances), and many skull bones have complex shapes with deep recesses. In addition, repairs on the bones were performed using a uniformly colored black plastic, which is the most difficult non-mirroring substance to digitize. Before the successful attempt reported here, the dentary T 28 had been photogrammetrized twice before. In the first attempt, the repairs at the posterior end of the bone were not modeled, and in the second several teeth were resolved as duplicate surfaces. The actual effort of digitizing was therefore approximately three times longer than for a single determination. In order to ensure success at the third attempt, the bone was coated with a thin layer of cyclododecane, applied as a spray. This layer reduces the shininess of the bone and altered the color to a wide variety of dark grey to light grey shades, increasing the probability of successful photogrammetric reconstruction. At the same time, however, the natural color of the specimen can no longer be captured accurately, thus sacrificing one of the key advantages of photogrammetric 3D imaging.

In comparison with the CT scan it is obvious that many factors influence the outcome of the quality of a photogrammetry-based 3D model, whereas the CT scan is mostly free of these variables. CT scanning time is more or less the same for large and small objects, and is independent of their complexity, whereas these factors can add a huge amount of acquisition and calculation time in photogrammetry, as its associated data-capture effort is directly linked both to the size of the specimen and to the complexity of its shape. The number of variables that need to be taken into account when photogrammetry is conducted appear to entail a high risk of error and to complicate workflows.

All in all, the distinct difference in the information obtained by these two methods is reflected in the depiction of color in the one case and internal structure in the other. Photogrammetry may be irreplaceable if very high spatial resolution and the correct reproduction of color are of crucial relevance, as in taphonomic analyses, geological analyses or analyses of descriptive character. In contrast, CT scanning offers a unique opportunity to acquire important and otherwise hidden information about the internal structures of fossil specimens, in addition to the surface structure, as similarly reported for micro-CT (Fahlke and Autenrieth, 2016). The possibility of merging these two methods in clinical medicine has been pointed out by several researchers, for example in the field of plastic reconstructive surgery (Tzou et al., 2014; Chen et al., 2015; Hoevenaren et al., 2015). Even now, photogrammetry has contributed in fields such as forensic medicine or reconstructive hand surgery to remarkable advances in imaging possibilities (Ey-Chmielewska et al., 2015; Hoevenaren et al., 2015). Furthermore, photogrammetry appears to offer a substantive alternative to CT in special circumstances in pediatric medicine, whereby radiation exposure can be omitted (Wilbrand et al., 2012).

In this study we compared two valuable imaging methods for paleontological studies. They provide different opportunities for the investigation and analysis of a paleontological specimen. Not only the possibility of virtual reconstruction of imaging data, but also the advantage of easily archiving, handling and sharing these data, lead to new opportunities in paleontology. Notwithstanding, an original fossil can be unique, fragile and difficult to examine, especially if several researchers are involved; in such cases the 3D reconstruction and cross-sectional data can be freely exchanged and made accessible to the scientific community.

Our study has some limitations. Since its focus was on the use of a clinical CT scanner, the process of photogrammetry was reported and evaluated in detail for direct comparison for three representative bones only, whereas CT scans were performed for the whole skull. The CT scan cost analysis is based on data from human patient examinations, not on fossil objects, since we did not consider increased wear and tear on the X-ray tube. The 3D reconstructions were conducted with different hardware and software, which might has affected the reconstruction times as well.

CONCLUSION

The use of a clinical CT scanner is feasible even for large paleontological objects with high density. Since the spatial resolution in computed tomography is considerably lower than in photogrammetry, while the latter lacks the ability to reveal internal structures, neither technique can replace the other. On the contrary, CT scanning and photogrammetry complement each other and can be used not only in paleontological research but also for comprehensive clinical imaging such as 3D simulation in reconstructive plastic surgery. The distinct characteristics of CT scanning and photogrammetry are of high interest in the context of clinical medicine, since the fusion of these two techniques gives opportunity for new ways in clinical imaging.

DATA AVAILABILITY STATEMENT

The specimen that is central to this work is privately owned, currently on display in the Museum für Naturkunde Berlin and has therefore a temporary inventory number (MB.R.91316). However, all digital data are deposited and accessioned in the Museum für Naturkunde (DOI: 10.7479/hyek-4pt0 (Clinical CT dataset *Tyrannosaurus rex* MB.R.91316 [Dataset], https://dx.doi.org/10.7479/hyek-4pt0; DOI: 10.7479/4b6c-n9rn (Photogrammetry data *Tyrannosaurus rex* MB.R.91216 [Dataset], https://dx.doi.org/10.7479/4b6c-n9rn).

ACKNOWLEDGMENTS

The authors would like to thank Niels Nielsen, the owner of the specimen, for making the skeleton of "Tristan Otto" available for this study. The authors would also like to thank the two reviewers, Lawrence M. Witmer, Athens, OH, and Thomas D. Carr, Kenosha, WI, for their valuable suggestions and comments.

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