A non-destructive investigation of the skull of the small theropod dinosaur, *Coelophysis rhodesiensis,* using CT scans and rapid prototyping

Anthea Bristowe[1*], Andrew Parrott[2], Jonathan Hack[3], Mervyn Pencharz[3] & Michael Raath[1]

[1]*Bernard Price Institute for Palaeontological Research, School of Geosciences, University of the Witwatersrand, Private Bag 3, WITS, 2050 South Africa*

[2]*School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, Johannesburg*

[3]*Drs Spiro, Wilson, Duncan and Fourie Inc., Sunninghill Radiology, P.O. Box 5566, Rivonia, 2128 South Africa*

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To solve preparation problems encountered in an exceptionally fragile skull of the small theropod dinosaur, *Coelophysis rhodesiensis,* CT scans were taken of the partially prepared skull, from which a three-dimensional wax model was built using a 'reverse engineering' rapid prototyping technique. The resulting wax model was then consulted to trace and describe cranial elements of the dinosaur that were otherwise concealed by the matrix or overlying bones, which could not be removed without risk of damage to the original fossil bone.

Keywords: *Coelophysis rhodesiensis, Syntarsus,* dinosaurs, Theropoda, CT scans, computed tomography, rapid prototyping, stereolithography.

INTRODUCTION

Skeletal material of the small Early Jurassic theropod dinosaur, *Coelophysis rhodesiensis* (formerly *Syntarsus rhodesiensis*), is notoriously fragile and delicate, especially its skull material (Raath 1977, 1985, 1990; Bristowe 2004). Recent preparation of a partially disarticulated skull of a juvenile specimen of this dinosaur encountered problems relating both to the fragility of the individual cranial elements and to the degree of disarticulation which had resulted in some bones from neighbouring parts of the skull being flattened together inextricably during burial (Bristowe 2004). To solve these problems, use was made of the well-established non-destructive technique of CT (computed tomography) scanning combined with the relatively new technology of rapid prototyping. Prototypes have become useful tools in engineering and biomedical applications, being used to prove constructional details and problem-solve manufacturing difficulties, as well as in designing prostheses, planning reconstructive surgery, or simply to find out how an object or product in development will finally look (Webb 2000). The comparable combination of magnetic resonance imaging with 3-D stereolithography has also been successfully used recently to study a mouldic fossil from Scotland (Clark *et al.* 2004).

The specimen studied in this project, catalogued as QG165 in the collections of the Zimbabwe Natural History Museum, Bulawayo, was recovered from a bone-rich deposit in the Early Jurassic fine-grained Forest Sandstone Formation in the Chitaki River, north-central Zimbabwe (approx. 16°07′S, 29°30′E) (Raath 1977). Within this deposit, poorly sorted isolated bones and occasional articulated partial skeletons were preserved jumbled together in a small fluvial channel within a thick aeolian sandstone unit.

Specimen QG165 consists of an incomplete partial skull of a juvenile individual in which the cranial elements are closely associated although partially disarticulated (Fig. 1). This degree of association is unusual for material from the Chitaki River deposit, where by far the bulk of the assemblage consists of isolated individual skeletal elements that have been randomly mixed together (Raath 1977). In spite of this, the preservation of the bones in QG165 is generally excellent (Fig. 2) and there is little evidence of abrasion or predation, thereby offering a rare opportunity to study each cranial element as an individual piece while at the same time clarifying contacts between adjacent bones whose association in a single individual is beyond question. However, to study the skull at this level of detail meant that extensive and detailed preparation was necessary. In order to avoid damage to the vulnerable fossil bone, it was decided to take physical preparation as far as it was considered prudent to go, and then to supplement this with alternative, non-destructive, methods that would allow the otherwise obscured details to be revealed without risk to the specimen.

Data from CT scans can form the basic framework for a computer-assisted three-dimensional reconstruction, which can then be visualized and manipulated in any number of other applications, and studies involving use of this technology are becoming commonplace in palaeontology (see e.g. Brochu 2003; Stokstad 2000; Torres *et al.* 2003). One of the problems, though, when CT-scanning fossils is variations in density between bone and matrix – the smaller the difference between the two, the more problematic the scan. Recent CT scans of a skull of *Tyrannosaurus rex* presented not only this problem, but also one related to its sheer size; it was too long to fit into the single rotational envelope of most industrial scanners, so a means had to be found whereby the one-ton skull could be scanned resting on its occipital plate where the

*Author for correspondence. E-mail: bristowea@yahoo.co.uk

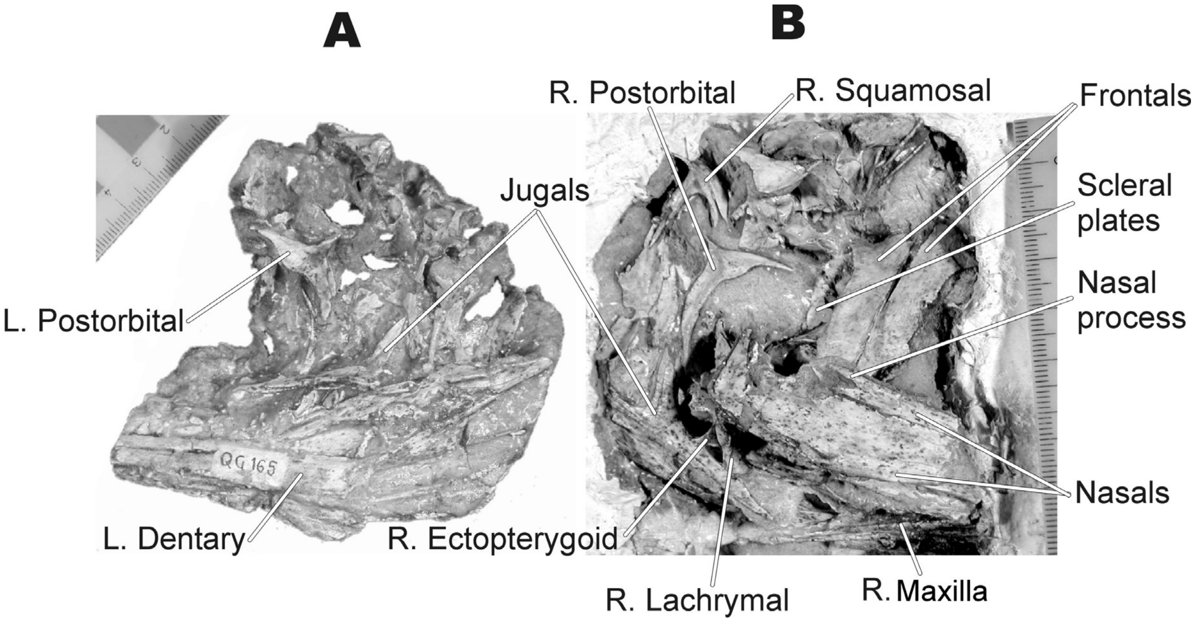

Figure 1. Two sides of the specimen QG165, showing slightly displaced elements of a juvenile skull. (Scale divisions = mm.)

bones are hollow and 2 mm thick (Brochu 2003). It was then discovered that most of the matrix filling the skull was a sandy siltstone that at times was nearly as dense as the bone, confounding attempts to digitally prepare the skull, or generate models of individual bones or internal structures (Brochu 2003). Specimen QG165 posed no such problems, as there was relatively little density-related 'noise' from the matrix and the specimen was small enough to be handled conveniently by a hospital-based CT-scanner.

The CT scans of QG165 were used to build a three-dimensional replica of the dinosaur skull in wax, by reference to which several of those cranial elements that were concealed by the matrix or by overlying bones could be traced and described.

MATERIALS AND METHODS

CT (computed tomography) scans

Specimen QG165 was scanned at the Sunninghill Hospital, Sandton, Johannesburg, in a series of fine slices using a Philips MX 8000 Multi-channel spiral scanner with effective slice thickness of 0.6 mm with 50% overlap, on a pitch of 0.875. Imaging was performed at 120 kV and 222 mAs, using an ultra high resolution algorithm, on a 512 × 512 image matrix. The resulting images (Fig. 3) were manipulated on a Philips MxView workstation using maximal intensity projection imaging techniques, and saved on CD in DICOM format. The thickness of the slice is critical to the success of the process, and while the slice thickness achieved in the project reported here was more

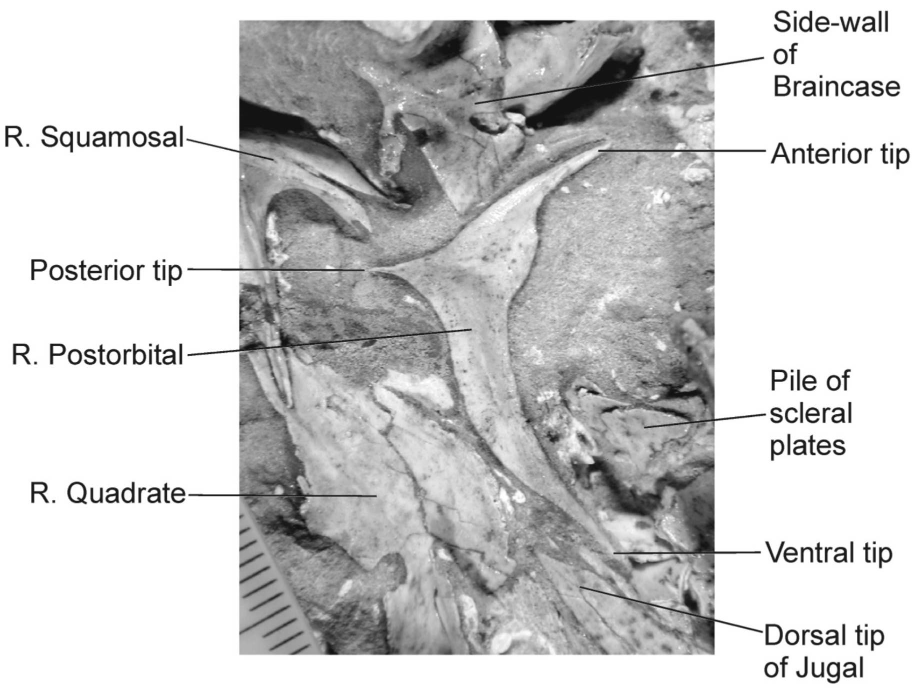

Figure 2. Right postorbital of QG165 in association with adjacent cranial elements, showing the perfect preservation of even delicate processes. (Scale divisions = mm.)

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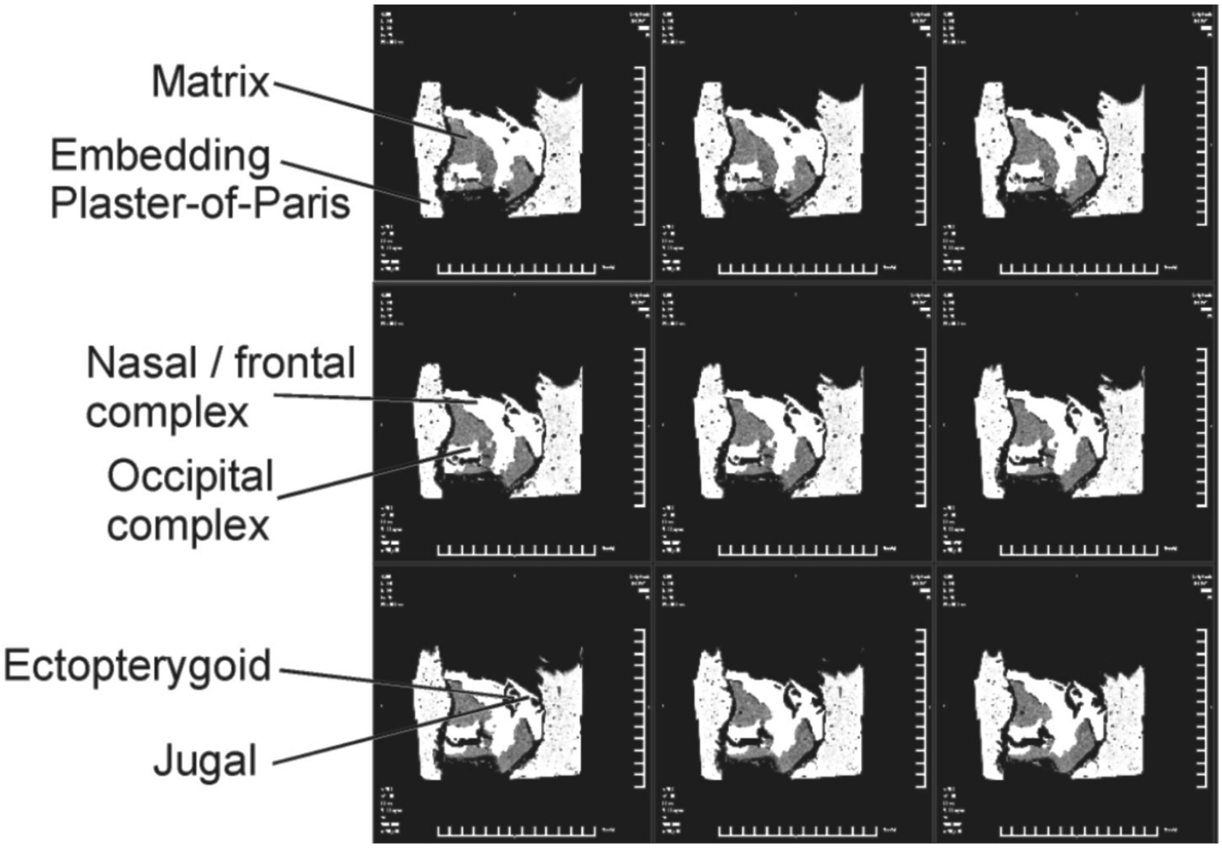

Figure 3. Selection of adjacent slice images derived from CT scan data.

than satisfactory for the purpose, when compared with achievable slice thicknesses of 0.2 mm or better on rapid prototyping machines, CT scans with a minimum slice thickness of 0.6 mm could be a limiting factor in some investigations (Webb 2000).

Using the Mimics Materialize software package (version 7.3), the formatted scan images of QG165 were converted into a digital volume where they were previewed and the density of the different substances, namely bone and matrix, were evaluated in order to establish their threshold values (Fig. 4). Once these were established it was possible to isolate bone from matrix. Threshold values were measured on a sliding scale in Hounsfield Units (HU), and these values were manipulated in order to eliminate as much of the matrix as possible from the image. It was not possible to eliminate all the matrix in the specimen because some of the densities were too close to those of the bone; densities of the dinosaur bone measured between 2000 HU and 3000 HU and those of the matrix were less than 2000 HU and greater than 3000 HU.

Building the model

The file was exported to .STL (stereolithographic) file format, a format that can be used to create physical three-dimensional parts. At this stage two methods of model building were investigated: a haptic modelling system using the FreeForm system (Sensable Technologies, MA, U.S.A.). Haptic interaction is a means of performing virtual preparation on the specimen in a virtual environment. A haptic modelling tool, known as a phantom haptic device, provides a sense of 'touch', making it possible to prod and probe the specimen and cut 'virtual matrix' away from the 'virtual bone'. However, the complex layering of the individual elements of bone in QG165 was unsuited to this approach, so haptic modelling was abandoned and the second method, that of rapid prototyping, was adopted.

The STL file was submitted to a commercial prototyping firm, Rapid Design Technologies, in Olivedale, South Africa, where it was directed to a Thermojet printer which grew the model in wax on a solid platform at a scale of 1:1 (Fig. 5). In common with all rapid prototyping systems, a

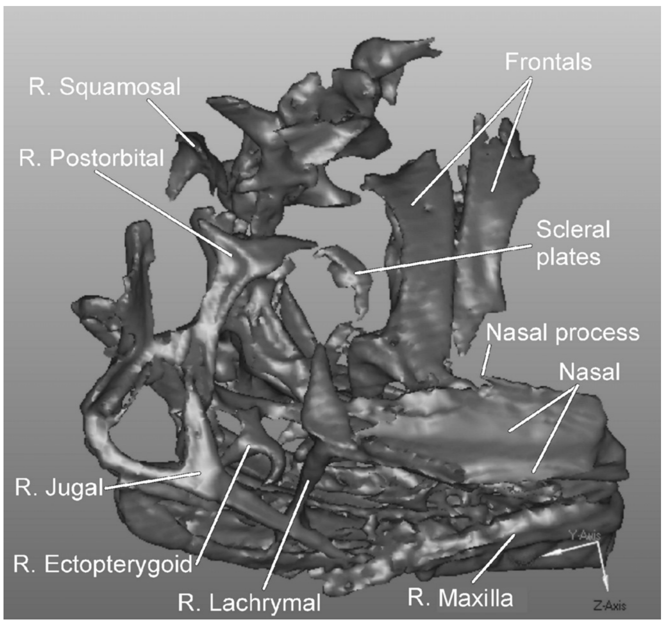

Figure 4. Digital volume of formatted images of right side of QG165, showing resolution of individual cranial elements.

layered manufacturing technique was used, which means that the model was built up in a series of physical slices, with each layer or slice being approximately 0.2 mm thick.

Voids around and within the resulting model are supported by regularly spaced fine pillars of wax, through which the general shape of the three-dimensional model is visible (Fig. 5). The model of QG165 was left on its platform with all its wax supports in place because it was small and delicate, and required support to protect the wax proxies of delicate and fragile processes on the original bones. The fine and brittle wax supports were easily brushed away when access to obscured parts of the model was needed. The three-dimensional model was used to supplement examination of areas of QG165 where details were obscured by overlying matrix or bone and where further physical preparation of the original fossil would have risked severe damage to the bone.

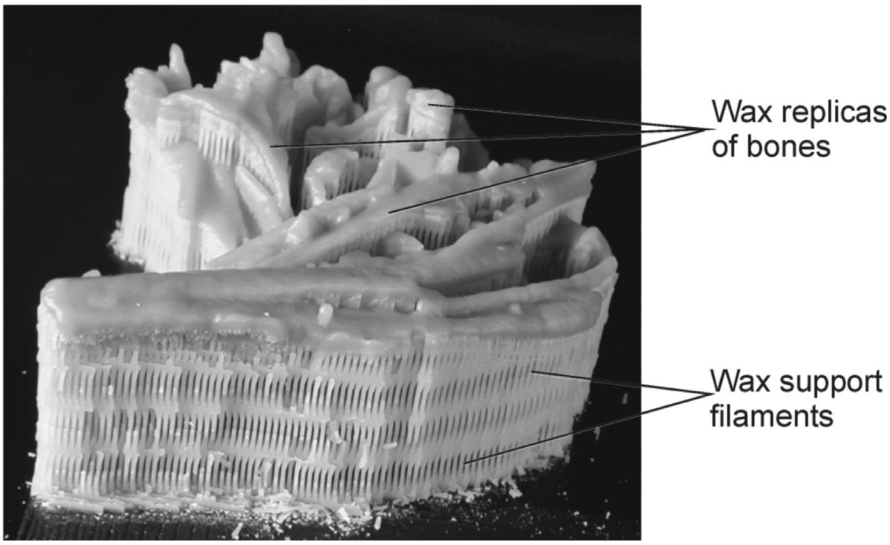

Figure 5. Wax replica of QG165 at a scale of 1:1 grown from the digital volume represented in Fig. 4.

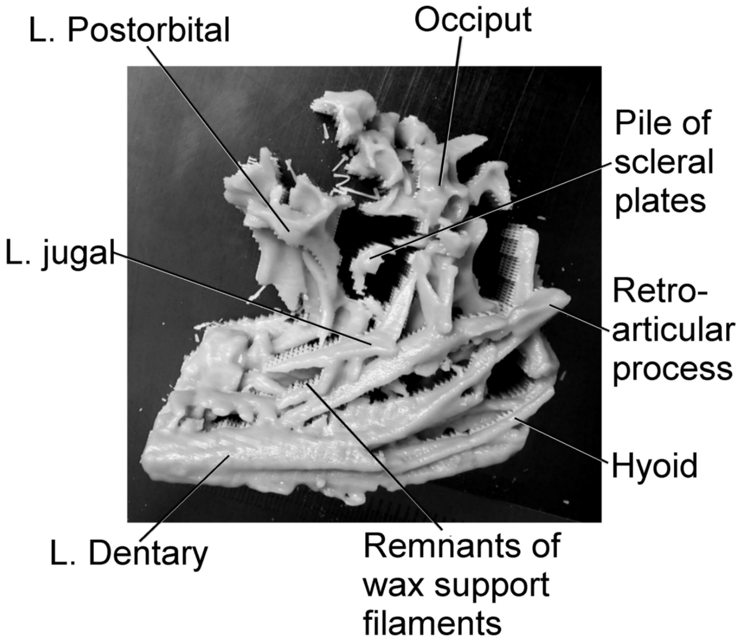

Figure 6. Wax replica of QG165 with most of the supporting wax filaments removed. Individual cranial elements are identifiable, including the previously unrecognized hyoids. Density differences were not sufficient to permit resolution of individual scleral plates.

RESULTS

The wax model of QG165 made it possible to identify and describe previously contested elements such as the hyoids, which are exceptionally slender and delicate bones (Fig. 6). In QG165 they were partially embedded in the matrix and therefore hidden from view. By examining the model it was possible to locate their contact with the dentary bones precisely. The left lachrymal was also located through examination of the model; during deposition of the specimen the skull had begun to disintegrate, as a result of which the nasal bones drifted over the left lachrymal, completely covering it and obscuring it from view. Physical excavation to expose it would have unavoidably damaged both the nasals and the frontal bones. The left maxilla was also tracked through the medium of the wax model as it too was buried deep beneath the nasal. This was especially useful as its posterior end was still preserved, unlike that of the right maxilla, so it was possible to reconstruct the maxilla-lachrymal-jugal contact (another contested region of the skull of *C. rhodesiensis*) using what could be directly observed on the right side of the skull combined with information on the morphology of the left maxilla gleaned from examination of the wax model.

The model failed in a few instances where there was minimal difference between the densities of the bone and the matrix, so that the CT scan was unable to differentiate between them, and this failure was consequently reflected in the model. It was not possible, for instance, to glean any new information on the small and very thin (<1 mm thick) scleral plates from the orbits, because they were interpreted as amorphous fused blobs. The scleral plates are wedge-shaped, paper-thin, flat plates of bone, each approximately 9 mm in width and 6 mm deep, and in QG165 they lay in two loose piles; in the model, each pile was interpreted as a single entity. One possible means of overcoming this limitation would be to digitally reprocess the scleral plates with a different HU value and then prototype them on their own. This limitation in discrimination did not, however, apply to other small but more robust elements, such as teeth. Using the model, it was possible to locate and count all the teeth preserved in the left dentary, even though several of them could not be seen in the original specimen.

CONCLUSIONS

The use of CT scans that can be transferred into digital format in order to build accurate three-dimensional models through rapid prototyping is a potentially powerful tool in the analysis and reconstruction of fossil skeletons (Torres *et al.* 2003). In the case of QG165, the physical preparation necessary to expose all the required details of skull construction would inevitably have resulted in damage to or destruction of many of the critical structures. The wax model obviated the need to take such risks. Combining direct observation of the original fossil with study of the wax model grown from the CT scan data allowed critical areas of the partially disarticulated skull to be reconstructed with confidence, from which a definitive identification of the taxon under study could be made, which in turn helped to resolve a long-standing taxonomic dispute (Bristowe 2004). With the rapid advance of these technologies there are exciting prospects ahead for the development of ever more useful non-destructive, even non-invasive, investigative techniques in many fields, not least in palaeontology.

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