Holding Eternity in One's Hand: First Three-Dimensional Reconstruction and Printing of the Heart from 2700 Years-Old Egyptian Mummy

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ABSTRACT

The heart in ancient Egyptian mummification procedure is the central organ that should stay in place in the chest and waiting for the afterlife judgment. Here, we show the first case of three-dimensional (3D) CT scan reconstruction of a mummified heart from a person embalmed in Egypt around 2,700 years ago, and present a 3D printing of the same heart using a low-cost yet accurate 3D printer. A multi-slice computed tomography scanner was used to scan the mummy. We applied the following radiological protocol: 80 keV and 140 keV, 140 mAs, with a slice thickness of 0.9 mm. The mummified heart and ascending aorta were extracted with semi-automatic segmentation. We used a low-cost 3D printer (Up plus 2) using fusion deposition modeling technology. The 3D printed model was then painted with acrylic paint to color code structures of interest. The 3D CT multi-resolution imaging allows us to identify the gross anatomy of the heart, the ascending aorta, the pulmonary arteries, and the presence of multiple atherosclerosis lesions. Using 3D printed model we recognized upper auricle, vein cave inferior, and the two coronary arteries. The brachiocephalic artery, common carotid artery, and left subclavian artery were clearly cut to dissociate the heart from surrounding tissues. This multi-3D approach allows for a better understanding of complex and distorted anatomy of the mummified heart, of paleopathology (arteriosclerosis), and of mummification techniques. Anat Rec, 2018. © 2018 Wiley Periodicals, Inc.

Key words: Egyptian mummification; computed tomography; 3D printing; heart

INTRODUCTION

Computed tomography (CT) was already practiced from 1979 as one of non-invasive technologies to study Egyptian mummies (Harwood-Nash, 1979; Hawass and Saleem, 2016). For ancient Egyptians, the heart represented the main body organ responsible for wisdom, memory, love, and

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emotions (Fanous and Couldwell, 2012). It was also the seat of the soul and thought (Dodson and Ikram, 1998). According to the Egyptian religion the heart of the deceased was weighted against the Feather of Ma'at, the goddess of truth and justice (Thomas et al., 2014). For these reasons, the heart was theoretically left in place after embalming procedure (Marx and D'Auria, 1986). However, case reports (Wade et al., 2012) and two major case series (Wade and Nelson, 2013; Allam et al., 2014) demonstrated that missing heart from the Egyptian mummy was not an exceptional finding. There exist also only few two-dimensional (2D) CT images of mummy's heart remnants in the literature (Wade et al., 2012; Conlogue, 2015). Here, we present the first case of a three-dimensional (3D) reconstruction and 3D printing (Maschio et al., 2016) of a heart and aorta of 2,700 years-old artificially embalmed person using a multi-slice high resolution CT scan. The 3D printing has previously been applied in archaeological research using stereolithography technology (Cesarani et al., 2004) which is a very time-consuming process (Materialize, Leuven, Belgium). In 2011, Tutankhamen's mummy was scanned with 3D CT scan, and a full-body replica was realized in laser polymerisable resin (http://www.materialise.com/en/cases/king-tut-3D-model) for a world-tour exposition. In 2015, the same technique was used to obtain a full 3D replica of the body of Ötzi, a 5,300-year-old iceman, found in the Otzal Alps in 1991 (http://www.smithsonianmag.com/science-nature/artist-creates-detailed-replica-otzi-5300-year). Here, we present the first 3D high resolution CT reconstruction and a 3D low-cost, full-color 3D printed model of a soft-tissue organ (the heart and the aorta) from the same ancient Egyptian embalmed mummy aged approximately 2,700 years. Our low-cost method for modeling soft-tissue structures is expected to be useful for a broader examination of mummified remains in the future.

MATERIALS AND METHODS

An Egyptian mummy attributed to Usirmose, a "doorkeeper of the Temple of Ra" is presently kept in the Royal Museums of Art and History (RMAH) (Brussels), Inv. E.5889 (It was bequeathed at the RMAH with its two coffins (middle and inner) in 1874 by the Belgian diplomat and collector É. De Meester de Ravestein (1813–1889). The outer coffin is at the Curtius Museum (Liège), Inv. I/628A = Eg. 83A. The three coffins of Usirmose were initially in the private collection of Giovanni Anastasi (1780–1860), merchant of antiquities from Alexandria, who was also appointed Consul-General in Egypt for the Kingdom of Sweden and Norway from 1828 (Dawson, 1949). After his death, a part of his collection was auctioned in Paris in 1857 (Dawson, 1949). The three coffins and the mummy were purchased by Antoine Schayes (1808–1859), the first curator of the RMAH. Schayes's archaeological collection was sold in 1859 after his unexpected death at the age of 51. At the time of this second sale, the outer coffin belonging to Usirmose and another coffin attributed to a certain Horsiesi were inverted. The middle and inner coffins of Usirmose, his mummy and the coffin of Horsiesi were then purchased by É. de Meester de Ravestein, while Usirmose's outer coffin was bought by Baron Albert d'Otreppe de Bouvette (1787–1871), the first director of the Archaeological Institute in Liège, Belgium. Further, É. De Meester de Ravestein donated his three coffins and the mummy to the RMAH in 1874, and Baron d'Otreppe offered Usirmose's outer coffin to the Curtius Museum in Liege in 1865 (Delvaux and Therasse, 2015). The funerary assemblage of Usirmose dates from the 25th dynasty and comes probably from the Theban necropolis. These chronological and geographical estimations are based on stylistic and typological criteria. Another chronological indicator is the presence of the mummy's artificial eyes. Those false eyes are one of the major innovations of the 21st dynasty (around 1069–945 BC). If this mode of embalmment is widespread at this period, it seems that the use of artificial eyes was occasionally maintained till the 25th and 26th dynasties (Gray, 1971). Usirmose was a member of an important family of Theban priests whose collective tomb was probably discovered by the merchant and collector Giovanni Anastasi during his excavations of the 1820s. The coffin, cartonnage and mummy of Usirmose's father, Padiamenet, "Chief Doorkeeper of the Domain of Ra, Chief Attendant of Ra and Chief Barber of the Domain of Ra and of the temple of Amun" (Taylor and Antoine, 2014), were in the collection of the collector and diplomat Henry Salt (1780–1827) and were sold in 1839 to the British Museum (Inv. EA.6682-6683). The mummy and coffins of Dismutenibtes, Usirmose's mother and Padiamenet's wife, were donated to the Oslo Museum of Cultural History by Giovanni Anastasi himself in 1826 (Inv. C.47705, C.47708) (Bettum, 2010). A 2D radiological study has already been attempted on the mummy of Usirmose in 1999 (Francot et al., 1999). Based on the radiographic information on the pelvic bones Francot's study concluded that the mummy inside Usirmose's coffins was indeed a female (Francot et al., 1999). This information was again reproduced in Taylor and Antoine's book on Egyptian mummies of the British Museum in 2014 (Taylor and Antoine, 2014). Since then, thanks to our investigations, the gender of the mummy has been identified as male, as we found a well preserved penis on 3D medical CT scan. The pelvic bones were broken in many places, so it was not possible to obtain gender identification from the pelvis. The mummy itself is covered by two layers of bandages. The deepest layer is the original bandaging, blackened with embalmers balms. The outer layer is made of large bandages that seem to have been put after a restoration. After obtaining permission from the curator of the Egyptian section at the Royal Museum of Art and History, Brussels, Belgium, a mummy was transported to our clinic, and a 3D scan was perfomed in the department of medical imaging with a multi-slice computed tomography scanner, Brillance ICT 256 (Philips Healthcare, Eindhoven, Netherlands). All necessary permits were obtained for the described study, which complied with all relevant regulations. The 3D CT scanning was performed in two separate sections: (1) from skull vertex to tibia and (2) from tibia to toes. We applied the following radiological protocol: 80 keV and 140 keV, 140 mAs, slice thickness of 0.9 mm, slice increment of 0.45 mm, pitch of 0.38, field of view of 400 mm, C filter, collimation 128×0.625, matrix of 512×512, and scan length of 1,400 mm. A region of interest, consisting of the mummified heart and ascending aorta was then extracted with semi- automatic segmentation. The three-dimensional reconstruction was saved in an STL

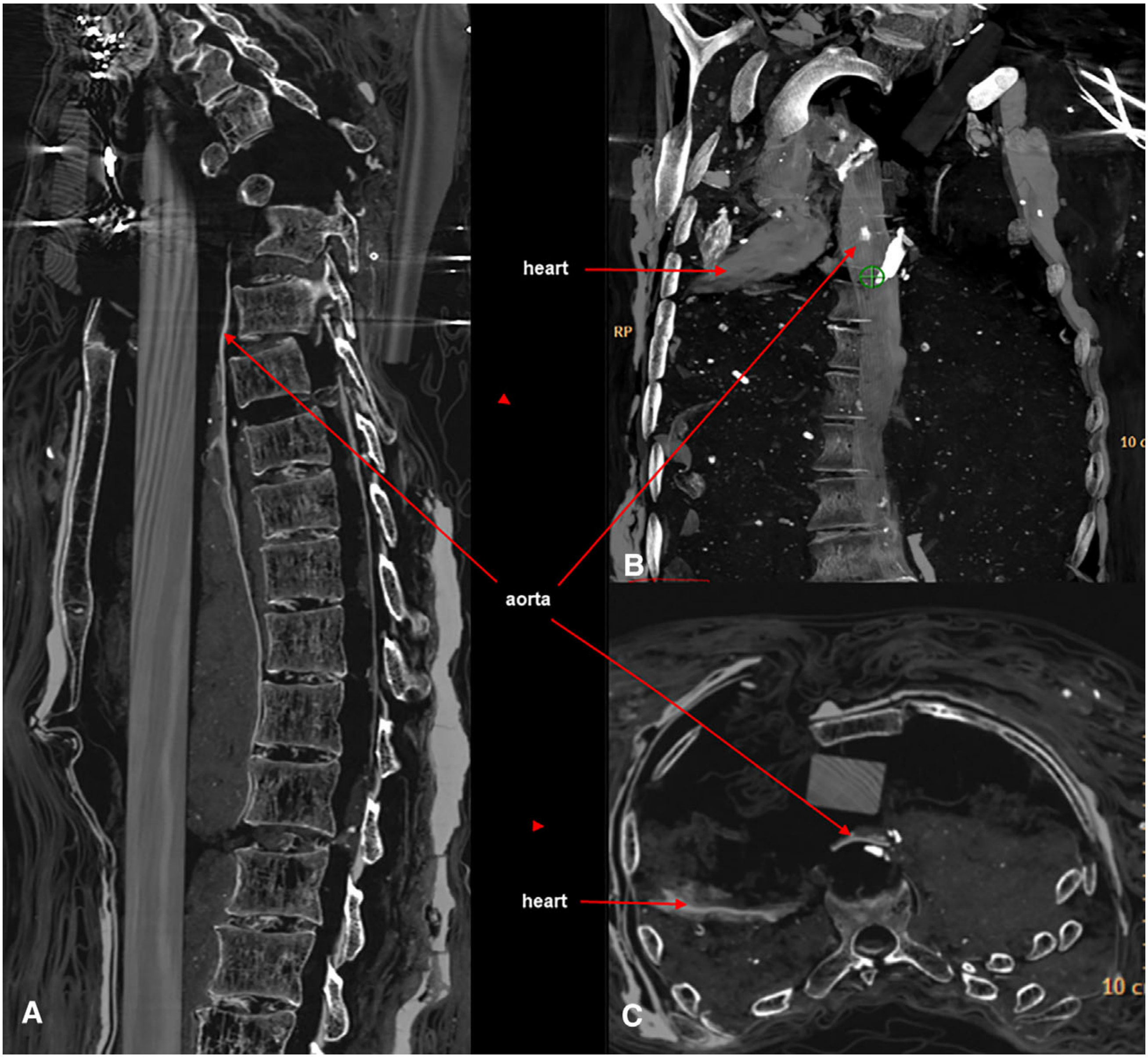

Fig. 1. Heart and aorta CT scan. (A) Sagittal view of mummified body and of aorta (red arrow). (B) Maximal intensity projection reconstruction of the aorta and the heart (red arrows). (C) Axial native view of the aorta and the heart (red arrows).

file. Then, STL file was repaired with Netfabb software (Netfabb, Lupburg, Germany) and with the software of the 3D printer. We used a low-cost 3D printer (Up plus 2, TierTime, Beijing) with fusion deposition modeling technology. Accuracy tests and clinical validation had already been performed on this specific type of low-cost 3D printer (Maschio et al., 2016). A white filament of plastic (ABS) is extruded from the head of the 3D printer and deposited layer by layer on a heated support. The head moves along the x- and y-axes, and the heat support moves along the z-axis. The cost of the 3D printer is approximately 1,500 USD, and the cost of 700 g of plastic filament is approximately 35 USD. We selected the minimal slice thickness of 150 μm. The 3D printing of the heart (21 g) took 2 hr and 57 min for 201 layers. The postprocessing for this type of 3D printed model was very easy and fast (just a few minutes). There are only a few layers of support material to detach from the final 3D model. Our 3D printed model was then painted with acrylic paint, which was purchased in a modeling hobby store. For a better understanding of our methodology see Video 1.

RESULTS

The heart and aorta were identified on 3D CT images inside the thoracic cage (Fig. 1). The aorta was also visible in the abdomen (Fig. 1). The heart tips over to the right side of the mummy (Fig. 2). The heart was 3D printed together with the initial part of the aortic arch

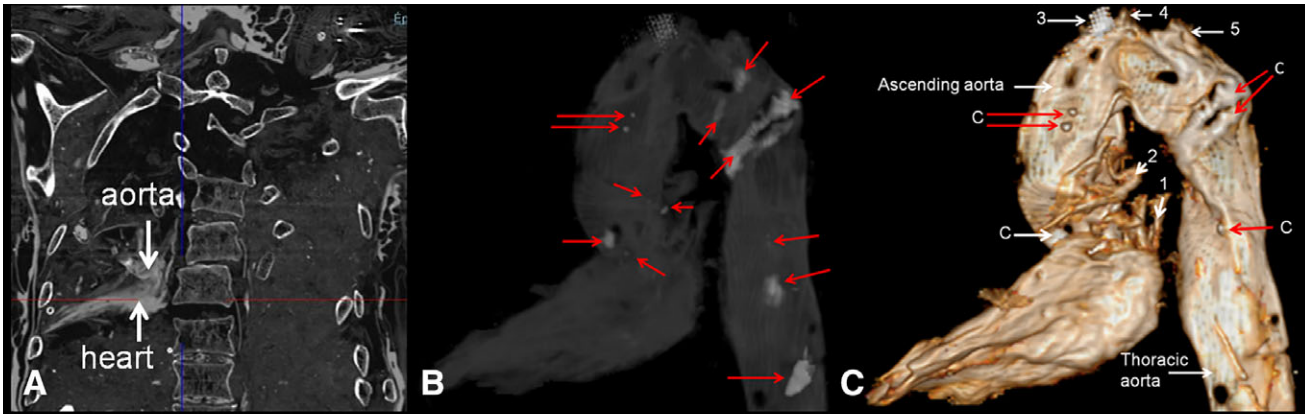

Fig. 2. Heart 3D CT scan. (A) 3D CT scan, frontal slice through the thoracic cavity. (B) Maximal intensity projection and multiple calcifications along aorta. (C) Three-dimensional reconstruction of pericardium and aorta. 1. Right auricle. 2. Pulmonary arteries. 3. Brachiocephalic artery. 4. Common carotid artery. 5. Left subclavian artery. C: calcifications.

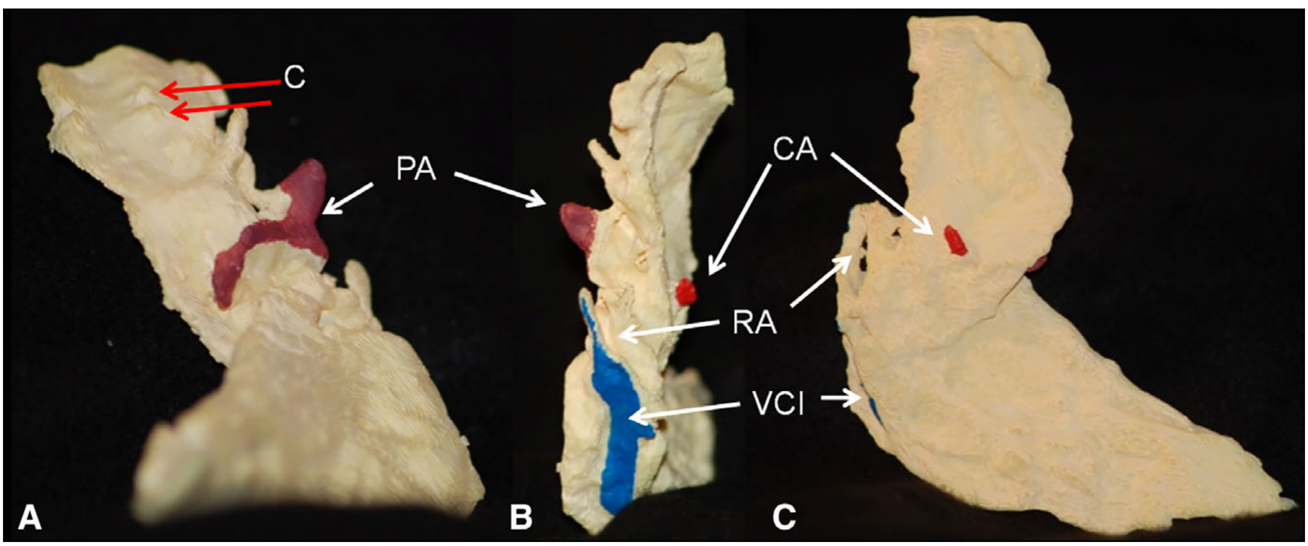

Fig. 3. 3D printed model of the heart and aorta. (A) Anterior and lateral view. (B) Medial view (C) Posterior view. C; Calcifications, PA: pulmonary arteries, CA: coronary arteries, RA: right auricle, VCI: vena cava inferior.

because our working space on the low-cost 3D printer was limited to only 10 cm × 10 cm (Fig. 3). The 3D printed and painted model allowed us to identify the right auricle (RA) and vena cava inferior (VCI) (blue), two coronal arteries (CA) (red) at the base of the ascending aorta, and pulmonary arteries (PA) (violet). Two potential atherosclerotic plaques (C) were identified on the ascending aorta, first by examining the 3D printed model, and then by confirming their presence on 3D CT scan images (Allam et al., 2014). Major arteries such as the brachiocephalic artery, common carotid artery, and left subclavian artery were intentionally and clearly sectioned from the aorta (Fig. 2C). The right auricle seems to be cut diagonally from the vena cava superioris (Fig. 3).

DISCUSSION

Currently, 3D printing technology is used as a diagnostic, training, and educational tool in cardiovascular surgery (Hermsen et al., 2017). However, the techniques used to obtain such accurate 3D models, including stereolithography and selective laser sintering, are also the most expensive. Therefore, the cost of the 3D printed model is still prohibitive and limits the use of this technique to only the most difficult and rare clinical cases (Bhatla et al., 2017). Moreover, only three types of 3D printers allow for full-color models. Mcor Arke (Mcor Technologies, Dunleer, Ireland) (+/– 20,000 USD) uses selective deposition lamination of sheets of colored paper but does not allow for the construction of hollow 3D shapes, which is essential for cardiac surgery (Olszewski et al., 2014). ProJet 660 (ZPrinter) (3D Systems, Rock Hill, SC, USA) (±70,000 USD) and 3D Pandoras (Sky-Tech, Taipei, Taiwan) (±15,000 USD) use selective powder sintering. The powder may interfere with electronic and mechanical parts and reduce the life of the 3D printer. Here, we combined a low-cost 3D printer based on fused deposition modeling with a manual full-color approach, which may seem trivial but is an efficient method to obtain a full-color 3D printed model. Moreover, multi-slice, high-resolution 3D CT scanning of a mummy together with low-cost, full color 3D printing allows archaeologists to examine the mummy's body more deeply without harming the museum artifact. Accurate 3D replica built with plastic polymer at the same scale as the internal organ of the mummy itself can now be handled and manipulated by specialists. A 3D printed heart model may serve as a tool for interdisciplinary discussion among medical doctors (radiologists, cardiovascular surgeons, forensic pathologists, and paleopathologists), physical anthropologists, anatomists, and archaeologists. The application of low-cost color to the 3D model allows for a better understanding of intricate anatomical structures, such as the differentiation of the right auricle and vena cava inferior from the heart itself, or the junction between the aorta and the coronal arteries. Full-color 3D printed models may also allow scientists to better transmit their knowledge to the general public through TV and other visual media. Low-cost 3D printed models may also be used to share museum treasures with blind visitors. Unfortunately, 3D printing technology is raising questions about the intellectual property of the STL files used in 3D printing and, the subsequent 3D-printed replicas, as well as questions about the private duplication of museum artifacts, and their potential commercial use. Our study presents also some limitations. We cannot provide histological analyses of internal organs because techniques on mummies belonging to our Museum collection are prohibited. The aim of our article was to describe the application of a new methodology on the example of the mummy's heart of Usirmose. Therefore, the article does not contain a full description of any other pathologies related to other anatomical areas or related to embalming techniques. Moreover, due to the dehydration of the mummified heart the 3D copy of it although useful for scientific study cannot be used for exhibition purposes. Finally, holding the oldest 3D printed heart in one's hands is a unique experience that opens our minds to an ancient culture and their view of eternity. The proposed multi-3D approach (CT and 3D low-cost printing) allows for a better understanding of complex and distorted anatomy of the mummified heart, of paleopathology (arteriosclerosis), and of mummification techniques.

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