

Histological, chemical, and morphological reexamination of the “heart” of a small Late Cretaceous *Thescelosaurus*

Timothy P. Cleland · Michael K. Stoskopf ·
Mary H. Schweitzer

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Abstract A three-dimensional, iron-cemented structure found in the anterior thoracic cavity of articulated *Thescelosaurus* skeletal remains was hypothesized to be the fossilized remains of the animal’s four-chambered heart. This was important because the finding could be interpreted to support a hypothesis that non-avian dinosaurs were endothermic. Mammals and birds, the only extant organisms with four-chambered hearts and single aortae, are endotherms. The hypothesis that this *Thescelosaurus* has a preserved heart was controversial, and therefore, we reexamined it using higher-resolution computed tomography, paleohistological examination, X-ray diffraction analysis, X-ray photoelectron spectroscopy, and scanning electron microscopy. This suite of analyses allows for detailed morphological and chemical examination beyond what was provided in the original work. Neither the more detailed examination of the gross morphology and orientation of the thoracic “heart” nor the microstructural studies supported the hypothesis that the structure was a

heart. The more advanced computed tomography showed the same three areas of low density as the earlier studies with no evidence of additional low-density areas as might be expected from examinations of an ex situ ostrich heart. Microstructural examination of a fragment taken from the “heart” was consistent with cemented sand grains, and no chemical signal consistent with a biological origin was detected. However, small patches of cell-like microstructures were preserved in the sandstone matrix of the thoracic structure. A possible biological origin for these microstructures is the focus of ongoing investigation.

Keywords Ornithischia · Computed tomography · X-ray diffraction · X-ray photoelectron spectroscopy

Introduction

Fisher et al. (2000) used computed tomography (CT) scans to diagnose a three-dimensional structure found in the anterior thoracic cavity of a specimen of *Thescelosaurus neglectus* (NCSM 15728; briefly discussed in Butler and Galton (2008) and recently described as *Thescelosaurus* sp. (Boyd et al. 2009)) as a heart, based upon topological, dimensional, and structural criteria, including identification of presumed cavities considered compatible with interpretation as ventricles and vascular spaces in a four-chambered heart. They argued that the presence of a four-chambered heart with a single aorta, which should minimize vascular shunting, would be capable of supporting an increased metabolic rate in this small ornithischian dinosaur (Fisher et al. 2000; Seymour et al. 2004). *Thescelosaurus* is considered to be a basal ornithopod dinosaur sensu Butler et al. (2008) or a basal neornithischian dinosaur sensu Boyd et al.

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T. P. Cleland (✉) · M. H. Schweitzer
Department of Marine, Earth, and Atmospheric Sciences,
North Carolina State University,
Raleigh, NC 27695, USA
e-mail: tpclelan@ncsu.edu

M. K. Stoskopf
Environmental Medicine Consortium and Department of Clinical
Sciences, College of Veterinary Medicine,
North Carolina State University,
Raleigh, NC 27606, USA

M. H. Schweitzer
North Carolina Museum of Natural Sciences,
Raleigh, NC 27601, USA

(2009) and is collected from Maastrichtian age sediments in the western interior of North America.

Rowe et al. (2001) raised four main objections to the original interpretation. They suggested that if the structure was indeed a heart, additional characteristics, including pulmonary vessels, cardiac veins, coronary arteries, vena cavae, and atria consistent with extant heart morphology, should be visible, but these were not seen in the purported heart. Rowe et al. also mentioned a partial rib, visible inside the heart margin on the original images. The presence of a second concretion distal to the heart but within the body wall of the dinosaur was proposed by Rowe et al. to suggest a geochemical environment favoring concretion formation, making the interpretation of a concretion more favorable than preservation of a soft tissue organ. Finally, Rowe et al. claimed that soft tissue preservation was not common in fluvial environments, such as the Hell Creek Formation sediments where this dinosaur was found.

In response, the original investigators argued that the identification of the object as a fossil heart did not require that it “assume structural identity with a crocodile heart or the preservation of relatively thin-walled structures” (Russell et al. 2001). They acknowledged that the rib was embedded in the heart structure but argued that most of the body of the rib was adjacent to the heart. They argued that the second smaller and less deeply colored concretion in close proximity to the pelvic area could have also formed around organic residues from the decaying animal and did not negate the diagnosis of a heart. Finally, Russell et al. (2001) objected to the idea that the fluvial environments of the Hell Creek Formation are not conducive to soft tissue preservation, citing several examples of soft tissues in similar environments, and argued that concretion formation was rapid enough to preserve the morphology of internal organs (Russell et al. 2001).

Ironstone concretions, typically consisting of siderite, goethite, and/or hematite differentially cementing the local sandstone, are hypothesized to form through mixing of chemically distinct pore waters, resulting in zones of iron oxide precipitation within sandstones (Sellés-Martínez 1996; Chan et al. 2007). Some of these polymetallic concretions have been found to have internal density variation that can be identified by CT (Duliu et al. 1997). Decaying organics may trigger this precipitation, as stated by Russell et al., and indeed, many siderite concretions surround biological remains; likewise, goethite and/or hematite concretions form around an initial seed of iron mineral present along grain boundaries (Allison 1988; Busigny and Dauphas 2007; Chan et al. 2007). Ironstone concretions are known to form rapidly (Allison 1988; Chan et al. 2007), not slowly as mentioned by Rowe et al. (2001), and hence, the original identification of the thoracic

structure in NCSM 15728 was not eliminated strictly on chemical grounds.

In light of these unresolved issues, we reexamined both hypotheses put forth regarding the origin of the thoracic structure, setting up criteria for acceptance of either alternative in advance of analyses. We applied advances in technology not available at the time of the original study and applied additional analytical techniques outlined below. For purposes of clarity and brevity, we herein refer to the thoracic structure in question as a “heart” in accordance with the original hypothesis.

Criteria to support a biological origin

We agree with Russell et al. that additional morphological structures consistent with a “heart” need not be present to support the diagnosis of a heart because preservation potential of the heart wall may be different than that of supporting structures. However, we suggest that additional criteria, beyond similar biological location, similar morphology and organization, are needed to support the original hypothesis that a dinosaurian “heart” is preserved along with the skeletal elements of NCSM 15728. First, we suggest that, if biological, the “heart” should demonstrate “chambers” that differ in radiodensity from the surrounding structures. If these “chambers” interconnected in a manner consistent with extant archosaurian hearts, identification as a heart would be strengthened; however, we recognize that diagenetic processes could obscure these connections. Second, a biological origin would be supported if histological examination of the proposed “ventricular walls” showed preservation of microstructure consistent with extant myocardium (i.e., single nuclei, striated muscle fibers, and intercalated disks; Katz 2006), or degraded biological components that differ in morphology and texture from the surrounding sandstone matrix. Third, we propose that a chemical signature consistent with a biological origin (e.g., carbon and nitrogen from proteins (Patience et al. 1992; Vairamurthy and Wang 2002)) would support a cardiac origin.

Criteria to support a geological origin

Alternatively, we proposed criteria for a geological origin that could be examined simultaneously with the above. If histological examination of the “myocardium” showed the presence of well-cemented sand grains rather than organic tissue/cells, or evidence for exogenous inclusions, such as plant material, not normally contained in vertebrate organs, a geological origin would be supported. Additionally, we proposed that if the structure is a concretion, the chemistry of the structure should be consistent with a geological

origin displaying the presence of minerals consistent with siliclastic sedimentary rocks (e.g., quartz).

Methods

Computed tomography

The original study was valuable in bringing the state-of-the-art technology to address a novel question in paleontology. But relative to currently available technology, the resolution of the original computed tomography data (acquired with a Picker PQ6000 CT scanner) was relatively low, with a 4-mm slice thickness and spacing of 2 mm apart (Fisher et al. 2000). For the current study, the entire specimen, including the abdominal and thoracic concretions as well as surrounding thoracic structures, was scanned using a Siemens Somatom Sensation 16, with a slice thickness of 0.75 mm and spacing of 0.0 mm at the North Carolina State University College of Veterinary Medicine. The Somatom Sensation 16 provided over five times greater resolution than the original study. Using the same instrument and imaging protocol, we examined an unfixed, isolated heart of an adult extant ostrich, obtained from a slaughter facility, for morphological similarities to the dinosaur “heart”. The ostrich (*Struthio camelus*) was chosen for its evolutionary proximity to dinosaurs (Gauthier 1986; Sereno 1997; Brochu 2001 and references therein) and its approximate size similarity to NCSM 15728. The ostrich heart was imaged unexpanded, then to more clearly visualize the size and orientation of the chambers, cotton balls soaked in radio-opaque dye were inserted to compensate for postmortem collapse of ventricles and atria. The ventricles and atria of the ostrich heart and the purported chambers from NCSM 15728 were extracted in three dimensions using segmentation tools in Amira 5.2 (Visage Imaging) to compare overall morphologies. This ostrich heart was purchased frozen from the BirdBrain Ostrich Farm in Sherrills Ford, NC, USA.

Light microscopy

A fragment taken from the right lateral surface of the “heart”, possibly corresponding to the location of myocardium in extant avian hearts, was embedded in Silmar resin (Interplastic Corporation) under vacuum at -84.6 kPa for 5 min and sectioned to 1.5 mm using a Buehler Isomet 1000 saw. Sections were mounted onto frosted glass slides (Binswanger Glass, Raleigh, NC, USA) using Professional Extra Time 60 Minute Epoxy (Loctite). Pressure was applied to remove bubbles and polymerized overnight at room temperature. Sections were ground to an approximate final thickness of 40 μm using a Buehler Ecomet 4000

grinder with decreasing grit as follows: 60 grit paper to 500 μm , 180 grit to 300 μm , 400 grit to 150 μm , and 600 grit to 40 μm . Sections were polished with 4,000 grit polishing paper to remove scratches and then examined using a Zeiss Axioskop 2 plus biological microscope and a Zeiss Axioskop 40 petrographic polarizing microscope. Images were obtained at various acquisition times, depending on magnification, as follows: $\times 4$ for 13 ms, $\times 20$ for 30 ms, and $\times 40$ for 132.25 ms using an AxioCam MRc 5 (Zeiss) with $\times 10$ ocular magnification on the Axioskop 2 plus in the Axiovision software package (version 4.7.0.0).

Tissue-like material observed in microscopic examination of the purported dinosaur “heart” wall was compared with samples of endothelium from an extant emu (*Dromaius novaehollandiae*) heart and plant epidermis from white onion (*Allium cepa*), prepared for microscopy as follows: ventricular endothelial tissue obtained from an extant emu heart was removed from the overlying myocardium and spread in a thin layer onto silane-coated slides (Electron Microscopy Sciences) and then fixed by applying 2% glutaraldehyde in 0.1 M sodium cacodylate buffer for 20 min at room temperature. The tissue was incubated sequentially in 0.9% NaCl (2 min), 5% glucose (15 s), silver nitrate (10 s), 5% glucose, and finally, fixed as above using cacodylate buffer (1 min). The silver nitrate taken up at cell margins was photo-oxidized for easier visualization by a 45-min exposure to an Ott-lite 20-W grow bulb and then stained with Harris’ modified hematoxylin with acetic acid (Fisher) for 20 s. A mounting medium consisting of 0.1 M Tris/glycerol (50:50) was added and coverslip applied. Images were obtained with an Axioskop 2 plus coupled to an AxioCam MRc 5 using the Axiovision software package. Images were acquired for 15 ms at $\times 20$ magnification. This emu heart was purchased from Carlhaven Emu Farm in Carroll County, MD, USA.

Epidermal cells of white onion were peeled from the outer surface of one layer of the onion to test an alternative hypothesis of a plant origin for the small patches of tissue, observed in the “heart” wall matrix. The cells were placed onto a droplet of water on silane-coated slides and stained with Harris’ modified hematoxylin with acetic acid for 20 s. Water was added to the surface and covered with a coverslip. Images were obtained as above.

Scanning electron microscopy

Previously described ground sections were coated with 5–7 \AA of iridium in an Emitech K575X peltier-cooled coater. Elemental profiles were obtained from distinct regions of the sections with the PGT/Bruker SiLi energy dispersive detector electron diffraction analysis (EDX) coupled to a Zeiss Supra 55VP field emission electron microscope (FESEM).

X-ray diffraction analysis

An intact block of the embedded fragment was cut to $31 \times 24 \times 10$ mm ($l \times w \times h$) and mounted intact in a Scintag X-1 powder X-ray powder diffractometer (XRD) with a copper k-alpha source (40 mA, 45 kV) to determine the overall mineralogy of the concretion using theta–theta scan. The sample was scanned stationary from 4° to 65° with a step of 0.050° at $0.03^\circ/\text{min}$. Counts were collected for 1.5 s. Beta and alpha2 were filtered. The spectra were interpreted by comparison with standard spectra from the International Centre for Diffraction Data, PDF1 and PDF2, using the software package Diffraction Management System for NT (Scintag).

X-ray photoelectron spectroscopy

Three representative subsamples (0.2–0.3 g) of the fragment were powdered using mortar and pestle. The powders were added to conductive 9-mm carbon tabs (SPI Supplies) and mounted on silicon wafers. The three samples were analyzed separately using a Riber LAS-3000 X-ray photoelectron spectrometer (XPS) with an Mg k-alpha X-ray source at 1,253.6 eV angled at a 20° to the sample. XPS is used to determine the bonding environments of the atoms identified (Cornell and Schwertmann 2003). Geological iron oxides and quartz have peaks at 711–711.9 eV for iron, 154.4 eV for silicon, and approximately 530 eV for oxygen (Cornell and Schwertmann 2003). A biological sample would be expected to yield carbon and nitrogen signals (284.6 and 400 eV, respectively; Cheng et al. 2006; Patience et al. 1992). XPS was used to determine the nitrogen content because EDX cannot easily distinguish carbon and nitrogen (Goldstein et al. 2003).

Results

Computed tomography

The closest living relatives of non-avian dinosaurs are extant archosaurs (represented by crocodiles and birds (Gauthier 1986; Brochu 2001)). Extant phylogenetic bracketing (Witmer 1995) allows the assumption that characteristics shared by extant end members were also present in dinosaurs. In extant archosaurs, the four cardiac chambers are tightly clustered, surrounded by myocardium, and the chambers differ in volume and configuration in life depending on the beat phase (Krautwald-Junghanns et al. 1995; West et al. 1981). Figure 1a–c shows that in a static isolated heart modified to expand all chambers simultaneously, the heart chambers surround the single aorta in

extant ostrich. This orientation is also observed in crocodylians around their left and right aortic arch (see Webb 1979: Fig. 3). In this isolated heart, the atria clearly interconnect with the ventricles, and the left ventricle attaches to the single aorta (Fig. 1b, c). Interconnections between the ventricles and atria, though much reduced, were still observed in the heart examined ex situ without expanding the ventricles artificially (Fig. 1d–f). Because the heart in Fig. 1 was imaged in isolation from other body structures, exact orientation of the chambers is expected to

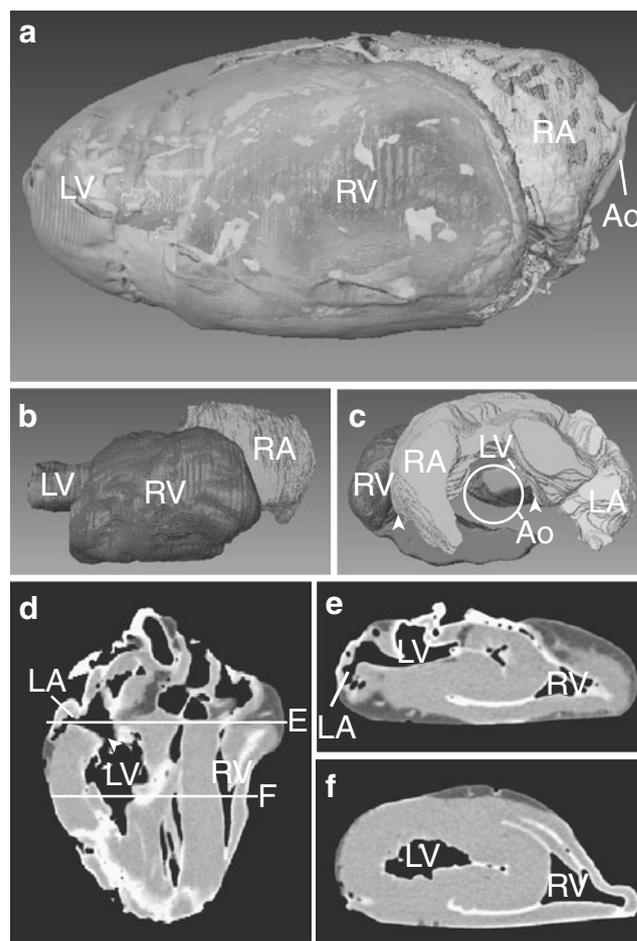


Fig. 1 a–c High-resolution CT of isolated ostrich heart with contrast medium soaked cotton packing of the chambers. **a** Extant heart in approximate right lateral anatomical orientation. **b** Ostrich cardiac chambers right lateral view with myocardium digitally removed. **c** Orientation of chambers from cranial view. *Arrowheads* indicate points of connection between the atria and ventricles. Note the tight “wrapping” of the chambers around the rising aorta and the overlap and interconnection of the chambers. **d–f** CT slices of an ostrich heart without the ventricles artificially expanded. **d** Longitudinal slice through the entire heart. *Arrow* indicates a connection between the left ventricle and left atrium. *Lines* indicate the position of slices in **e** and **f**. **e** Slice through the dorsal heart. **f** Slice through a more ventral portion of the heart. *RV* right ventricle, *LV* left ventricle, *RA* right atrium, *LA* left atrium, *Ao* aorta

be skewed and deformed from what might be observed in situ (Martinez-Lemus et al. 1998).

In NCSM 15728, regions of lesser density were interpreted as chambers in earlier analyses (Fisher et al. 2000). With higher resolution, it can be seen that these areas of reduced density are filled with mineral/sediment of different composition and radiodensity than the surrounding iron-cemented sandstone and comprise three distinct sections with no apparent interconnections between chambers (Fig. 2a–d). The concretion located in close proximity to the pelvis also displays an apparent “chamber” of lower radiodensity than the surrounding structure (Fig. 2e, f).

Light microscopy

Petrographic examination of sections from a small region that represented a fragment from the purported “heart” wall reveals distinct quartz and feldspathic sand grains, surrounded by opaque crystalline cement (Fig. 3a). At least three types of clasts consistent in texture and morphology with plant material are dispersed within the sections (Fig. 3b–d). Because of its blade-like shape, sharp external outline, and visible internal structure (Tyson 1995: Table 20.4, 20.5), the phytoclast in Fig. 3b (arrows) is identified as wood debris. Figure 3c (arrow) shows a phytoclast with definitive cell structure but diffuse margins. Figure 3d is an angular phytoclast with definitive internal structure. The latter phytoclast resembles the cuticular phytoclast described in Tyson (1995: Plate B6). The patch of material in Fig. 3e represents enigmatic “tissue” of uncertain origin that cannot be determined from morphology alone.

Scanning electron microscopy

FESEM with EDX data show submicron chemical differentiation within regions of the unidentified “tissue” (Fig. S1a–c). The central “nuclei” are composed of iron and oxygen (Fig. S1a), while iron, sulfur, and oxygen (Fig. S1b) dominate in the surrounding regions. The borders surrounding each cell-like structure are also compositionally distinct and are composed of iron, carbon, and oxygen (Fig. S1c).

X-ray diffraction analysis

XRD analyses of the powdered “heart” fragment produced peaks consistent with goethite (α -FeOOH; Fig. S2a), albite (NaAlSi₃O₈; Fig. S2a), anorthite (CaAl₂Si₃O₈; Fig. S2a), quartz (SiO₂; Fig. S2a), and gypsum (CaSO₄·2H₂O; Fig. S2a). All are common geological minerals and not part of biological systems, although there is some evidence that goethite may form from biological minerals such as ferrihydrite (Cornell and Schneider 1989).

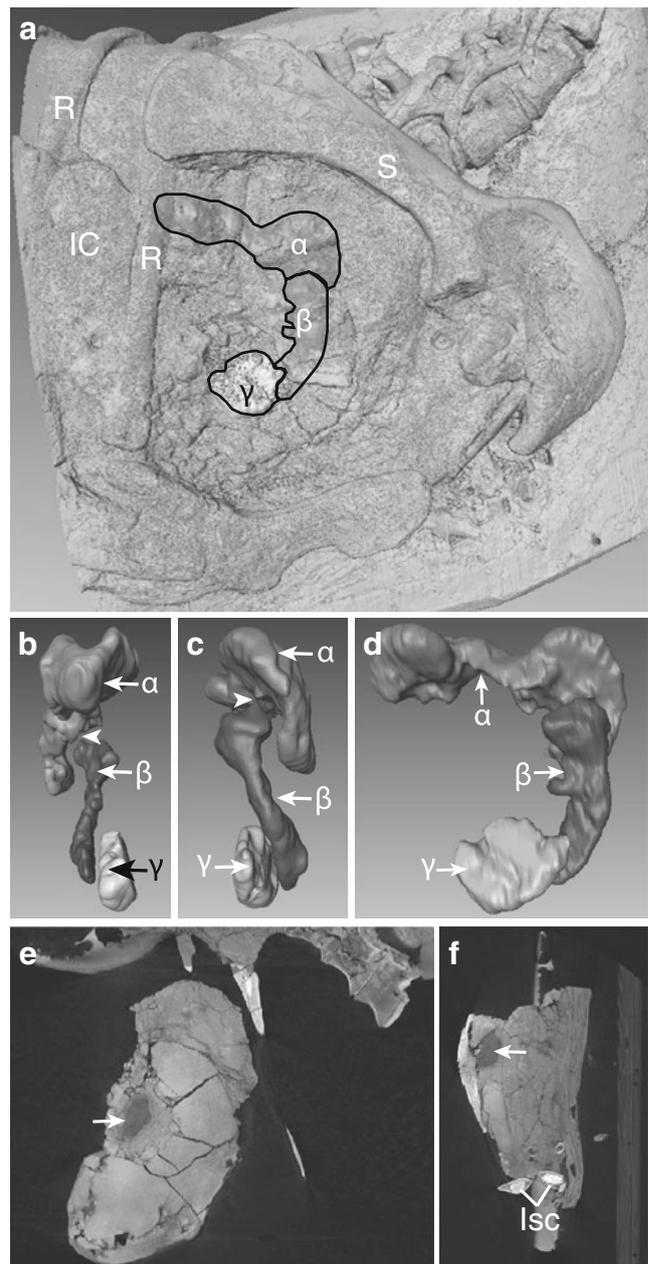
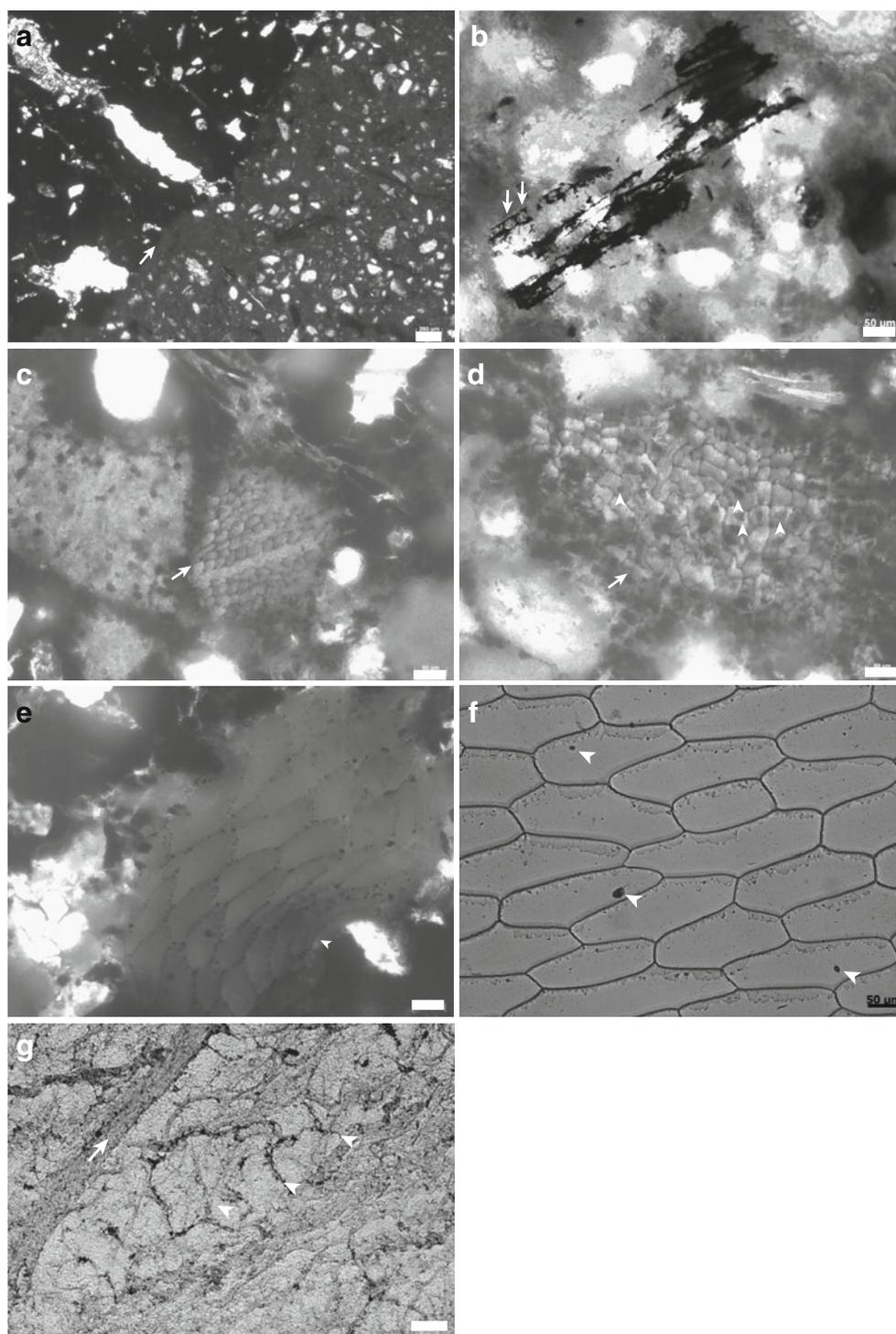


Fig. 2 a–d High-resolution CT of the purported heart within the thoracic cavity of the *Thescelosaurus* sp. (NCSM 15728). **a** Overview image of NCSM 15728 with in situ orientation of the chambers (outlined and labeled α , β , and γ) in right lateral view. **b** Extracted chambers in caudal view, showing complete separation of the γ chamber from the remaining structure. **c** Extracted chambers in cranial view, for comparison with Fig. 1c. **d** Extracted chambers in right lateral view. Arrows in **c** and **d** indicate complete separation of the structures α and β . *R* rib, *S* scapula, *IC* intercostal plates. **e**, **f** High-resolution CT of the assumed concretion in close proximity to the pelvis. **e** Lateral view of the pelvic concretion showing a low radiodensity area (arrow) similar to the ones in the chest cavity. **f** Cranial view of the pelvic concretion with low radiodensity area (arrow). *lsc* ischia

Fig. 3 Petrographic ground section of the wall of the NCSM 15728 thoracic “heart”.

a Representative image of sandstone cemented by opaque mineral, most likely goethite. *Arrow* indicates boundary between different cements and may indicate multiple stages of mineralization. *Scale bar*= 200 μm . **b** Carbonized phytoclast with preserved cellular structure (*arrows*) corresponding to xylem. **c** Regular microstructure possibly consistent with cellular morphology (*arrow*) from an isolated region of the NCSM 15728 “heart” wall. **d** A second isolated region with slightly less regular microstructure. *Arrowheads* indicate dark regions within the borders of the apparent “cells” that are consistent with nuclei in morphology. While the regions in **c** and **d** are clearly not consistent with sand grains, they may represent phytoclast cuticle (*arrow*). **e** Enigmatic polygonal clast with morphology resembling either plant epidermal cells or endothelial cells from a third small, isolated region of a single petrographic section of the fragment from the region of the NCSM 15728 “heart” wall. **f** Epidermal cells taken from an onion (*A. cepa*). *Arrowheads* indicate isolated nuclei. **g** Cardiac endothelial tissue obtained from the right ventricle of an extant emu heart, imaged after staining with silver nitrate to define cell membranes. *Arrow* indicates cardiac muscle fiber, and *arrowheads* show endothelial cell membranes. *Scale bar* on **b–g**=50 μm



X-ray photoelectron spectroscopy

XPS identified only iron, oxygen, and silicon (Fig. S2b), consistent with the XRD data. Carbon was not found in the XPS data, unlike the EDX data, because these data are averaged across the sample and no point data can be taken. Neither nitrogen nor phosphorus was identified within

examined regions. If these subsamples had biological signal, a peak representing nitrogen would be present at 400 eV (Patience et al. 1992) and a peak representing carbon would be present at 284.6 eV (Cheng et al. 2006). Each peak of the doublet corresponds to oxygen molecules bound to iron and silicon, respectively. XPS was not performed on the polygonal structures separately because

the area was too small to be separated with accuracy and because powdering is required. This would destroy the material and prevent further analyses to determine origin.

Discussion

Advances in technology have allowed us to further test two previously proposed hypotheses regarding the origin of the structure within the thoracic cavity of NCSM 15728: a geological concretion (Rowe et al. 2001) or a fossilized biological heart (Fisher et al. 2000; Russell et al. 2001). Increased detail of the gross morphology of the structure provided by higher-resolution imaging confirmed three regions of lesser radiodensity, as reported in previous studies (Fig. 2); however, there was no evidence for interconnections between these regions in their current state. Such interconnectivity would have strengthened the hypothesis of a cardiac origin, but the processes involved in diagenesis of vertebrate organs are not well studied (Schweitzer 2011 and references therein); thus, if connections between the “chambers” existed, this might have been completely obscured by diagenetic processes. Experiments to track the breakdown of these tissues under varying conditions may resolve this in the future.

Similarly, examination of the microstructure of the sections taken from the fragment of NCSM 15728 did not support a cardiac origin. No striated cardiac muscle, intercalated disks, cell membranes, central nuclei, or other features that define vertebrate heart microstructure were observed (Hodges 1974; Julian 1996; Farrell et al. 1998). Grains of quartz and plagioclase feldspar cemented by goethite dominated the regions we examined, supporting the hypothesis of geological origin. Subcellular detail consistent with vertebrate tissues has been reported in other well-preserved specimens, including intestines (Dal Sasso and Signore 1998), skeletal muscle (Kellner 1996a, b; Chin et al. 2003), and skin (Chiappe et al. 1998; Coria and Chiappe 2007), showing that cellular detail in preserved tissue is possible and confirms their diagnoses in these specimens.

Intriguingly, between cemented sand grains, microscopy revealed extremely small regions of isolated bioclasts (Fig. 3b–e); however, none of these structures are definitive vertebrate tissues. Many are clearly similar in texture and morphology to plant material seen in other fossils (Fig. 3b–d) lending more support to the hypothesis of a geological origin for the structure. The only possible exception so far identified is the bioclast in Fig. 3e, which suggests either plant cuticle with “nuclei” only present within a few of the “cells,” as in the onion tissue (Fig. 3f), or nucleated epithelial cells similar to those from emu cardiac endothelium (Fig. 3g). These cell-like structures show submicron

chemical differentiation by EDX, revealing taphonomic processes that are currently poorly understood, and this chemical sequestration may indicate the possibility of preservation of original chemical signatures. Complete characterization of this unusual material is required to determine its source and to identify its preservational mode.

Our chemical analyses also failed to support a biological origin for the “heart.” Neither carbon nor nitrogen, elements required for the synthesis of biological tissues, was identified in multiple analyses of the fragment we examined. Because diagenetic changes at the molecular level are poorly understood, these tests do not rule out the possibility of a biological origin. The chemical analyses are consistent with the petrographic interpretation supporting a geological origin. EDX data (Fig. S1c) of the “membranes” of the structures in Fig. 4a, b do identify carbon, but it is not associated with the “cytoplasm” or “nuclei” and therefore could be exogenous either from entombing sediments or as an artifact of preparation (Silmar resin used to embed for sectioning contains carbon).

Detailed examination of the gross morphology of the three-dimensional “heart” within the anterior thoracic cavity of NCSM 15728 and analyses of microstructure and chemical composition of a fragment associated with that “heart” failed to support the original hypothesis of a

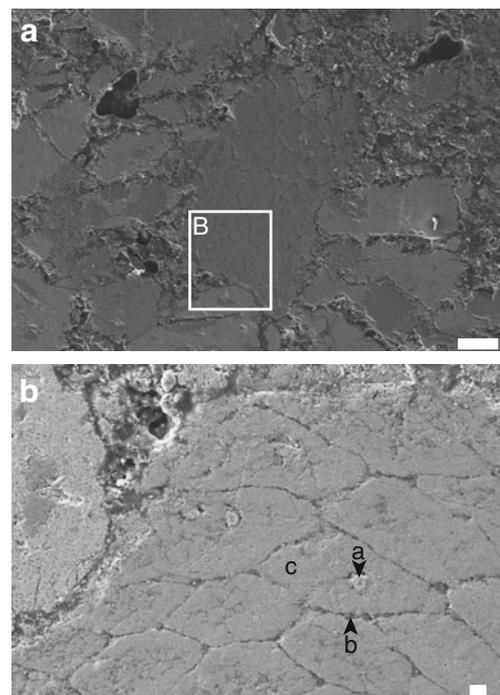


Fig. 4 FESEM images (a, b) of isolated regions within the petrographic section of the fragment from NCSM 15728. **a** FESEM micrograph of polyagonal structure depicted in Fig. 3e. Scale bar=100 μ m. **b** Higher magnification of region contained within box in a. Regions labeled a, b, and c correspond to the similarly labeled profiles in Fig. S1. Scale bar=10 μ m

heart origin; however, previously proposed hypotheses that dinosaurs possess four-chambered hearts are unaffected by this study because they are based on phylogenetic bracketing by extant birds and crocodylians (Witmer 1995; Brochu 2001). The data from this study support the hypothesis that the thoracic structure was formed by influx of sand into the carcass in a fluvial environment, followed by localized cementation with iron-laden waters, perhaps microbially mediated (Mozley and Davis 2005). However, as mentioned above, trapped within the concretion are very small regions that might correspond to isolated tissue fragments, and the possibility that these may represent remains of the original tissues has not been eliminated. More importantly, whether of plant origin or remnants of the original tissues of the dinosaur, the presence of these patches of cell-like material demonstrates chemical sequestration that is not predicted by current models, and further study holds promise for understanding fossilization processes at the cellular level. Because ironstone concretions are known to form very rapidly (Chan et al. 2007 and in contrast to Rowe et al. 2001), the decaying organs of the dinosaur may have “seeded” the formation of this structure. This seeding could have stabilized small regions by mineralization, outpacing the decay process (Briggs 2003). In addition, we have not eliminated the possibility that the iron cementing the sand grains may be derived from the degradation and mobilization of iron-rich hemoglobin and myoglobin associated with and concentrated in a decaying heart. Experiments in degradation show that metabolically active organs, such as heart or other muscles, degrade more rapidly than other organismal parts potentially freeing iron that may be incorporated into the cement of the structure (Turner-Walker 2007). If so, chemical examination may yet shed light on the biology of the animal; however, at present, it is not possible to determine a biological origin for the iron observed in the specimen. Even high-resolution stable isotope studies would be inconclusive because both geologically and biologically derived irons have completely overlapping signals (Anbar 2004: Fig. 5).

This study shows the importance of reevaluating controversial paleontological samples using new and higher-resolution technologies as they become available. This study also shows the importance of evaluating preservation of “soft tissue” structures with multiple methods rather than simply their location and morphology. While the original hypothesis of cardiac origin was consistent with the data presented by Fisher et al. (2000), new technologies and methods allowed retesting of this controversial hypothesis.

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