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Three-Dimensional Reconstruction of Gangneung Mummy's Heart and Liver Based on the Computed Tomography Images

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Abstract: *The data obtained through mummy research provide researchers with abundant archaeological and medical information of pre-industrialized Korean people. Over the years, autopsy becomes a research tool rarely conducted in mummy studies, which has been increasingly replaced by non-invasive radiological technique. In this report, a novel three dimensional (3D) segmentation and model reconstruction has been conducted on the heart and liver CT images acquired from Gangneung mummy of Joseon period in Korea. By successful estimation of the mummy's preservation and pathological status by exclusively calling the data of specific target organs, our report could reveal how efficiently 3D reconstruction grasps spatial interrelationship between multiple mummified structures.*

Keywords: *Computed Tomography, Segmentation, Three-dimensional reconstruction, Heart, Liver, Korea, Joseon Dynasty*

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Introduction

Around the world, ancient or medieval mummies have been reported and researched over the past decades. Since mummy research provides a wide range of data to infer ancient or medieval people's

health and disease status, it rapidly becomes a topic of interest to anthropologists and paleopathologists worldwide (Cockburn *et al.* 1998; Aufderheide 2003; Shin *et al.* 2018).

Nevertheless, a recent claim that mummies should be investigated using non-destructive method has become increasingly dominant among archaeologists and museum curators (Cesarani *et al.* 2003; Lynnerup 2007; Münnemann *et al.* 2007; Rühli 2007; Panzer *et al.* 2013; Machi *et al.* 2018). To keep mummies intact as much as possible, computed tomography (CT) imaging has been selected as the most preferred non-destructive technique. However, years of mummy research have made it clear that the CT radiography is not perfect in itself. Considering that a human body is a complex 3D structure with a curved surface, it is not easy to accurately estimate the internal structure of the mummy only by the interpretation of simple 2D CT images.

In this regard, for a long time, multiple attempts have been made to apply 3D reconstruction, a technique that has recently been in the spotlight in clinical medicine, to many mummy cases worldwide. After 3D reconstruction was first introduced into a study of ancient Egyptian mummy (Hughes 1996), similar studies have been repeated to estimate the preservation and pathological status of the mummies (Melcher *et al.* 1997; Hoffman *et al.* 2002; Cesarani *et al.* 2003; Gerloni *et al.* 2009; Cavka *et al.* 2010; Pelo *et al.* 2012).

Noting such a technical potential of 3D reconstruction, in the current report, a novel 3D segmentation and model reconstruction is conducted on the heart and liver CT images attained from a Gangneung mummy of Joseon dynasty. By revealing how correctly 3D reconstruction data grasp spatial interrelationship of mummified organs, we try to evaluate this technique's future potential in the paleopatholol gical research without tissue destructions.

Archaeological Information

In 2007, a Gangneung mummy of Joseon period (1392-1910 CE) was found at the archaeological excavation site in Gangneung, South Korea (Fig. 1A). At the initial investigation of this case, CT analysis and autopsy were performed on the mummy (Fig. 1B). Archaeologists confirmed that the mummified male was the 16th to 17th general from Gangneung Choi clan (Fig. 1C) (Lee *et al.* 2009).

3D Segmentation and Model Reconstruction

As for Gangneung mummy, anatomical and 2D CT analysis have been conducted in 2007 (Lee *et al.* 2009); but 3D reconstruction has not been conducted on the same case so far. In this report, a novel 3D segmentation and model reconstruction technique (Goo *et al.* 2020; Bae *et al.* 2021; Dho *et al.* 2021a; Dho *et al.* 2021b; Koh *et al.*, 2022) is applied to the Gangneung mummy's extant 2D radiology data, and the resultant 3D outcomes are compared to the autopsy or 2D CT findings in our previous report (Lee *et al.* 2009).

Our reconstruction process is summarized in Figure 2. In brief, the Gangneung mummy's CT data (scanned by 1.2-1.3 mm intervals) was stored in DICOM format and accessible using PACS (Lee *et al.* 2009). Among Gangneung mummy's organs in body cavity, heart and liver were selected as target organs for 3D segmentation and model reconstruction. The mummy's DICOM file was loaded into the MEDIP PRO (https://medicalip.com/Medip; MEDIP PRO, version 2.3.0, MEDICALIP Co., Ltd., Seoul, Korea)" and then preprocessed to improve image quality.

Next, we did a task of image segmentation to differentiate those target organs from surrounding structures. To find a boundary between the target and other structures, semi-automatic technique was used; but for some not-easily-distinguishable areas, we manually decided the boundary. Using a

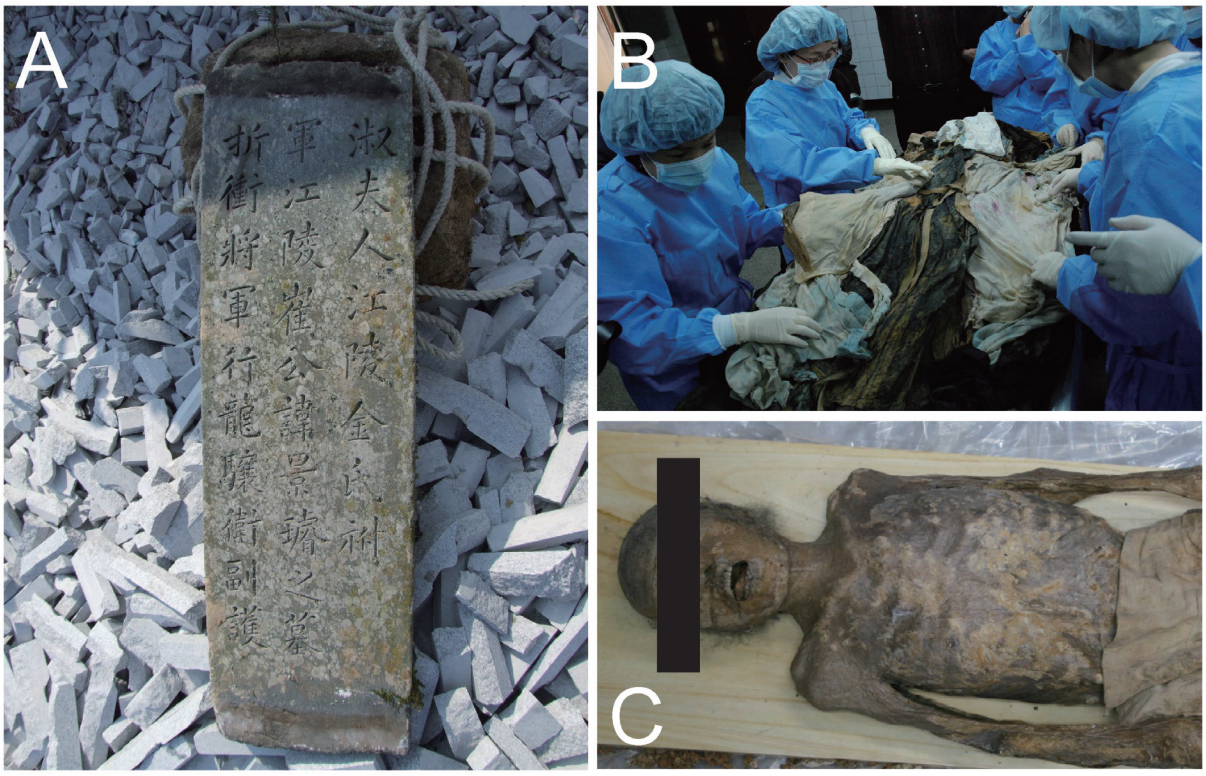

Figure 1: Investigation of Gangneung mummy. (A) A tombstone of the grave. (B) Initial investigation in 2007. (C) The male mummy was a descendant of a long-established gentry

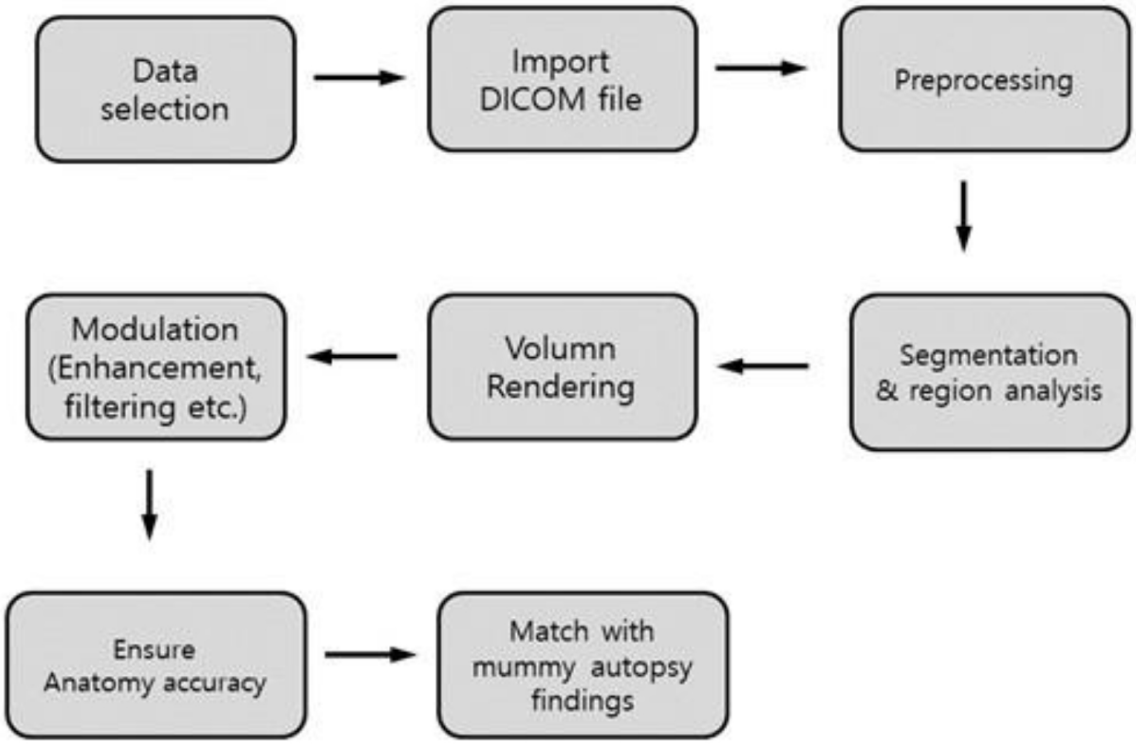

Figure 2: Process of 3D segmentation and model reconstruction in this report

MEDIP program, the segmenting data were used to form a 3D structure (3D rendering). 3D organ's angle and color was adjusted to facilitate easy reading and interpretation.

Gangneung mummy's 3D segmentation and model reconstruction data are shown in Figures 3 and 4. Figure 3 shows 3D reconstructed heart from different angles. In 2D axial views of Gangneung mummy (Lee *et al.* 2009), a mummified heart was found at the center of the chest cavity (Fig. 3A). The autopsy view of mummified heart (Figure 3B; Lee *et al.* 2009) could be well matched with the current 3D data of the same organ (Fig. 3C).

In general, normal people's heart is located at the height of the 3rd to 4th-5th rib cartilages or the 4th to 9th thoracic vertebrae (TV). By merging heart and bony structure 3D images, we then try to confirm if there was any positional change of the Gangneung mummy's heart. As seen in Figs 3D and 3E, Gangneung mummy's heart does not exihibit any positional shift to the left or right, with the boundaries at the height of TV 4 (highest) and TV 8-9 (lowest). Take together, we confirm that Gangneung mummy's heart maintains its original position even after mummification process.

In Gangneung mummy's abdominal cavity (Fig. 4), the liver is dorsally skewed, extending from the right upper abdomen to the midline. From the front, it seems that the liver was maintaining its original shape, although it was atrophied (Figs. 4A and 4B). The mummy's liver is located under the diaphragm, mostly in the right upper abdomen but some in the left upper quadrant (Fig. 4A). In the figure from the caudal, the mummy's liver was flattned and placed upon the spine and ribs, forming the shape of an 'S' throughout (Fig. 4B). This is almost the same view as seen in the 2D axial image of Gangneung mummy (Fig. 4C; Lee *et al.* 2009). In reconstruction image, the mummy's liver range from TV 7-8 (highest) to TV 11 (lowest). Comparing to the normal people's liver (Musculoskeletal Key 2017), a slight upward shift could be observed. 3D reconstruction also exhibits a spatial interrelationship between heart and liver from different angles (Figs. 4D and 4E).

Volume Estimation

A big advantage of 3D segmentation and model reconstruction is to get data on the size of mummified organs. In Gangneung mummy's 3D reconstruction, the volumes of target organs could be successfully measured. The data is summarized in Table 1.

Discussion

A 3D segmentation and model reconstruction is an excellent tool to attain biometric data from a given 2D CT images, which making a certain diseases' diagnoses very easy and efficient (Goo *et al.* 2020; Bae *et al.* 2021; Dho *et al.* 2021a; Dho *et al.* 2021b; Koh *et al.* 2022). Noticing such technical advantages, in this report, we applied a 3D segmentation and model reconstruction technique to Gangneung mummy's 2D CT data.

In this report, we are able to see what advantages this 3D reconstruction technique has over conventional 2D CT analysis. We could see a spatial interrelationship between multiple mummified organs, which could be successfully grasped by our 3D analysis of Gangneung mummy. Moreover, it is also a great advantage that Gangneung mummy's 3D organs can be freely rotated to be observed from different angles. 3D segmentation and model reconstruction can also generate images without overlapping structures, by calling the data of Gangneung mummy's target organs specifically. By exclusively selecting the mummy's heart, liver, and skeletons, background structures can be removed from virtual working scenes, thus minimizing our errors in CT reading that could be caused by overlapping organs. In this report, we can also estimate the size and location of mummified organs

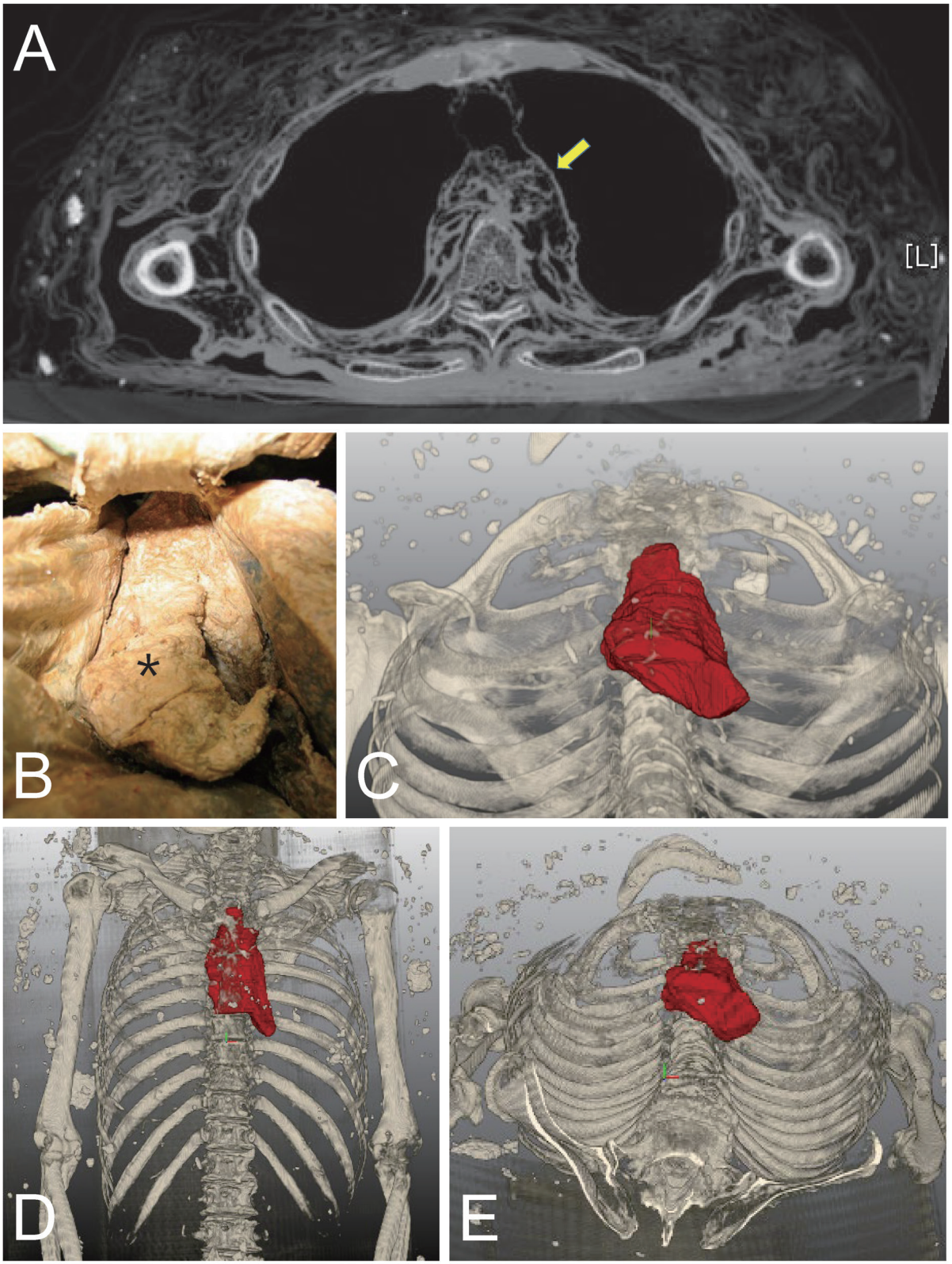

Figure 3: **The results of 3D segmentation and model reconstruction of Gangneung mummy's heart. (A) 2D axial view image of the heart (indicated by arrow). (B) The autopsy view of mummified heart (marked by asterisk) is very similar to (C) the data of current 3D segmentation and model reconstruction (heart marked in red). (D) and (E) Gangneung mummy's heart was implemented on a 3D image screen along with bony structures. No left or right shift found. The mummified heart ranges between TV 4 and TV 8-9**

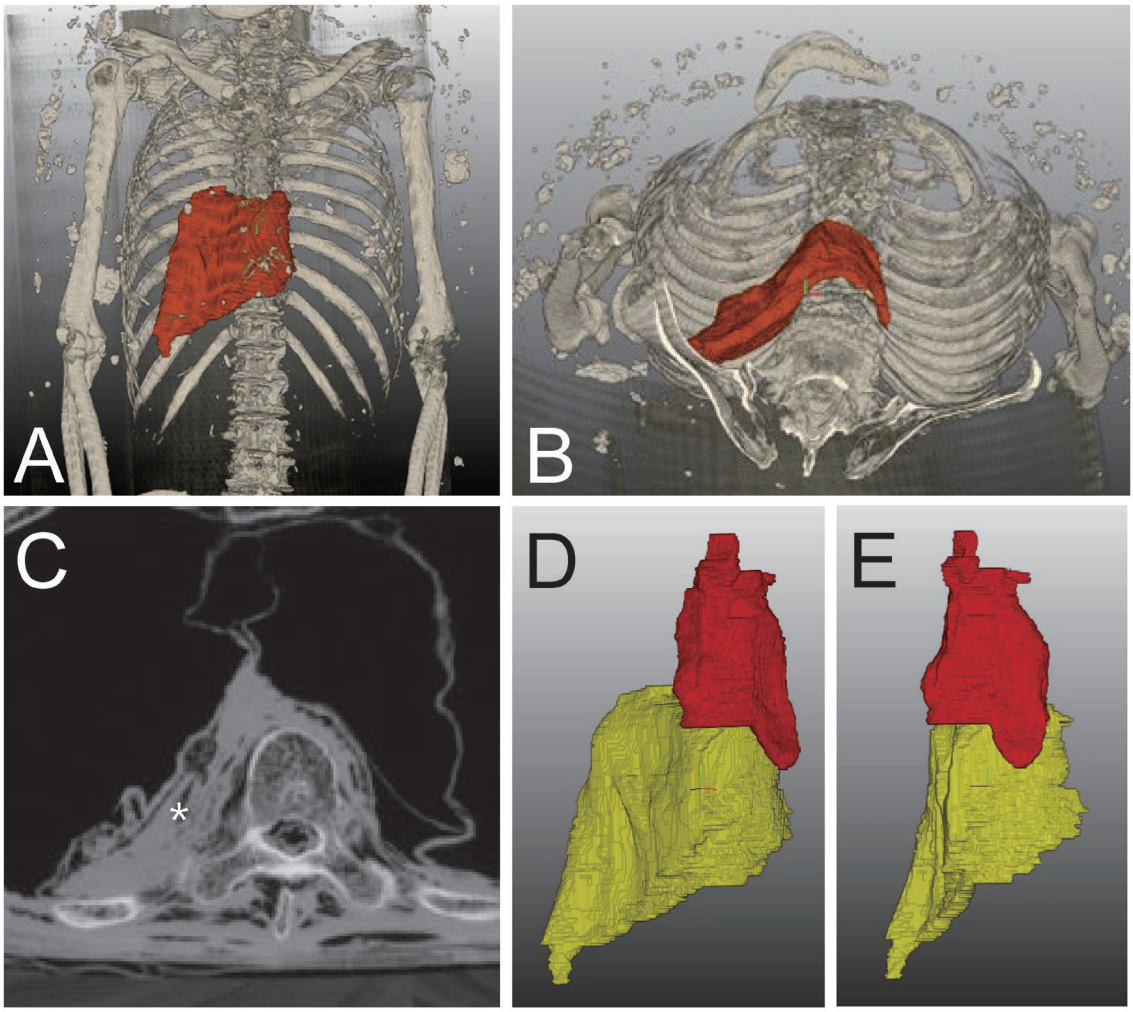

Figure 4: **The spinal column, ribs, and liver are placed in the same 3D image of Gangneung mummy. (A) Front view. (B) A looking up view from the caudal. The liver's shape is generally maintained. The 3D view of (B) is mostly similar to (C), a 2D axial view of Gangneung mummy's liver (marked by asterisk). (D) and (E) Spatial interrelationship of liver (yellow) and heart (red) from different angles. (D) Frontal view. (E) Image viewed by rotating 90 degrees to the right.**

Table 1: Volume and length measurements of Gangneung mummy's heart and liver

Measurements	*Heart*	*Liver*
Mesh volume (cc)	112.35	240.90
Voxel volume (cc)	112.50	241.12
Maximum 3D axis diameter (cm)	13.19	19.21
Maximum 2D diameter (Slice) (cm)	6.76	12.47
Maximum 2D diameter (Column) (cm)	12.44	17.10
Maximum 2D diameter (Row) (cm)	10.36	12.91

more accurately than conventional 2D analysis, with the time and effort required for the estimation remarkably reduced.

In conslusion, 3D reconstruction techniques have been applied to various cases to obtain necessary data without causing excessive damage to the mummy (Hughes 1996; Melcher *et al.* 1997; Hoffman *et al.* 2002; Cesarani *et al.* 2003; Lee *et al.* 2007; Gerloni *et al.* 2009; Cavka *et al.* 2010; Pelo *et al.*

2012). Although these works are very significant in itself, but 3D reconstruction has not yet been fully established as absolutely reliable techniques for mummy research, so continuous related reports are still needed. The 3D reconstruction technique used in this report may not be said to be perfect yet, but we suppose the academic meaning can be evaluated as one of the academia's efforts to develop non-destructive techniques in mummy study.

Competing interests

DYL works in the MEDICALIP as a researcher. SJP is the founder of the same company. The other authors can declare that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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