Automated segmentation of the craniofacial skeleton with "Black Bone" MRI

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Abstract:

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Previously acquired adult volunteer (n=15) BB datasets of the head were utilised. Imaging was initially 3D rendered with our conventional manual technique. An algorithm to remove the outer soft-tissue envelope was developed and 3D rendering completed with the processed datasets (semi-automated). Finally, a fully automated 3D-rendering method was developed and applied to the datasets. All 3D rendering was completed with *Fovia High Definition Volume Rendering®* (Fovia Inc, Palo Alto, CA. USA). Analysis was undertaken of the 3D visual results and the time taken for data processing and interactive manipulation.

The mean time for manual segmentation was 12.8 minutes, 3.1 minutes for the semi-automated algorithm, and 0 minutes for the fully automated algorithm. Further fine adjustment was undertaken to enhance the automated segmentation results, taking a mean time of 1.4 minutes.

Automated segmentation demonstrates considerable potential, offering significant time saving in the production of 3D BB imaging in adult volunteers. We continue to undertake further development of our segmentation algorithms to permit adaption to the paediatric population in whom non-ionising imaging confers the most potential benefit.

[Key Words: skull; three-dimensional imaging; magnetic resonance imaging; facial bones; image processing]

Introduction:

Three-dimensional (3D) reconstructed imaging is a vital component in the surgical planning of a wide range of pathologies affecting the bony skull and facial skeleton, enabling the visualisation of complex craniofacial anatomy and pathology in an intuitive manner. As a result, computed tomography (CT) forms the mainstay of medical imaging for both congenital and acquired abnormalities of the craniofacial skeleton. The benefits of this imaging technique are clear, with both very rapid acquisition and 3D reconstruction capabilities.

Whilst the subject of much debate, the potential risks of ionising radiation remain a concern, with a lifetime cancer mortality risk from a single CT examination in a one-year old child estimated to be 0.07% - an order of magnitude higher than for adults [1]. The lenses of the eye are particularly susceptible to ionising radiation, with a near linear trend of increasing cataract incidence with increasing number of CT examinations demonstrated in one large population based study [2]. Irrespective of the debate and uncertainty surrounding the accuracy of these figures, the “as low as reasonably achievable” (ALARA) approach is widely accepted and is fundamental to the principles of radiation protection. There have been several technical advances in dose-reduction techniques with the introduction of tube current modulation, peak voltage optimisation, noise-reduction reconstruction algorithms, adaptive dose collimation, and improved detection-system efficiency [3]. The preferable alternative however is to utilise non-ionising methods of imaging wherever possible, particularly in children with benign conditions.

Whilst MRI offers a non-ionising alternative to CT, simple thresholding-based segmentation techniques are unsuitable due to the overlapping pixel values of bone, air and soft tissues, thus preventing these structures from being separated (segmented) from one another. We have previously reported the “Black Bone” (BB) MRI technique, which minimises the contrast between soft tissue species, to enhance the soft-tissue – bone boundary [4-9]. Utilising this technique, the previously impossible task of creating 3D rendered imaging of the craniofacial skeleton became possible. Unfortunately, even in the most experienced hands, BB image segmentation is often time consuming and is therefore not currently viable for routine clinical use.

The objective of this study was to develop and test methods to reduce segmentation time, with the final goal of producing a fully automated segmentation method, which could be utilised in routine clinical practice.

Materials and Methods:

BB MRI datasets of the head previously acquired from 15 adult volunteers were utilised for the study. The age range of those included was between 25 and 39 years. Imaging was acquired on a 1.5T or 3.0T magnet (GE Healthcare Ltd, Chicago, IL. USA), using a standard head coil. The imaging acquisition parameters are demonstrated in Table S1. Imaging was anonymised at the point of acquisition.

Firstly, imaging was 3D rendered using our previously reported manual technique for segmentation of the craniofacial skeleton with Fovia High Definition Volume Rendering® (Fovia Inc, Palo Alto, CA. USA) (*Phase 1 - Manual Segmentation*) [5-7]. In brief, this requires adjustment of the Transfer Function (whereby each pixel is assigned a colour and opacity) and manual removal of the skin surface layer. This then requires further interaction to optimise the 3D imaging with manual removal of unwanted structures such as the nasal cartilages (**Figure 1**).

Secondly, an automated algorithm to remove the outer soft-tissue envelope was developed and all of the datasets processed before import into Fovia for completion of the 3D rendering (*Phase 2 - Semi-Automated Segmentation*) (**Figure 2**). The algorithm comprised: isotropic denoising, intensity normalization, head and bone mask generation (by thresholding, connected component selection and hole filling), 2 mm skin erosion, N4 homogeneity correction, intensity inversion and rescaling.

Finally, a fully automated 3D-rendering method was developed and applied to all available datasets. The method, implemented in C++ using the Insight Segmentation and Registration Toolkit (ITK), consisted of image denoising, intensity normalisation, head mask generation, N4 bias correction, skin removal, intensity rescaling and masking (*Phase 3 - Fully-Automated Segmentation*). The 3D datasets were imported into Fovia to permit direct comparison between the three methods, and further refinement of the final 3D results.

Analysis was undertaken of the 3D visual results and the time taken for data processing and interactive manipulation.

Results:

Representative BB 3D rendered images obtained during Phase 1, 2 and 3 are shown in **Figures 3 and 4.** Manual segmentation (Phase 1) of the BB datasets was undertaken with a mean of 12.8 minutes, compared to 3.1 minutes for semi-automated segmentation (Phase 2), and 0 minutes for fully automated segmentation (Phase 3). The automated output was configured to provide both static 3D images and a movie clip of the rotating 3D imaging. Fine adjustment (comparable to that which would ordinarily be performed on CT imaging) was achieved in Phase 3 with a mean time of 1.4 minutes. Both pre-processing for semi-automated segmentation and automated processing required ~140s on a MacBook Pro, 2.8 GHz Intel Core i7, 16 GB 1600 MHz DDR3, without parallelisation (Full cranium FOV).

The main areas of difficulty were in regions with dense muscular attachments, or structures with similar signal intensity to bone on BB. For example, the low signal intensity of the nasal cartilages resulted in these areas not being amenable to automatic segmentation using our current algorithm. These were identified and removed manually in Phase 1 to provide a comparable result to CT.

Discussion:

Radiation protection is an important consideration in imaging the craniofacial skeleton. Whilst the adverse effects of ionising radiation continue to be debated, the potential for inducing malignancy and cataracts remain serious concerns. Infants and young children are at greatest risk in view of their longer anticipated life expectancy and the increased sensitivity of their developing organs, with the dose incurred by these young patients being up to three times that of an adult. This is particularly concerning in children with benign pathology, in whom alternative methods of imaging should be considered. In craniofacial abnormalities, the complex surgical interventions require accurate 3D visualisation of the complex bony anatomy. Not only is accurate segmentation of MRI desirable in the management of craniofacial anomalies, robust and accurate automated identification of the skull is a required component for PET/MR attenuation correction, radiotherapy planning and neuroscience research.

We have demonstrated that in skeletally mature patients, fully automated segmentation is achievable using BB MRI. Applying these techniques to children, who would benefit most from non-ionising imaging, is challenging due to the reduced bone density and thickness of the overlying soft tissues of the craniofacial skeleton. We continue to work on this problem to address the fundamental need for radiation protection in this patient group.

The BB MRI technique utilises a gradient echo sequence with short TR/TE and low flip angle, and can therefore be utilised on all MRI systems irrespective of vendor or field strength. This simple MRI technique has been shown to be useful in the distinction between normal and prematurely fused cranial sutures, in addition to a range of craniofacial pathologies [4, 7]. Dremmen et al [10] demonstrated the potential of BB MRI in the identification of skull fractures in children on axial imaging, and we subsequently highlighted the added benefit of 3D reconstructed imaging in such cases [11].

Whilst retrospective volunteer MRI data was used for this study, imaging had been acquired in a standardised manner with consistent parameters, thus producing optimal 3D results. This has not been the case in some of our clinical work, where non-optimised parameters have resulted in variable results.

With a mean acquisition time of 4 minutes for the whole skull in an adult patient, the technique brings with it the risk of motion artefact in a sub-set of patients. We are currently working on techniques to decrease acquisition time, moving towards motion free imaging in the most vulnerable patient groups such as young children.

The main limitation of the 3D BB technique occurs in areas where there is an air-bone interface, since both return little to no signal and in simplistic terms, appear black. Short TE sequences capable of acquiring the weak and fast-decaying signal from cortical bone offer a potential solution for this problem but are limited in resolution due to the inefficient k-space sampling of radial trajectories. Further work is underway to explore potential synergies between these approaches.

In conclusion, this preliminary study demonstrates the considerable potential for automated 3D reconstruction of the craniofacial skeleton, with the potential to change how we image patients in the future.

Figure Legends:

Figure 1: Steps for manual segmentation of BB datasets using Fovia High Definition Volume Rendering® (Phase 1). A transfer function is applied and adjusted before the soft tissue envelope is segmented. Fine adjustment is then undertaken.

Figure 2: Steps for semi-automated segmentation of BB datasets. The images are processed to remove the outer soft tissue envelope and then imported into Fovia High Definition Volume Rendering®, where adjustment of the Transfer Function and minor segmentation adjustments are required.

Figure 3: Examples of the final segmentation results for two volunteers for each of the three phases.

Figure 4: Example of automated segmentation results and following manual fine adjustment.

Supplemental Table S1: BB Imaging parameters

References:

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Figure 1

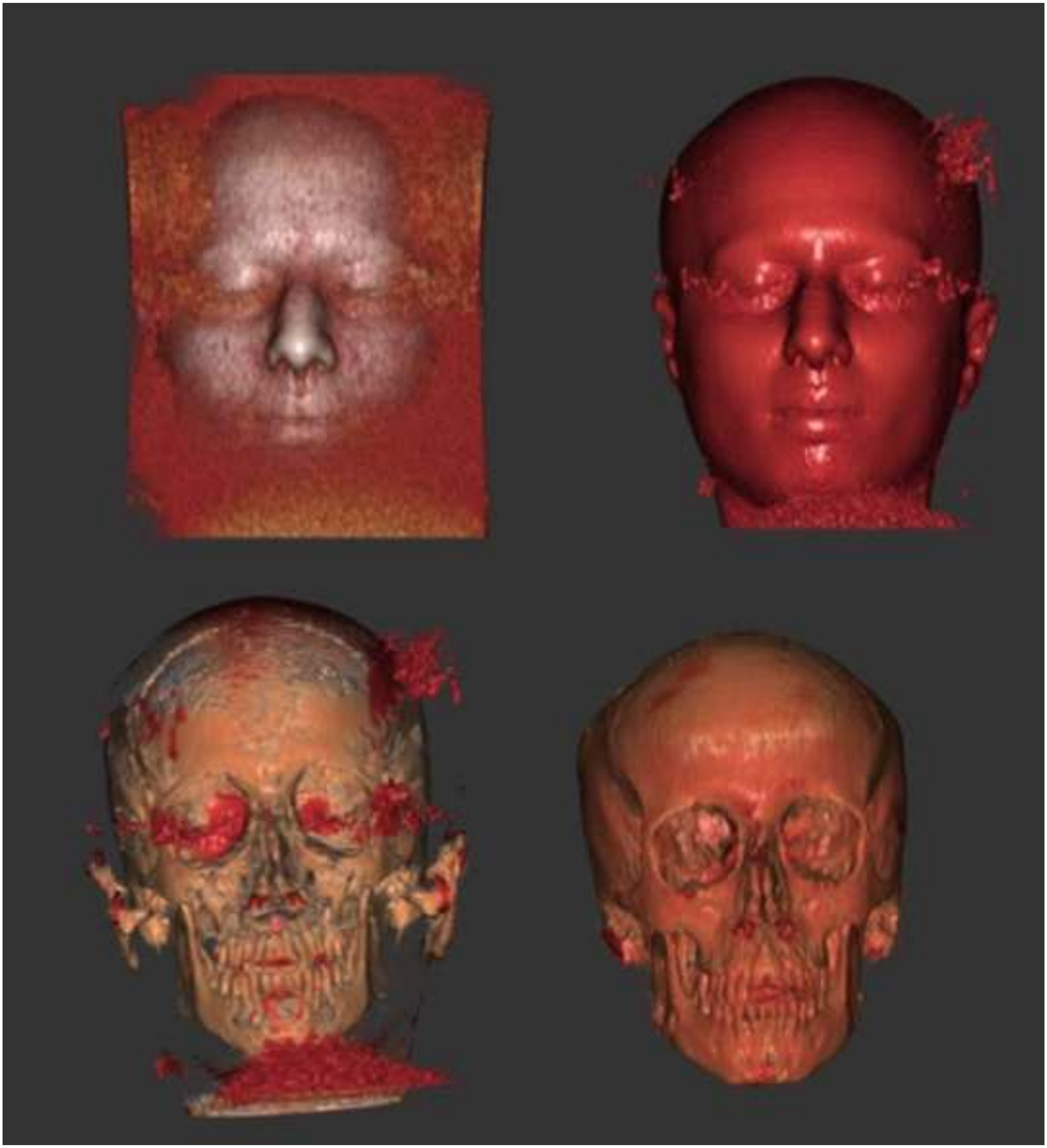

Figure 2

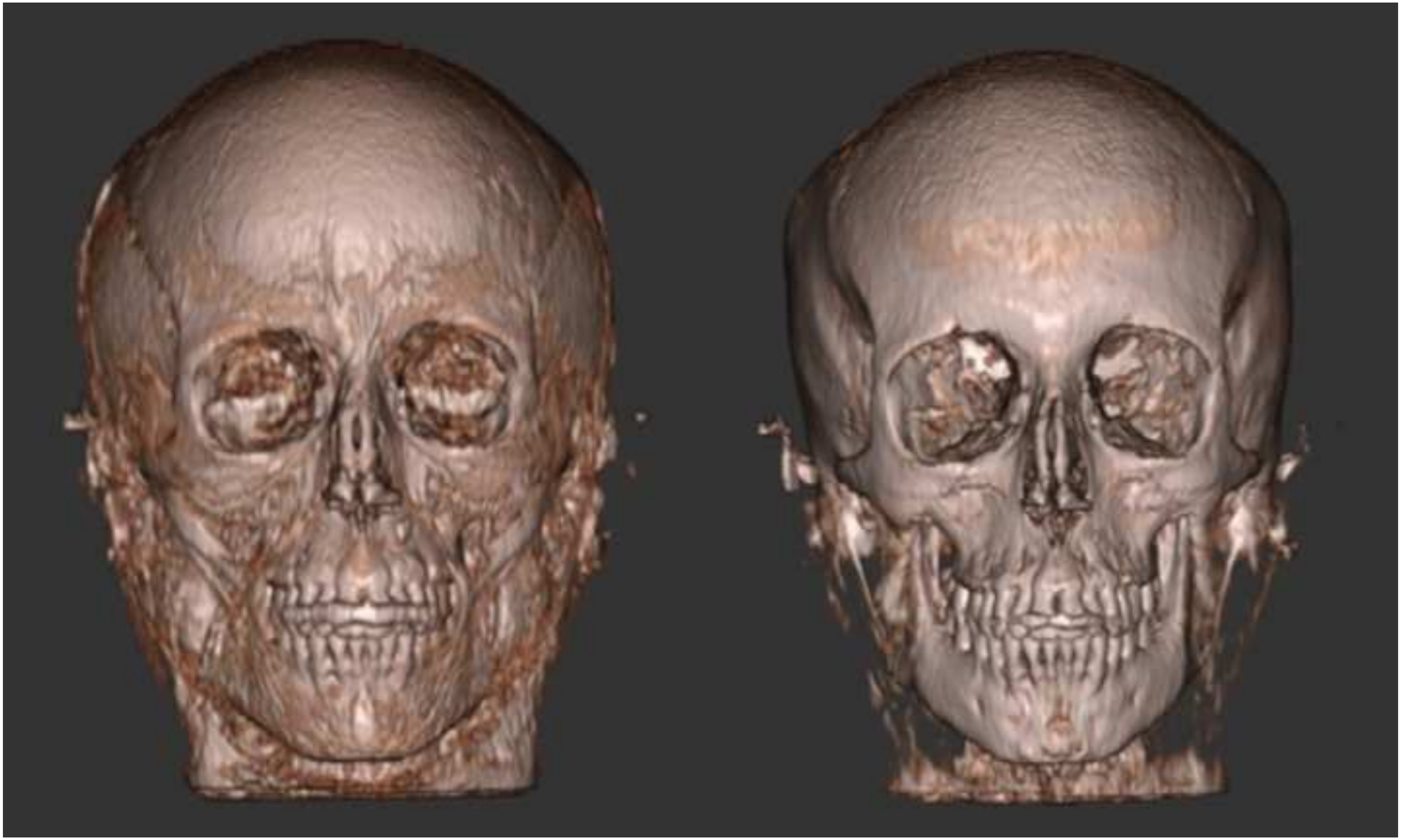

Figure 3

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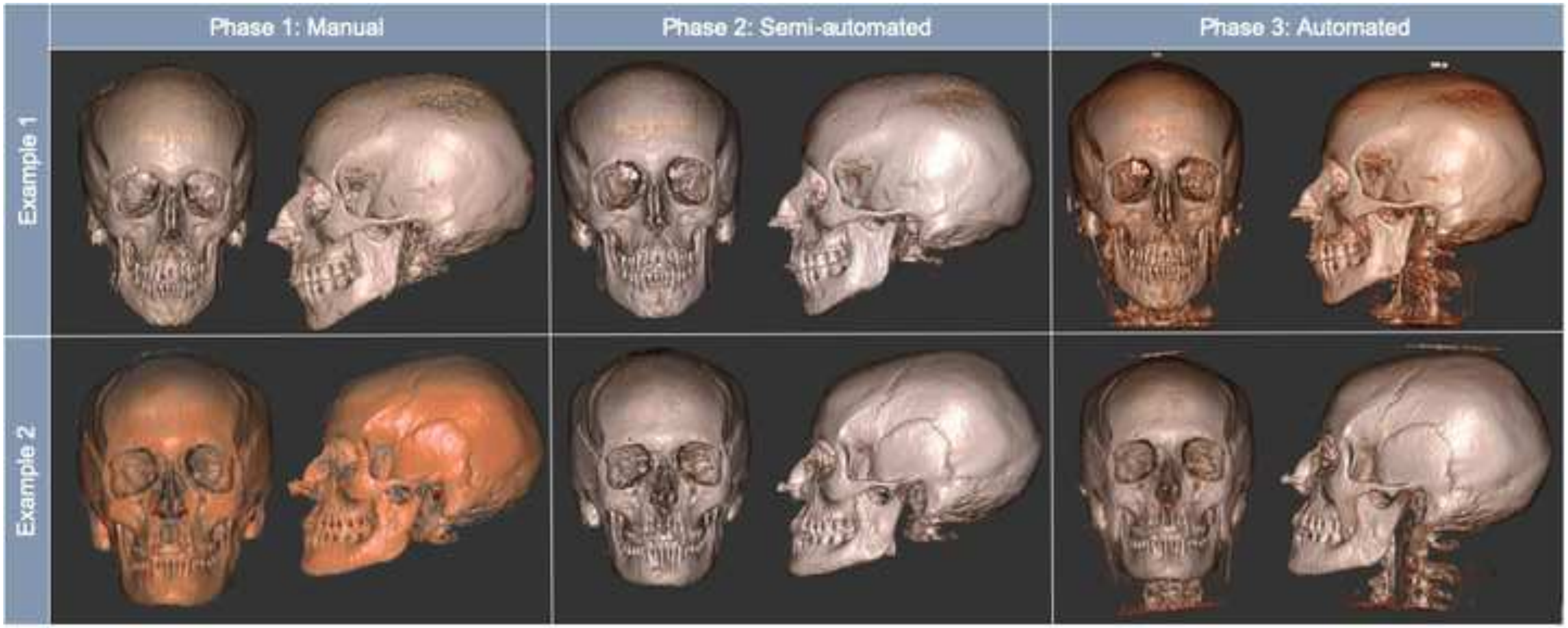
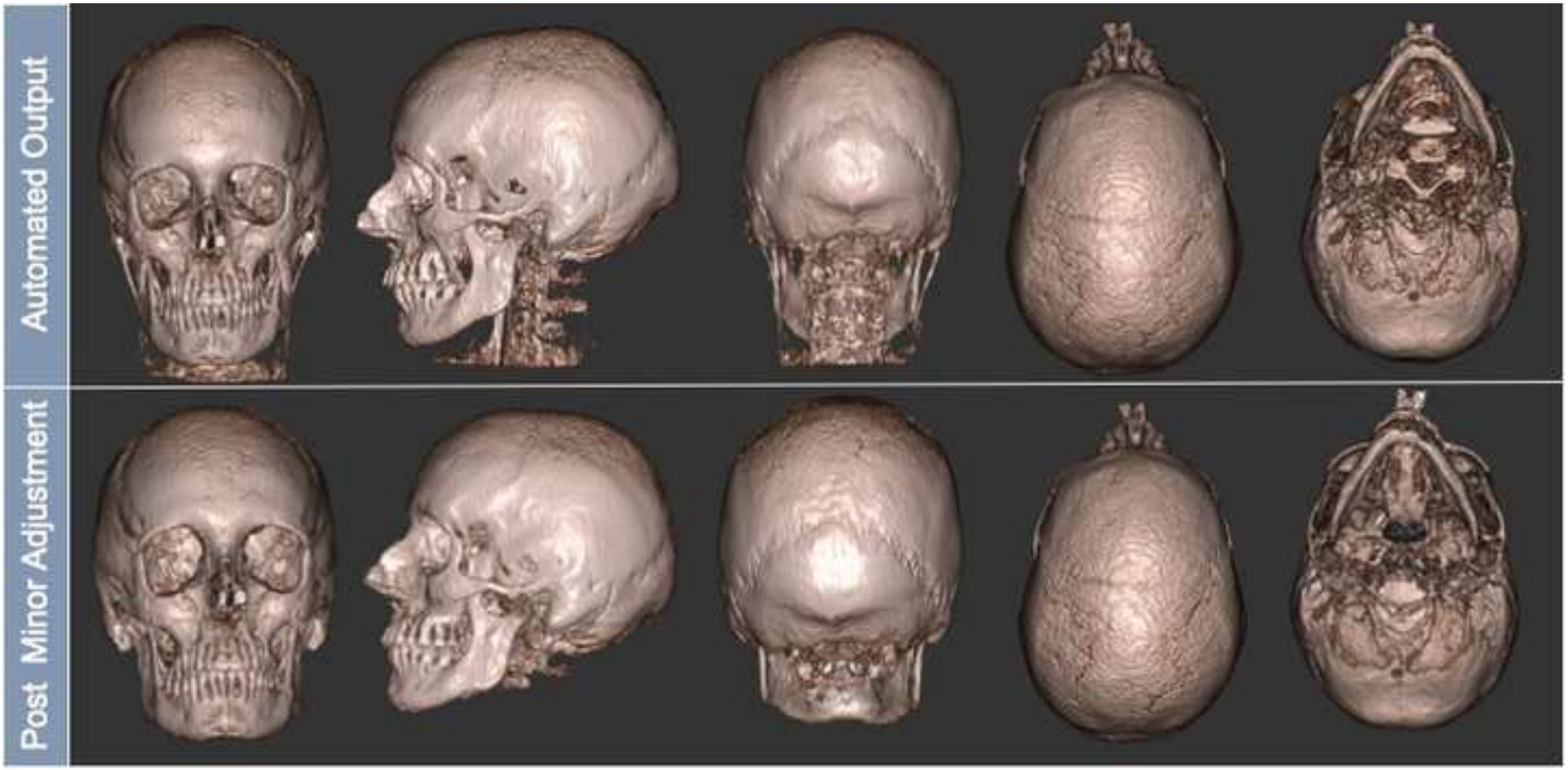


Figure 4



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Supplemental Data File (.doc, .tif, pdf, etc.)
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