



## Broad application of non-invasive imaging techniques to echinoids and other echinoderm taxa\*

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### Abstract

Tomographic imaging techniques such as micro-computed tomography ( $\mu$ CT) and magnetic resonance imaging (MRI) permit the gathering of digital anatomical data from whole animal specimens non-invasively. The resulting datasets can be used for direct observation of the two-dimensional tomographic image data as well as for manual and semi-automated three-dimensional modelling. Freshly fixed specimens as well as preserved museum material can be successfully analyzed using this approach, giving the zoomorphologist a powerful tool for large-scale comparative studies. In order to demonstrate the principle suitability of non-invasive imaging in echinoderm research,  $\mu$ CT scans of 199 and MRI scans of 92 sea urchin (Echinodermata: Echinoidea) species were acquired, resulting in a total of 203 analyzed echinoid species. The taxa selected represent 50 of the currently recognized 60 extant sea urchin families. The present article lists all species that have been analyzed so far and provides information about the scanning parameters employed for each dataset. Furthermore, the workflow established to generate three-dimensional models of sea urchins is outlined. Using a number of examples from  $\mu$ CT as well as MRI scans performed on echinoids, the potential of the systematic approach described here is highlighted. Finally, the suitability of non-invasive imaging techniques for the study of other echinoderm taxa is assessed based on multimodal datasets of representative species.

**Key words:** Micro-CT,  $\mu$ CT, MRI, Echinodermata, Echinoidea, imaging, 3D visualization

### Introduction

Micro-computed tomography ( $\mu$ CT) and magnetic resonance imaging (MRI) can currently be considered the most promising non-invasive techniques for imaging of whole specimens at the centimeter scale (Walter *et al.* 2010). While MRI provides excellent soft tissue contrast (Jakob 2011),  $\mu$ CT can be used to gather information primarily on hard tissues (Stauber & Müller 2008). Over the course of the last five years, I have employed both methods to visualize soft and hard parts in sea urchins (Echinodermata: Echinoidea). Because  $\mu$ CT and MRI are in principle entirely non-invasive imaging techniques, museum material (including type specimens) was successfully integrated into this study, resulting in an unprecedented taxon sampling for comparative morphological purposes. The acquired datasets can be used for computer-based two-dimensional (2D) as well as three-dimensional (3D) visualization and interaction in real-time. In fact, sea urchins constitute the first metazoan taxon to have been systematically documented on such a broad scale using the two complementary imaging

modalities  $\mu$ CT and MRI.

The present article provides an overview of the species that have been scanned so far, and presents visual examples for the properties as well as the quality of the datasets obtained. Furthermore, the approach described here is assessed for its principle suitability for large-scale analyses of the other echinoderm groups, that is, feather stars (Crinoidea), brittle stars (Ophiuroidea), sea stars (Asteroidea), and sea cucumbers (Holothuroidea).

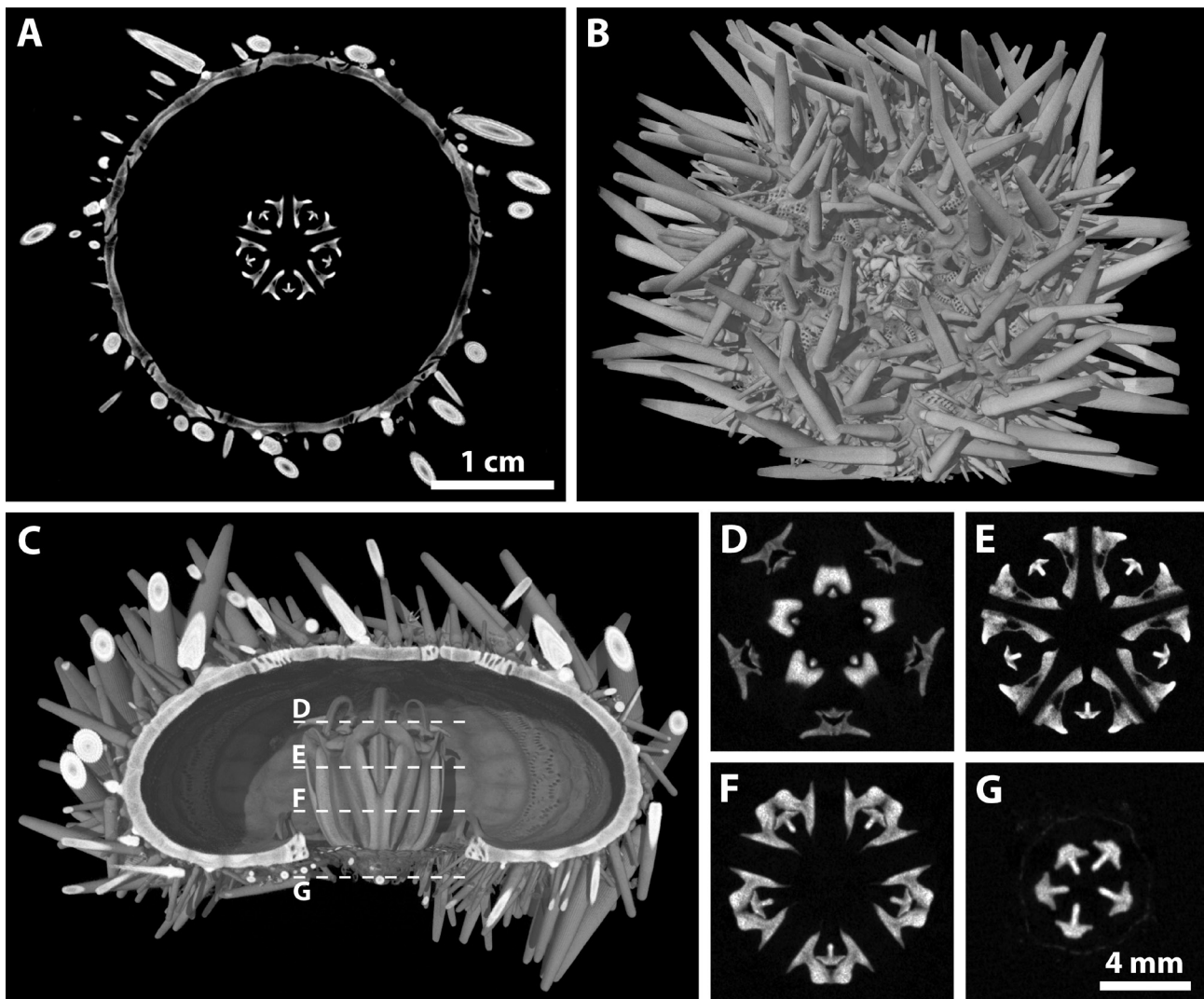
## Materials and Methods

Specimens were obtained from various sources, including natural history museums and private collections. Almost all specimens scanned during this study have been (re-)deposited in museum collections after scanning and most of these samples are kept in specially marked containers to facilitate potential future re-scanning. The table in the appendix lists the source for each sample together with the respective catalogue number.

Micro-computed tomography ( $\mu$ CT) scanning was performed at the outstation of the Helmholtz-Zentrum Geesthacht at the Deutsches Elektronen-Synchrotron in Hamburg, Germany and at the Center for Nanoscale Systems in Cambridge, MA, USA. The two scanners used were X-ray tube tomography systems equipped with a tungsten X-ray source (Phoenix Nanotom, GE Sensing & Inspection Technologies, Wunstorf, Germany and X-TEK HMX-ST 225, Nikon Metrology, Leuven, Belgium). The parameters of the scanning protocols were: 90–120 kV source voltage, 80–160  $\mu$ A source current, 0.1–0.2 mm copper filter, 750–2,000 ms exposure time, 1–3 frames averaged, 1–2 frames skipped, 1,200–3,200 frames acquired over 360°, 2,304 x 2,304 and 2,000 x 2,000 pixel detector size, and about 50 min to 2 h 10 min scan time. Reconstruction was performed with and without compression (2x binning) using the software provided with the scanner (*i.e.*, DatosX Reconstruction 1.5 in case of the Phoenix system and Metris XT 2.2 in case of the X-TEK system). Compressed datasets with doubled voxel resolution were created to facilitate rapid access to the raw data (Ziegler & Menze in press). These compressed datasets were about 0.5 to 4 GB large, whereas the uncompressed datasets had individual sizes of about 6 to 30 GB. The table in the appendix lists the voxel resolution of the uncompressed dataset for each specimen.

Magnetic resonance imaging (MRI) using 3D scanning protocols was performed at the Charité-Universitätsmedizin Berlin, Germany, the Institut für Klinische Radiologie in Münster, Germany, and at the Physikalisches Institut in Würzburg, Germany using horizontal-bore small animal scanners with 7 T, 9.4 T, and 17.6 T magnet strength, respectively (Bruker BioSpin GmbH, Ettlingen, Germany). 2D MRI scanning protocols were implemented at the Leibniz-Institut für Molekulare Pharmakologie in Berlin, Germany using a 9.4 T vertical-bore nuclear magnetic resonance scanner equipped for imaging (Bruker BioSpin GmbH, Ettlingen, Germany). Detailed information on sea urchin MRI scanning parameters has been published elsewhere (Ziegler & Mueller 2011; Ziegler *et al.* 2008a). The table in the appendix lists the voxel resolution achieved for each specimen.

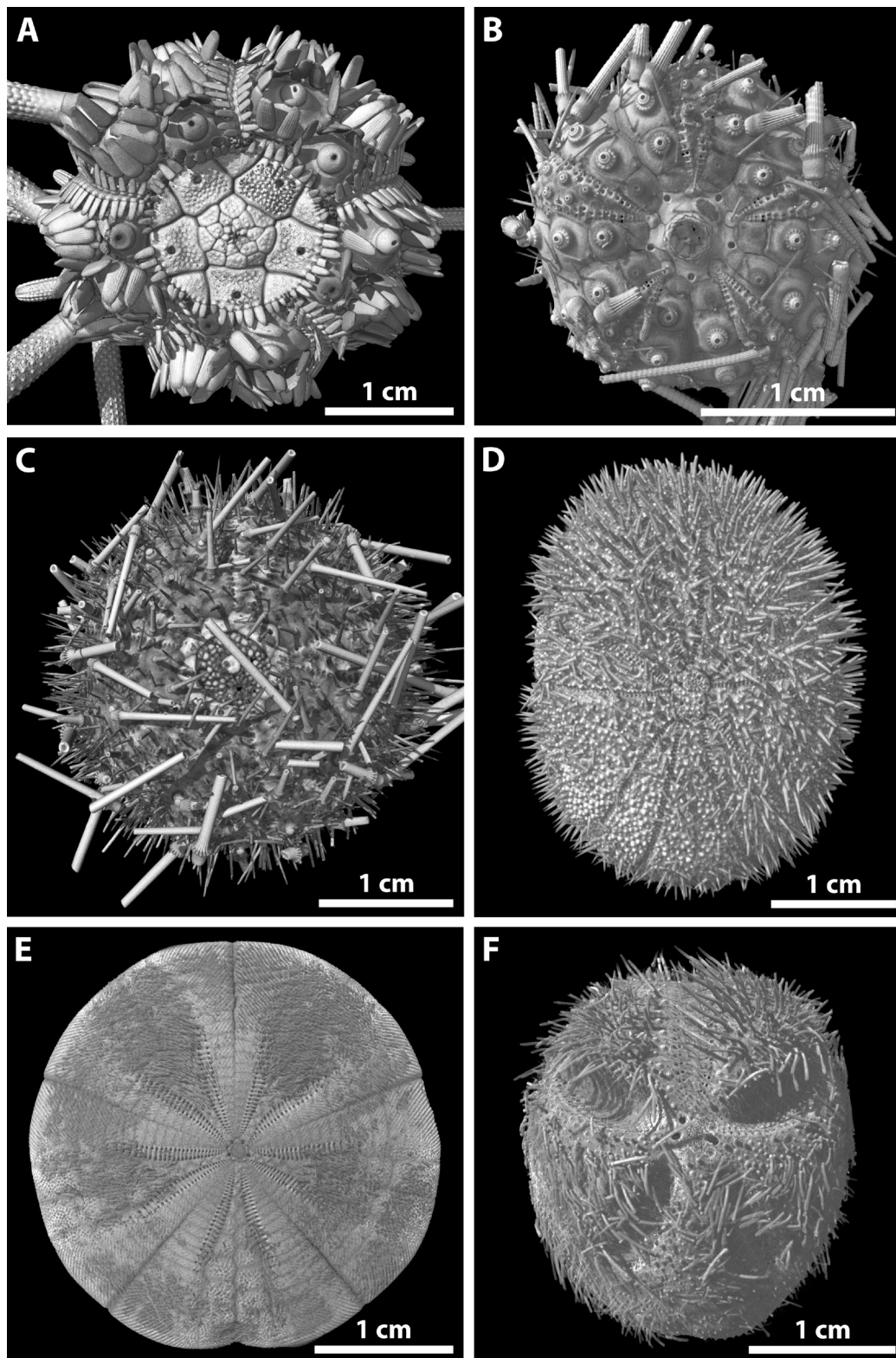
The computer equipment used for image reconstruction after  $\mu$ CT and MRI scanning depended on the hardware components provided with the respective scanner. However, all subsequent image analysis and processing was performed using conventional desktop computers. Common specifications for these systems were a 64-bit Windows 7 operating system, a multi-core processor with a minimum



**FIGURE 1.** Visualization of a micro-computed tomography ( $\mu$ CT) scan of a sea urchin (*Strongylocentrotus purpuratus*). This museum wet specimen, with soft tissues preserved, was scanned directly in ethanol. The voxel resolution of the original dataset is 13.91  $\mu$ m isotropic, but for reasons of hardware limitations the images shown here are based on the compressed (2x binned) dataset with an isotropic voxel resolution of 27.82  $\mu$ m. (A) Virtual transverse section at the mid-level of Aristotle's lantern. (B) Aboral view of a volume rendering of the sea urchin's test and spines. Ambulacrum III is facing to the right. (C) Lateral view of a volume rendering of a virtually dissected specimen showing Aristotle's lantern *in situ*. The four virtual transverse sections (D–G) reveal the cross-sectional morphology of the masticatory apparatus of this species. Isotropic tomographic datasets can be virtually sectioned at any given angle and can also be interactively rotated in real-time using the appropriate soft- and hardware.

of 6 GB RAM, and a graphics card with a minimum of 1 GB RAM. Interactive dataset inspection and slicing was accomplished using myVGL 2.1 (Volume Graphics GmbH, Heidelberg, Germany) for  $\mu$ CT datasets and the ImageJ (National Institutes of Health, Bethesda, MD, USA) Volume Viewer plug-in for MRI datasets. Image post-processing was accomplished using Adobe Photoshop and Illustrator CS3 (Adobe Systems, San Jose, CA, USA). 3D volume rendering was performed for all  $\mu$ CT datasets using myVGL 2.1, while MRI datasets were manually segmented and 3D surface rendered using Amira 3, 4, and 5 (Visage Imaging GmbH, Berlin, Germany). Interactive 3D PDF models were created using Adobe 3D Toolkit and Adobe 3D Reviewer (Adobe Systems, San Jose, CA, USA). See Ziegler *et al.* (2011a) for more information on the integration of multimedia files into PDF documents.





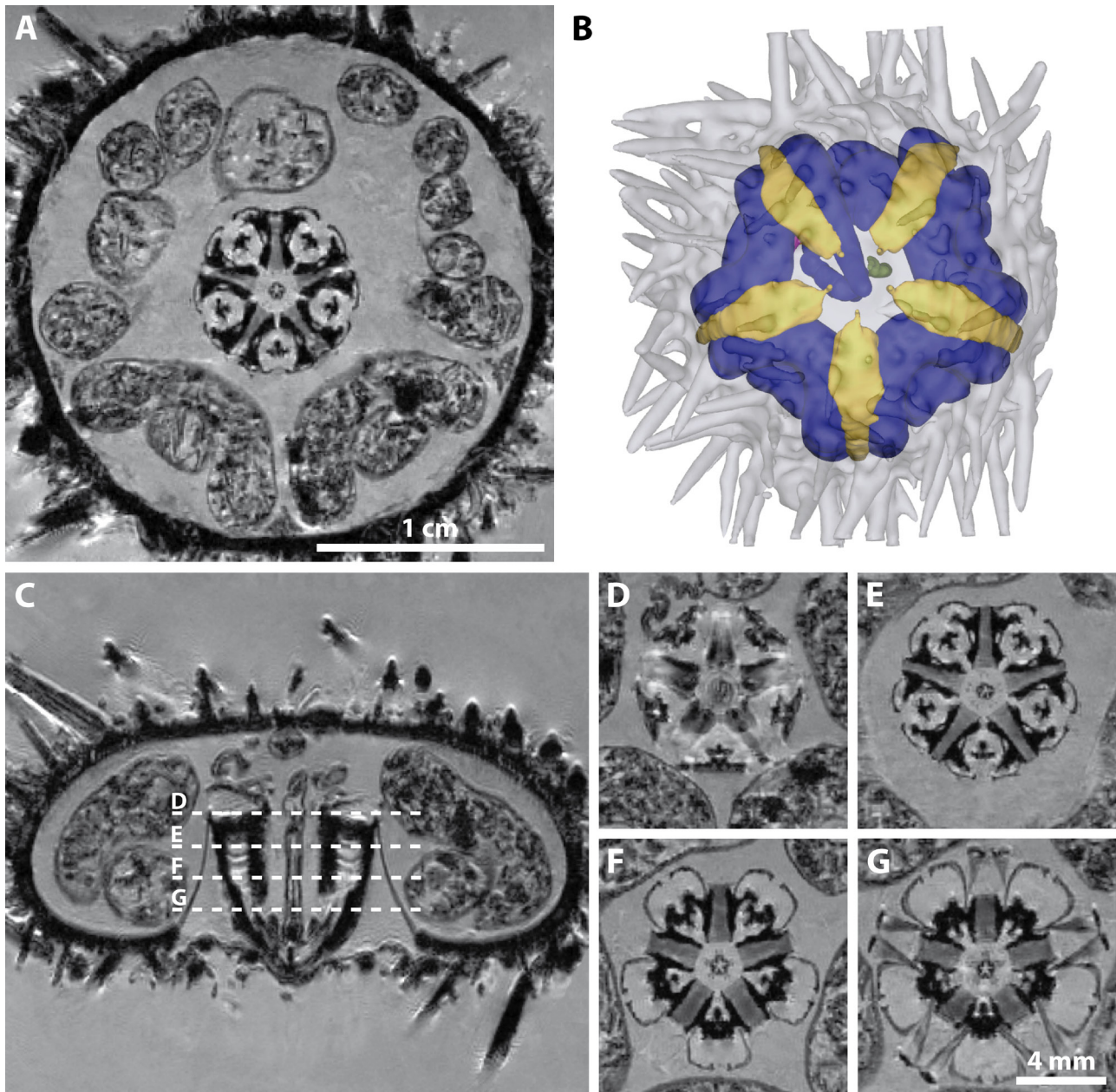
**FIGURE 2.** Systematic scanning of sea urchins using  $\mu$ CT. This selection of six of the 199 sea urchin species for which  $\mu$ CT scans were gathered shows volume-rendered aboral views of the test with spines. For reasons of hardware limitations, the images depicted here are based on compressed (2x binned) datasets. Ambulacrum III is facing upwards in all images. (A) *Eucidaris metularia* (Cidaridae), a derived cidaroid. (B) *Diadema savignyi* (Diadematidae), a basal 'regular' euechinoid. (C) *Sterechinus agassizii* (Echinidae), a derived echinacean. (D) *Echinoneus cyclostomus* (Echinoneidae), a basal irregular. (E) *Arachnoides placenta* (Clypeasteridae), a clypeasteroid. (F) *Abatus cordatus* (Schizasteridae), a spatangoid. Plate patterns, lantern morphology, and spine architecture are made visible non-invasively using  $\mu$ CT, which opens up the possibility to partly base echinoid taxonomy on this technology in the future. Using  $\mu$ CT, the hard parts of presumably every sea urchin species can be successfully analyzed. Fig. 4 shows complementary, MRI-based models of selected soft tissue structures in combination with virtual transverse sections.

## Results

As the aim of this project was to gather tomographic data for comparative morphological purposes, care was taken to cover the full breadth of gross morphological diversity that sea urchins display on the whole. To this end, representative members of as many families as possible were initially selected, while the scanning of one representative member per genus was a later objective. Digital tomographic datasets were finally obtained for 203 sea urchin species (Appendix), with 199 species being scanned using  $\mu$ CT (Figs. 1–2 provide examples) and 92 species being scanned using MRI (see Figs. 3–4 for examples). The specimens selected represent 50 of the currently recognized 60 families of extant sea urchins (Kroh & Mooi 2011).

The workflow established for this study consisted of six consecutive steps. 1) Specimen acquisition: material was either collected in the wild or was loaned from museum collections. Since the objective was to image hard as well as soft structures, primarily wet material with preserved soft tissues was selected. However, dry material was additionally used to increase taxon coverage in cases where no wet specimens were available. In order for the specimens to fit into the scanning chamber, the diameter of each specimen was usually not larger than three cm, although specimens with diameters of up to 20 cm were scanned as well using special scanner setups. In some cases spines had to be removed for tight fit. 2) Specimen preparation: for MRI scanning, specimens were rehydrated and then placed inside containers filled with distilled water, while for  $\mu$ CT scanning specimens were kept in ethanol-filled containers in case of wet material or in air-filled containers in case of dry material. In most cases, the animals were mechanically fixed using plastic or glass rods to prevent movement artifacts during scanning (Ziegler & Mueller 2011). 3) Specimen imaging: once suitable protocols had been established in cooperation with the personnel responsible for the scanner equipment, high-throughput scanning was initiated either in the form of overnight scans (MRI) or during extended scanning sessions ( $\mu$ CT). 4) Dataset processing: in case of MRI, the generated volumetric datasets were transformed to 8-bit TIFF format as well as cropped in their pixel dimensions in order to reduce the final file size, and were then rotated to a standardized orientation using the ImageJ TransformJ plug-in.  $\mu$ CT datasets were reconstructed and then additionally compressed (2x binning) to produce datasets with an individual file size that would be possible to manage interactively on conventional desktop computers, instead of having to rely on high-end visualization clusters (Ziegler *et al.* 2010a). 5) Image analysis: all datasets were repeatedly screened slice by slice for characteristic morphological features. This exploratory approach has so far resulted in MRI-based comparative morphological studies on three internal soft tissue structures: the axial organ (Ziegler *et al.* 2009), the gastric caecum (Rolet *et al.* 2012; Ziegler *et al.* 2010b), and the lantern protractor muscle (Ziegler *et al.* 2012a). In addition, an extended study of sea urchin tooth macro- and microstructure using  $\mu$ CT datasets was initiated (Ziegler *et al.* 2012b). 6) 3D rendering: apart from analyzing the 2D tomographic slices, surface and volume rendered models were produced to study soft and hard parts in 3D. These renderings were threshold-based (*i.e.*, grayscale-dependent) in case of  $\mu$ CT data and segmentation-based (*i.e.*, performed manually) in case of MRI data. To facilitate the communication of complex morphological structures, interactive 3D PDF models were created, some of which are available for download on the Echinoid Directory website (Ziegler *et al.* 2008b) or have been embedded directly into publications (Ziegler *et al.* 2010a, 2010b).



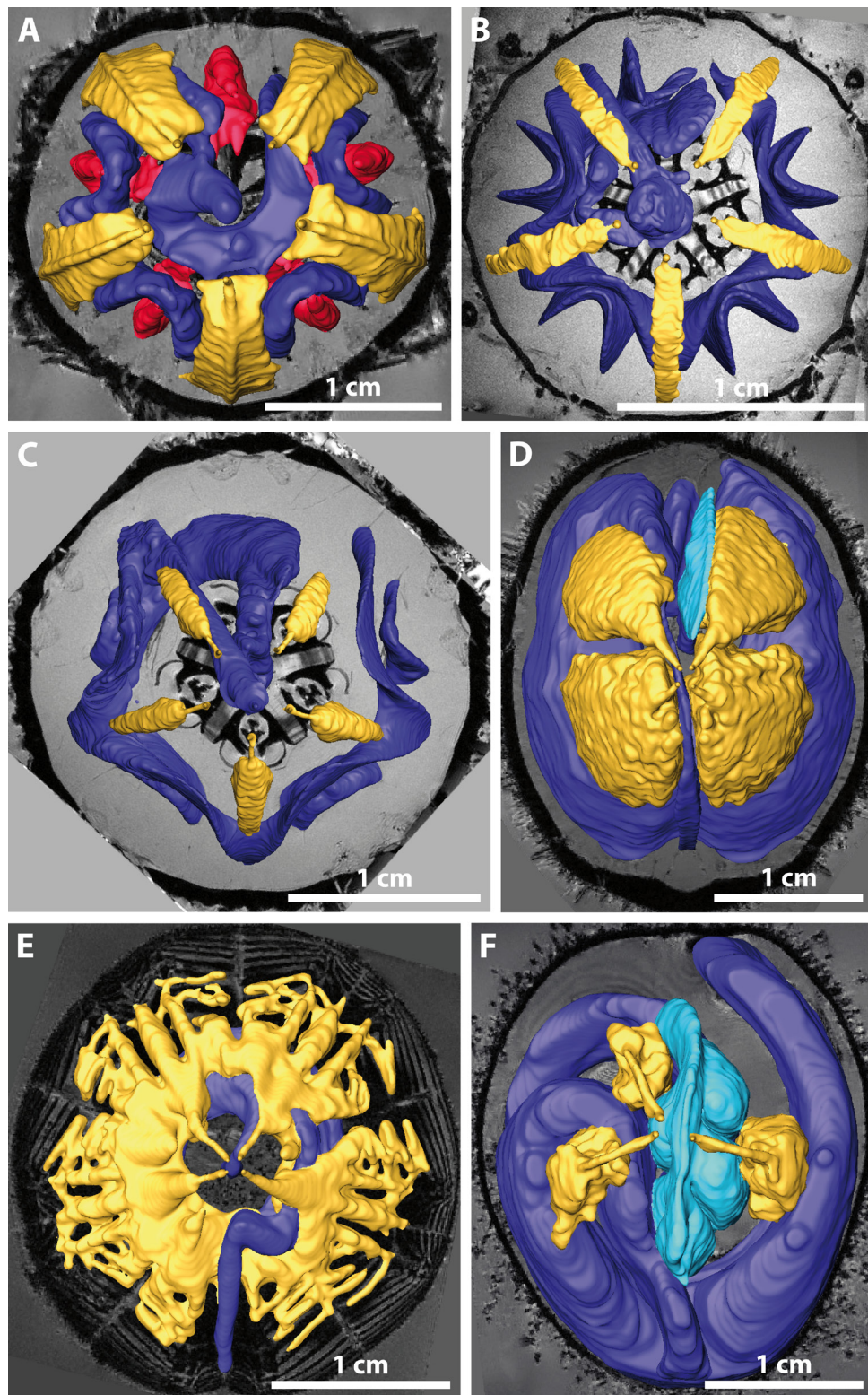


**FIGURE 3.** Visualization of a magnetic resonance imaging (MRI) scan of a sea urchin (*Strongylocentrotus purpuratus*). This museum wet specimen was scanned in distilled water with a contrast agent added to increase signal strength. The voxel resolution of the dataset is 81  $\mu\text{m}$  isotropic. (A) Virtual transverse section at the mid-level of Aristotle's lantern showing internal organs such as the festooned digestive tract, ampullae, gonads, and lantern muscles. Hard tissue contrast is achieved because of the negative delineation caused by the strong signal from water molecules surrounding calcified elements, which themselves do not generate any signal. (B) Aboral view of a semi-transparent 3D surface rendering of the sea urchin's test showing selected internal organs *in situ*. (C) Longitudinal virtual section through the sample at the level of the pharynx. The four virtual transverse sections (D–G) illustrate the cross-sectional morphology of the masticatory apparatus of this species. Ambulacrum III is facing upwards in all images except in (C). Blue = digestive tract, green = axial complex, grey = endoskeleton, violet = siphon, yellow = gonad.

## Discussion

The power of the approach established during this study must be seen in the possibility to conduct large-scale, high-throughput morphological analyses non-invasively. By including museum specimens from collections worldwide,  $\mu\text{CT}$  and MRI have enabled the semi-automated, almost industrialized gathering of morphological data from representative members of an entire invertebrate





**FIGURE 4.** Systematic scanning of sea urchins using MRI. This selection of six of the 92 sea urchin species scanned using MRI shows aboral views of 3D surface renderings of selected internal organs in combination with virtual transverse sections through the respective MRI dataset. Ambulacrum III is facing upwards in all images. (A) *Eucidaris metularia* (Cidaridae), a derived cidaroid. (B) *Diadema savignyi* (Diadematidae), a basal ‘regular’ euechinoid. (C) *Psammechinus miliaris* (Parechinidae), a derived echinacean. (D) *Echinoneus cyclostomus* (Echinoneidae), a basal irregular. (E) *Arachnoides placenta* (Clypeasteridae), a clypeasteroid. (F) *Abatus cavernosus* (Schizasteridae), a spatangoid and congener of *Abatus cordatus* shown in Fig. 2F. Using MRI, most sea urchin species can be successfully analyzed, although some species may ingest large amounts of para- or ferromagnetic sediment that will cause pronounced MRI artifacts. Fig. 2 shows complementary,  $\mu$ CT-based aboral views of test and spines. Blue = digestive tract, cyan = gastric caecum, red = Stewart's organs, yellow = gonad.

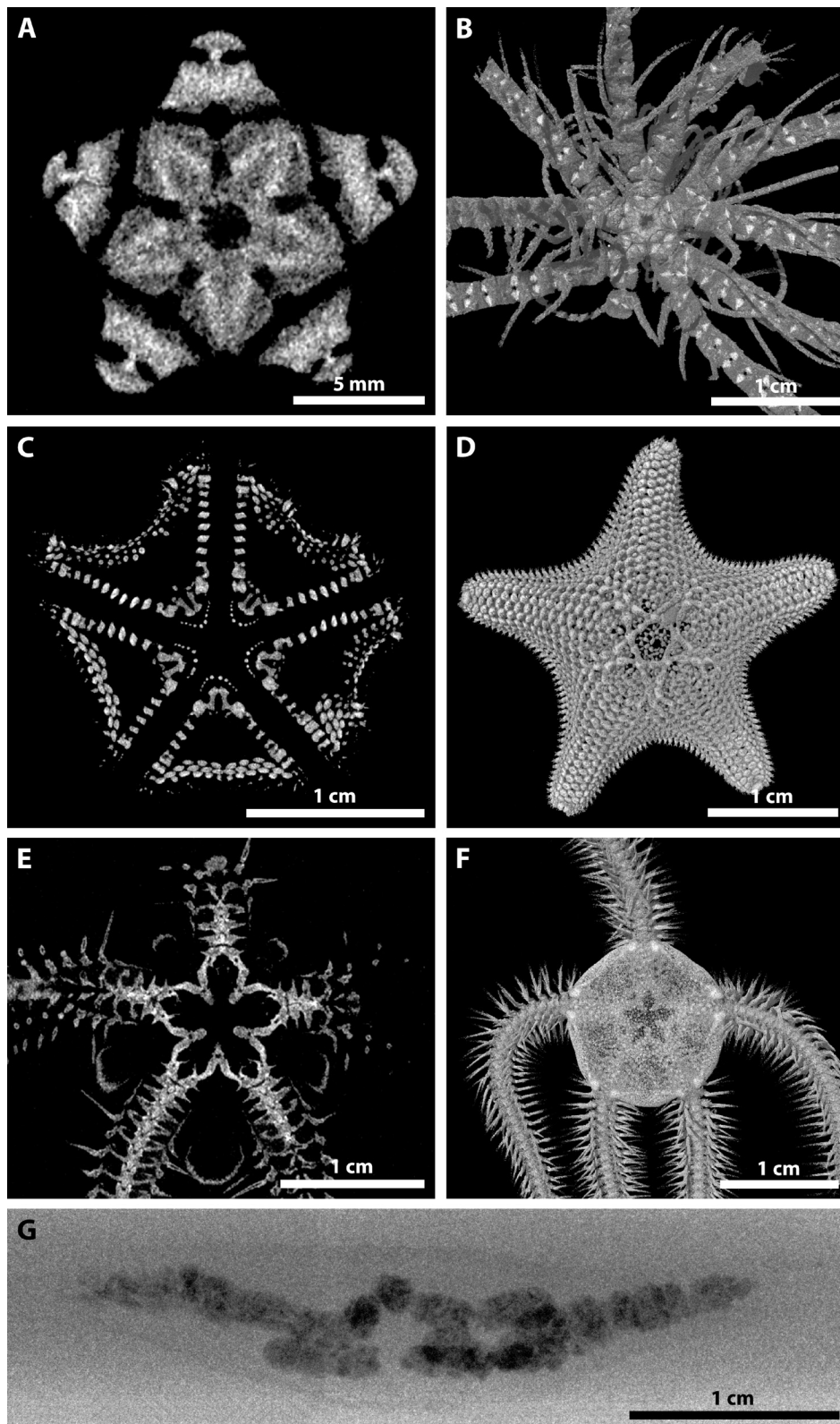
taxon. Given the limited funding in taxonomy and systematics, it does not appear unreasonable to predict that the study of many metazoan taxa will be carried out in this way already within the near future (MacLeod *et al.* 2010). Although this study focused on the analysis of extant echinoid taxa, non-invasive imaging techniques, in particular  $\mu$ CT, can be applied to the study of fossil echinoderms as well (Dominguez *et al.* 2002; Rahman & Clausen 2009; Rahman & Zamora 2009; Zamora *et al.* 2012). Despite tremendous technological advances in non-invasive imaging techniques, which are primarily fueled by the application of these techniques in human diagnostics and industrial quality control, a number of aspects remain to be discussed that are of importance for studies of echinoids and other echinoderm taxa.

Although desirable, presumably not all described sea urchin species can be analyzed using the two complementary imaging modalities employed here. This might be due to limitations in specimen availability (some samples may have been lost), specimen size (some samples may be too small or too large for the scanner), specimen properties (some samples may be too fragile to handle), and the occurrence of pronounced artifacts in particular when using MRI (Ziegler & Mueller 2011; Ziegler *et al.* 2011b). In fact, 10 of the currently recognized 60 sea urchin families are not represented in this study for some of the above-mentioned reasons (Appendix). Furthermore, it may become necessary to scan numerous individuals or several ontogenetic stages of a given species in order to fully understand an initial morphological observation, but the required scanning time may not be available or affordable for such projects.

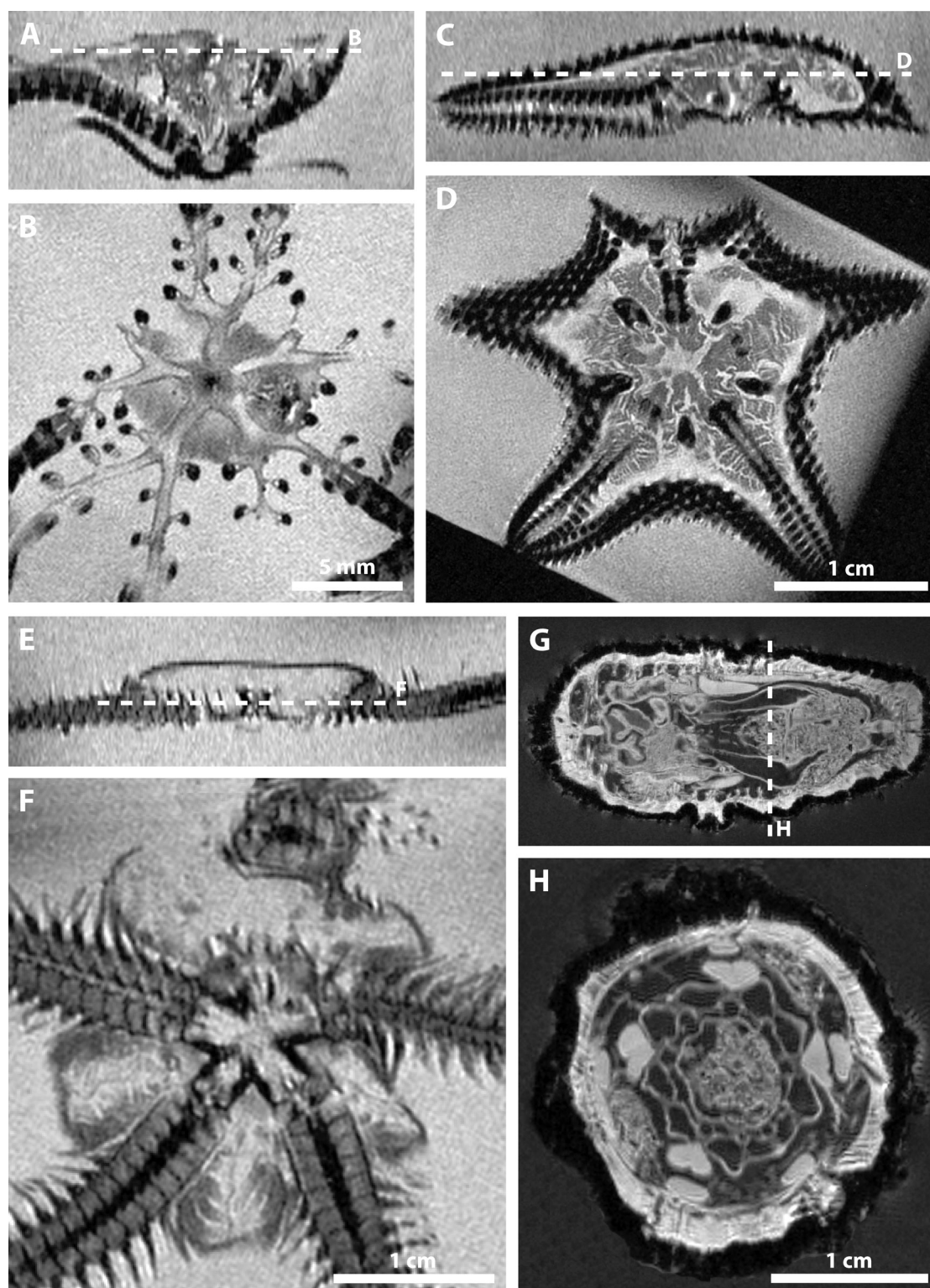
Although MRI and  $\mu$ CT can in principle be considered non-invasive imaging techniques, contrast agents may have to be applied in order to increase signal intensity or to stain soft tissues. For example, in this study Magnevist (BayerSchering, Berlin, Germany) was continuously used during MRI scanning as it improves the signal-to-noise ratio significantly, in turn permitting to achieve higher voxel resolutions (Ziegler *et al.* 2008a; Ziegler *et al.* 2011b). This circumstance, and the fact that about 10% of the specimens on loan suffered mechanical damage during transport and specimen handling, somewhat qualifies the applicability of the term 'non-invasive'. In addition, the approach advocated here necessitates the comprehensive management of large amounts of digital data (tera- or even petabytes) as well as the availability of sophisticated computer infrastructure.

Nonetheless, MRI and  $\mu$ CT have shown to be valuable tools for studies on sea urchin morphology and the first scans of selected species belonging to the other echinoderm groups reveal that both techniques can be successfully applied to these organisms as well (Figs. 5–6).  $\mu$ CT is particularly well suited for studies on crinoids (Fig. 5A–B, see also Aschauer *et al.* 2010), asteroids (Fig. 5C–D, see also Laforsch *et al.* 2012), and ophiuroids (Fig. 5E–F). In contrast, most holothuroids (Fig. 5G) lack the dense, X-ray-absorbing endoskeleton present in most other echinoderm taxa, making whole specimen scanning using  $\mu$ CT in this group particularly difficult. However, the calcareous ring, for example, constitutes a calcified structure in sea cucumbers that is likely to absorb sufficient X-rays for visualization, while some sea cucumbers (*e.g.*, Psolidae) possess calcareous plates that cover the trunk and that should be well visible in  $\mu$ CT scans. In addition, the application of soft tissue staining techniques (Degenhardt *et al.* 2010; Faraj *et al.* 2009; Jeffery *et al.* 2011; Metscher 2009a, 2009b) could be successfully applied to visualize sea cucumber anatomy, although at current there is no data available regarding potentially detrimental long-term effects of these staining agents on museum material. However, because alpha taxonomy and systematics for most echinoderms are primarily based on hard part morphology, in particular  $\mu$ CT has the potential to become a standard diagnostic tool in echinoderm research. This is especially so in cases where diagnostic characters are accessible





**FIGURE 5.** Suitability of  $\mu$ CT for its application to further echinoderm taxa. All specimens were scanned in ethanol. (A–B) *Antedon mediterranea* (Antedonidae, ZMH E6859), a feather star (Crinoidea). (C–D) *Asterina gibbosa* (Asterinidae, ZMH E1195), a sea star (Asteroidea). (E–F) *Ophiocoma nigra* (Ophiocomidae, ZMH E2025), a brittle star (Ophiuroidea). (G) *Holothuria pardalis* (Holothuriidae, ZMH E5131), a sea cucumber (Holothuroidea). Location of virtual transverse sections: upper body (A), near mouth (C), at level of bursae (E). In contrast to feather stars, sea stars, and brittle stars, sea cucumbers are only partly suitable for whole specimen scanning using  $\mu$ CT, because of the absence of large amounts of calcified structures. The long dark structure at the center of the 2D X-ray projection shown here (G) is sediment incorporated within the digestive tract. The only slightly X-ray-absorbing integument of this holothuroid species can be seen as a faint outline.



**FIGURE 6.** Suitability of MRI for its application to further echinoderm taxa. All specimens were scanned in distilled water. The first three specimens (A–F) were scanned with a contrast agent added and using a 2D protocol with  $50 \times 50 \times 200 \mu\text{m}$  voxel resolution. The fourth specimen (G–H) was scanned without a contrast agent using a 3D protocol with an isotropic voxel resolution of  $81 \mu\text{m}$ . (A–B) *Antedon mediterranea*, a feather star (Crinoidea). (C–D) *Asterina gibbosa*, a sea star (Asteroidea). (E–F) *Ophiocoma nigra*, a brittle star (Ophiuroidea). This specimen had suffered mechanical damage to one of its bursae. (G–H) *Aslia lefevrei* (Cucumariidae), a sea cucumber (Holothuroidea). In principle, all echinoderm taxa can be successfully analyzed using MRI. The achievable voxel resolution depends on the size of the specimen under study and the properties of the MRI scanner. However, pronounced artifacts must be expected in species that ingest para- or ferromagnetic sediment.



only through destructive analysis (*e.g.*, the morphology of Aristotle's lantern in sea urchins).

Equivalent to the successful studies on hard parts using  $\mu$ CT, MRI can be employed for the analysis of soft tissue anatomy in echinoderms. This applies to crinoids (Fig. 6A–B), asteroids (Fig. 6C–D, see also Laforsch *et al.* 2012), ophiuroids (Fig. 6E–F), as well as holothuroids (Fig. 6G–H). Large-scale scanning of sea cucumbers using MRI could be of particular interest, because  $\mu$ CT does not reveal many structural features in most holothuroids if applied to unstained whole specimens (Fig. 5G). However, the applicability of MRI might be limited by the currently achievable resolution and potentially pronounced artifacts caused by para- or ferromagnetic sediment located inside the specimen (Ziegler *et al.* 2011b).

The last point that I would like to stress is that due to the digital nature of the morphological data obtained using  $\mu$ CT and MRI, data deposition and data sharing are poised to lead to an improved transparency of anatomical findings in general. However, a prerequisite for this would be the availability of adequate voxel data repositories that permit long-term data storage and curation analogous to conventional museum specimens. These aspects are currently under debate and will hopefully be resolved in the coming years (Berquist *et al.* 2012; Rowe & Frank 2011; Ziegler *et al.* 2010a).

## Conclusions

The two non-invasive tomographic imaging techniques  $\mu$ CT and MRI constitute powerful tools for zoomorphologists that are interested in gathering 3D datasets of whole specimens. Because of the wide-spread presence of calcified structures in echinoderms (except for most sea cucumbers), these organisms are well suited for systematic whole specimen scanning using  $\mu$ CT. Although exceptions do exist, for example because of artifacts related to para- or ferromagnetic inclusions, the visualization of soft part anatomy can be successfully performed in most echinoderm taxa using MRI. The broad application of non-invasive imaging techniques to echinoids has resulted in novel insight into the evolution of important organ systems such as axial complex, gastric caecum, lantern protractor muscles, and teeth—these studies would not have been undertaken using conventional destructive modalities.

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**APPENDIX.** List of sea urchin species analyzed in the course of this study. Families have been grouped according to Kroh & Smith (2010), while species names have been adapted using Kroh & Mooi (2011). Please refer to these two references for taxon authorship. Numbers in the columns ‘MRI’ and ‘ $\mu$ CT’ indicate the voxel resolution (in  $\mu\text{m}$ ) of the isotropic, uncompressed dataset. ‘2D’ refers to non-isotropic datasets with 50 x 50 x 200  $\mu\text{m}$  voxel resolution. BMNH = British Museum of Natural History, London, UK; CASIZ = California Academy of Sciences Invertebrate Zoology, San Francisco, CA, USA; MCZ = Museum of Comparative Zoology, Cambridge, MA, USA; MNHN = Muséum national d’Histoire naturelle, Paris, France; NHMW = Naturhistorisches Museum Wien, Vienna, Austria; NIWA = National Institute of Water & Atmospheric Research, Wellington, New Zealand; USNM = National Museum of Natural History, Washington, DC, USA; ZMB = Systematische Zoologie am Museum für Naturkunde, Berlin, Germany; ZMH = Zoologisches Institut und Museum Hamburg, Germany; ZMK = Zoologisk Museum København, Copenhagen, Denmark; ZSM = Zoologische Staatssammlung München, Munich, Germany.

Family	Species	MRI	Specimen No.	$\mu$ CT	Specimen No.
Histocidaridae	<i>Histocidaris elegans</i>	81	ZMH E307	16	ZMH E307
	<i>Histocidaris purpurata</i>	-	-	16.07	ZMH E309
Ctenocidaridae	<i>Aporocidaris incerta</i>	-	-	13.91	ZMH E8038
	<i>Aporocidaris milleri</i>	-	-	13.91	ZMB Ech 5412
	<i>Ctenocidaris nutrix</i>	79	BMNH 1956.10.5.1	14	BMNH 1956.10.5.1
	<i>Ctenocidaris perrieri</i>	-	-	12.61	MCZ 8379
	<i>Notocidaris gaussensis</i>	79	ZMB Ech 5456	14	ZMB Ech 5456
Cidaridae	<i>Rhynchocidaris triplopورا</i>	-	-	13.91	ZMB Ech 5460
	<i>Acanthocidaris hastingeria</i>	-	-	13.91	ZMB Ech 5874
	<i>Austrocidaris canaliculata</i>	79	ZMB Ech 2244	13.39	ZMB Ech 2244
	<i>Calocidaris micans</i>	-	-	35.01	MCZ 283
	<i>Centrocidaris doederleini</i>	-	-	9.78	MCZ187
	<i>Cidaris cidaris</i>	81	BMNH 1925.10.30.103-113	18.87	BMNH 1925.10.30.103-113

Family	Species	MRI	Specimen No.	μCT	Specimen No.
	<i>Cidaris nuda</i>	-	-	20	ZMB Ech 2167
	<i>Compsocidaris pyrsacantha</i>	-	-	29.64	MCZ 7861
	<i>Eucidaris metularia</i>	44	BMNH 1969.5.1.15-40	13.91	BMNH 1969.5.1.15-40
	<i>Eucidaris thouarsii</i>	2D	ZMB Ech 1369	13.91	ZMB Ech 1369
	<i>Eucidaris tribuloides</i>	2D	ZMB Ech 5474	13.91	ZMB Ech 5474
	<i>Goniocidaris biserialis</i>	-	-	13.91	ZMB Ech 6764
	<i>Goniocidaris tubaria</i>	-	-	9.82	ZMH E288
	<i>Hesperocidaris panamensis</i>	2D	ZMB Ech 5407	13.91	ZMB Ech 5407
	<i>Ogmocidaris benhami</i>	-	-	12.78	MCZ 984
	<i>Phyllacanthus imperialis</i>	-	-	13.39	ZMB Ech 6513
	<i>Plococidaris verticillata</i>	-	-	15	ZMH E305
	<i>Prionocidaris bispinosa</i>	-	-	18.57	ZMH E267
	<i>Rhopalocidaris gracilis</i>	-	-	12.08	MCZ 4860
	<i>Stereocidaris indica</i>	79	ZMB Ech 7364	16.07	ZMB Ech 7364
	<i>Stylocidaris affinis</i>	-	-	14.62	MCZ 234
	<i>Tretocidaris bartletti</i>	-	-	11.3	MCZ 4561
Psychocidaridae	<i>Psychocidaris ohshimai</i>	79	NHMW 2010/0240/0001	15	NHMW 2010/0240/0001
Kamptosomatidae	<i>Kamptosoma asterias</i>	-	-	7	CASIZ 182429
Phormosomatidae	<i>Phormosoma bursarium</i>	-	-	15.7	MCZ 911
	<i>Phormosoma placenta</i>	-	-	13.91	USNM E17633
Echinothuriidae	<i>Araeosoma belli</i>	-	-	15.15	MCZ 7765
	<i>Asthenosoma varium</i>	-	-	19.64	ZMH E3
	<i>Calveriosoma gracile</i>	-	-	15	BMNH 1881.11.22.21
	<i>Hapalosoma pellucidum</i>	-	-	22.42	MCZ 6094
	<i>Hygrosoma petersii</i>	-	-	25.61	MCZ 2970
	<i>Sperosoma obscurum</i>	-	-	20	MCZ 903
	<i>Tromikosoma uranus</i>	-	-	23.57	BMNH 1976.7.30.74
Micropygidae	<i>Micropyga tuberculata</i>	81	BMNH 98.8.8.45/6	13.91	BMNH 98.8.8.45/6
Diadematidae	<i>Astropyga radiata</i>	-	-	8.21	ZMB Ech 3877
	<i>Centrostephanus coronatus</i>	-	-	9.82	CASIZ 100820
	<i>Centrostephanus longispinus</i>	66	BMNH 1952.3.26.64-8	13.91	BMNH 1952.3.26.64-8
	<i>Chaetodiadema granulatum</i>	-	-	20.53	NHMW 10745
	<i>Chaetodiadema pallidum</i>	-	-	20	CASIZ 98074
	<i>Diadema antillarum</i>	2D	ZMB Ech 4374	13.91	CASIZ 98084
	<i>Diadema ascensionis</i>	-	-	13.39	BMNH 1972.8.22.50-52
	<i>Diadema savignyi</i>	40	ZMB Ech 7411	13.91	ZMB Ech 7411
	<i>Diadema setosum</i>	2D	ZMB Ech 4814	13.91	NHMW 10755
	<i>Echinothrix diadema</i>	2D	ZMB Ech 2346	13.39	ZMB Ech 2346
	<i>Eremopyga denudata</i>	-	-	43.56	MCZ 685



Family	Species	MRI	Specimen No.	μCT	Specimen No.
	<i>Lissodiadema lorioli</i>	-	-	8.2	CASIZ 103520
Aspidodiadematidae	<i>Aspidodiadema arcitum</i>	-	-	9.82	USNM 27568
	<i>Aspidodiadema hawaiiense</i>	81	USNM 27590	13.91	USNM 27588
	<i>Aspidodiadema tonsum</i>	-	-	9.82	BMNH 81.11.22.24
	<i>Plesiodiadema horridum</i>	-	-	8	MCZ 607
	<i>Plesiodiadema indicum</i>	81	ZMB Ech 7232	13.91	ZMB Ech 7232
Pedinidae	<i>Caenopedina mirabilis</i>	81	USNM 31182	13.91	USNM 31182
	<i>Caenopedina otagoensis</i>	-	-	8.2	ZMB Ech 7403
	<i>Caenopedina porphyrogigas</i>	-	-	20.53	ZMB Ech 7404
Saleniidae	<i>Salenia goesiana</i>	81	USNM 10649	8.87	USNM 14581
	<i>Salenocidaris hastigera</i>	81	ZMB Ech 5816	13.91	ZMB Ech 5816
	<i>Salenocidaris varispina</i>	-	-	7.4	MCZ 4883
Stomopneustidae	<i>Stomopneustes variolaris</i>	81	USNM E45930	13.91	USNM E45930
Glyptocidaridae	<i>Glyptocidaris crenularis</i>	90	ZSM 20011444	23.38	ZSM 20011444
Arbaciidae	<i>Arbacia dufresnii</i>	2D	ZMB Ech 2222	13.91	ZMB Ech 2222
	<i>Arbacia lixula</i>	44	BMNH 1952.3.26.31-36	13.91	BMNH 1966.5.6.57-65
	<i>Arbaciella elegans</i>	-	-	6.11	ZMH E185
	<i>Coelopleurus sp.</i>	-	-	13.91	ZMB Ech 7412
	<i>Dialithocidaris gemmifera</i>	-	-	10.92	MCZ 8317
	<i>Habrocidaris scuttata</i>	-	-	6.3	MCZ 7787
	<i>Podocidaris sp.</i>	-	-	9.82	ZMB Ech 7409
	<i>Pygmaeocidaris prionigera</i>	-	-	6.05	MCZ 8741
	<i>Tetrapygyus niger</i>	2D	ZMB Ech 1346	19.27	ZMH E198
Parasaleniidae	<i>Parasalenia gratiosa</i>	79	BMNH 1983.2.15.7	14	BMNH 1983.2.15.7
Temnopleuridae	<i>Amblypneustes pallidus</i>	2D	ZMB Ech 6334	13.91	ZMB Ech 6334
	<i>Erbechinus spectabilis</i>	-	-	18.56	MCZ 4955
	<i>Holopneustes inflatus</i>	2D	ZMB Ech 2639	13.91	ZMB Ech 2639
	<i>Mespilia globulus</i>	44	ZMB Ech 5620	13.91	ZMB Ech 5620
	<i>Microcyphus rousseaui</i>	-	-	19.64	ZMH E4143
	<i>Opechinus variabilis</i>	-	-	6.69	MCZ 3944
	<i>Pseudechinus magellanicus</i>	2D	ZMB Ech 2188	13.91	BMNH 1967.4.3.24-25
	<i>Salmaciella oligopora</i>	-	-	35.82	MCZ 4283
	<i>Salmacis sphaeroides</i>	2D	ZMB Ech 4337	16.43	NHMW 10786
	<i>Temnopleurus hardwickii</i>	-	-	20	NHMW 10772
	<i>Temnopleurus michaelseni</i>	2D	ZMB Ech 6331	-	-
	<i>Temnopleurus reevesii</i>	2D	ZMB Ech 3588	13.91	BMNH 1981.2.6.55-56
	<i>Temnopleurus toreumaticus</i>	2D	ZMB Ech 2802	13.91	ZMB Ech 2802
	<i>Temnotrema elegans</i>	-	-	8.2	ZMB Ech 6332
Trigonocidaridae	<i>Desmechinus rufus</i>	-	-	12.25	MCZ 4735
	<i>Genocidaris maculata</i>	36	ZMB Ech 5827	9.82	ZSM 20011685
	<i>Hypsiechinus coronatus</i>	-	-	3.86	MCZ 1400

Family	Species	MRI	Specimen No.	μCT	Specimen No.	
Echinidae	<i>Prionechinus sagittiger</i>	-	-	5.5	ZMB Ech 6498	
	<i>Trigonocidaris albida</i>	32	ZSM 20012468	10	ZSM 20012468	
	<i>Dermechinus horridus</i>	-	-	24.37	MCZ 4252	
	<i>Echinus esculentus</i>	81	ZMB Ech 3826	13.91	ZMB Ech 3826	
	<i>Gracilechinus acutus</i>	2D	ZMB Ech 3714	13.91	NHMW 10833	
	<i>Gracilechinus affinis</i>	-	-	15.71	ZMH E7707	
	<i>Gracilechinus alexandri</i>	2D	ZMB Ech 4340	13.91	ZMB Ech 4340	
	<i>Polyechinus agulhensis</i>	2D	ZMB Ech 7219	13.91	ZMB Ech 7219	
	<i>Sterechinus agassizii</i>	79	BMNH 1914.8.12.126-127	13.91	BMNH 1914.8.12.126-7	
Parechinidae	<i>Sterechinus antarcticus</i>	2D	ZMB Ech 5439	-	-	
	<i>Sterechinus neumayeri</i>	2D	ZMB Ech 5442	13.91	ZMB Ech 5442	
	<i>Loxechinus albus</i>	2D	BMNH 1966.5.1.61-75	16	BMNH 1966.9.27.35	
	<i>Paracentrotus lividus</i>	81	ZMB Ech 7406	13.39	ZMB Ech 7406	
	<i>Parechinus angulosus</i>	2D	ZMB Ech 5644	13.91	NHMW 10869	
	<i>Psammechinus microtuberculatus</i>	2D	ZMB Ech 4770	13.91	ZMB Ech 4770	
	<i>Psammechinus miliaris</i>	44	Author's collection	13.91	ZMB Ech 2011	
	<i>Gymnechinus robillardii</i>	79	BMNH 1890.6.27.5-8	13.91	BMNH 1890.6.27.5-8	
	Toxopneustidae	<i>Lytechinus variegatus</i>	81	ZMB Ech 5517	13.91	ZMB Ech 7408
<i>Nudechinus scotiopremnus</i>		2D	ZMB Ech 6130	13.91	ZMB Ech 6130	
<i>Nudechinus verruculatus</i>		-	-	9.82	ZMH E506	
<i>Pseudoboletia indiana</i>		-	-	21.43	NHMW 10830	
<i>Sphaerechinus granularis</i>		81	ZMB Ech 2366	13.91	ZMB Ech 2366	
<i>Toxopneustes pileolus</i>		2D	ZMB Ech 3871	9.82	ZMB Ech 3871	
<i>Tripneustes gratilla</i>		-	-	19.64	ZMB Ech 1527	
<i>Tripneustes ventricosus</i>		2D	ZMB Ech 5498	13.91	ZMB Ech 5498	
Strongylocentrotidae		<i>Hemicentrotus pulcherrimus</i>	2D	ZMB Ech 6425	13.91	NHMW 10893
		<i>Mesocentrotus franciscanus</i>	-	-	22	MCZ 7313
	<i>Pseudocentrotus depressus</i>	2D	ZMB Ech 6426	13.91	ZMB Ech 6426	
	<i>Strongylocentrotus droebachiensis</i>	2D	ZMB Ech 4422	12.5	BMNH 1969.6.12.512-522	
	<i>Strongylocentrotus fragilis</i>	-	-	30.39	MCZ 4086	
	<i>Strongylocentrotus purpuratus</i>	42	CASIZ 5724	13.91	CASIZ 5724	
Echinometridae	<i>Caenocentrotus gibbosus</i>	2D	ZMB Ech 5405	13.91	ZMB Ech 5405	
	<i>Colobocentrotus atratus</i>	2D	ZMB Ech 4985	25	NHMW 10960	
	<i>Colobocentrotus mertensii</i>	-	-	35.89	MCZ 2136	
	<i>Echinometra lucunter</i>	-	-	19.27	NHMW 10928	
	<i>Echinometra mathaei</i>	81	BMNH 1969.5.1.61-75	13.91	BMNH 1969.5.1.61-75	
	<i>Echinometra mathaei oblonga</i>	2D	ZMB Ech 3862	13.91	ZMB Ech 3862	
	<i>Echinometra viridis</i>	2D	ZMB Ech 5503	-	-	
	<i>Echinostrephus molaris</i>	2D	ZMB Ech 4000	13.91	ZMB Ech 4000	
	<i>Evechinus chloroticus</i>	-	-	30	NHMW 10898	

Family	Species	MRI	Specimen No.	μCT	Specimen No.
	<i>Heliocidaris australiae</i>	-	-	13.91	ZMH E7966
	<i>Heliocidaris crassispina</i>	2D	ZMB Ech 6424	13.91	ZMB Ech 6424
	<i>Heliocidaris erythrogramma</i>	2D	ZMB Ech 5745	13.91	ZMB Ech 5745
	<i>Heterocentrotus mammillatus</i>	2D	ZMB Ech 1567	13.91	ZMB Ech 1567
	<i>Zenocentrotus paradoxus</i>	-	-	20.34	MCZ 6004
Echinoneidae	<i>Echinoneus cyclostomus</i>	66	BMNH 1969.5.1.105	13.91	BMNH 1969.5.1.105
Apatopygidae	<i>Apatopygus recens</i>	-	-	8.62	ZMK Mortensen coll'n
Cassidulidae	<i>Cassidulus caribaeorum</i>	81	CASIZ 112632	8.87	ZMK Mortensen coll'n
	<i>Rhyncholampas pacificus</i>	-	-	22	ZMH E755
Neolampadidae	<i>Neolampas rostellata</i>	-	-	9	MNH EcEh330
Echinolampadidae	<i>Echinolampas depressa</i>	81	USNM E32955	13.91	USNM E32955
Clypeasteridae	<i>Ammotrophus cyclius</i>	-	-	20.61	MCZ 7005
	<i>Arachnoides placenta</i>	81	ZMB Ech 1439	13.91	ZMB Ech 1439
	<i>Clypeaster fervens</i>	-	-	18.57	BMNH 1948.12.9.15-16
	<i>Clypeaster reticulatus</i>	81	USNM 34282	13.91	USNM 34282
	<i>Clypeaster rosaceus</i>	96	ZMB Ech 2520	17	ZMB Ech 2520
	<i>Fellaster zelandiae</i>	-	-	23.57	ZMB Ech 7402
Echinocyamidae	<i>Echinocyamus pusillus</i>	20	ZMB Ech 7410	9	ZMB Ech 7410
	<i>Mortonia australis</i>	-	-	8	CASIZ 108132
Fibulariidae	<i>Fibularia ovulum</i>	36	USNM E35308	6.82	USNM E35308
	<i>Fibulariella acuta</i>	-	-	3.8	CASIZ 188798
Laganidae	<i>Jacksonaster depressum</i>	86	BMNH 1932.4.28.227-34	13.91	BMNH 1932.4.28.227-34
	<i>Laganum decagonale</i>	-	-	19.28	BMNH 79.1.2.3
	<i>Laganum joubini</i>	44	BMNH 1979.1.25.52-60	13.91	BMNH 1979.1.25.52-60
	<i>Laganum laganum</i>	81	USNM E09175	13.91	USNM E09175
	<i>Peronella japonica</i>	-	-	25.71	CASIZ 94528
	<i>Peronella lesueuri</i>	81	MNH EcEh79	13.91	MNH EcEh79
	<i>Peronella orbicularis</i>	81	MNH EcEh77	13.91	MNH EcEh77
Rotulidae	<i>Heliophora orbicularis</i>	-	-	25	ZMH E6864
	<i>Rotula deciesdigitatus</i>	81	ZMB Ech 2169	27.03	ZMH E742
Taiwanasteridae	<i>Marginoproctus sp.</i>	-	-	4.12	USNM Acc. 357890
Echinarachniidae	<i>Echinarachnius parma</i>	44	BMNH 55.10.3.125	13.91	ZSM 20011676
	<i>Sinaechinocyamus mai</i>	-	-	4.6	CASIZ 188797
Dendrasteridae	<i>Dendraster excentricus</i>	-	-	22.86	ZMB Ech 7400
Scutellidae	<i>Scaphechinus mirabilis</i>	-	-	13.91	ZMB Ech 7405
Astriclypeidae	<i>Astriclypeus manni</i>	-	-	36.48	MCZ 7300
	<i>Echinodiscus auritus</i>	-	-	22.86	ZMB Ech 2647
	<i>Echinodiscus bisperforatus</i>	-	-	19.44	BMNH 1964.10.13.20-23
Mellitidae	<i>Encope micropora</i>	-	-	20.38	MCZ 2625
	<i>Leodia sexiesperforata</i>	-	-	18.78	MCZ 4460



Family	Species	MRI	Specimen No.	μCT	Specimen No.
	<i>Mellita isometra</i>	-	-	29.37	ZMH E737
	<i>Mellita quinquiesperforata</i>	-	-	25.71	ZMB Ech 7401
	<i>Mellitella stokesii</i>	-	-	13.91	USNM E40733
Calymnidae	-	-	-	-	-
Corystusidae	-	-	-	-	-
Urechinidae	<i>Antrechinus mortenseni</i>	81	ZMH E7381	13.91	ZMH E7381
	<i>Urechinus naresianus</i>	81	ZSM 20012380	13.91	ZMK Mortensen coll'n
Plexechinidae	<i>Plexechinus planus</i>	-	-	13.91	ZMH E7345
Pourtalesiidae	<i>Pourtalesia jeffreysi</i>	81	ZSM 20011456	13.91	ZSM 20011456
	<i>Pourtalesia wandeli</i>	86	BMNH 1976.7.30.76-95	16.6	BMNH 1976.7.30.76-95
Palaeostomatidae	-	-	-	-	-
Hemiasteridae	-	-	-	-	-
Micrasteridae	-	-	-	-	-
Aeropsidae	<i>Aeropsis rostrata</i>	-	-	9.3	ZMK Mortensen coll'n
Schizasteridae	<i>Abatus cavernosus</i>	81	ZMB Ech 5854	-	-
	<i>Abatus cordatus</i>	-	-	13.91	ZSM 20011462
	<i>Brisaster fragilis</i>	-	-	13.91	ZMK Mortensen coll'n
	<i>Moira atropos</i>	-	-	17.39	ZMB Ech 5491
	<i>Schizaster lacunosus</i>	-	-	16.67	ZMB Ech 3551
Prenasteridae	-	-	-	-	-
Pericosmidae	-	-	-	-	-
Paleopneustidae	<i>Plesiozonus hirsutus</i>	-	-	64.45	CASIZ 186314
Palaeotropidae	<i>Palaeobrissus hilgardi</i>	-	-	23.38	CASIZ 112853
Brissidae	<i>Brissopsis luzonica</i>	-	-	15	ZSM 20011858
	<i>Brissopsis lyrifera</i>	-	-	20	ZMB Ech 4841
	<i>Brissus unicolor</i>	-	-	23.57	ZMB Ech 1371
	<i>Metalia sp.</i>	-	-	19.28	ZMB Ech 5019
Spatangidae	<i>Spatangus purpureus</i>	81	ZMB Ech 3236	13.91	ZMB Ech 3236
Eupatagidae	-	-	-	-	-
Eurypatagidae	-	-	-	-	-
Maretiidae	<i>Maretia planulata</i>	-	-	13.91	ZMB Ech 2127
	<i>Nacospatangus alta</i>	81	ZSM 20011608	13.91	ZSM 20011608
Macropneustidae	-	-	-	-	-
Loveniidae	<i>Echinocardium cordatum</i>	81	ZMB Ech 7407	13.91	ZMB Ech 7407
	<i>Echinocardium flavescens</i>	-	-	13.91	ZSM 20011403/1
	<i>Echinocardium pennatifidum</i>	-	-	13.91	ZSM 20011401
	<i>Lovenia subcarinata</i>	-	-	15	ZSM 20011447
<i>Incerta sedis</i>	<i>Amphipneustes lorioli</i>	-	-	24	ZMH E7354
	<i>Brachysternaster chesheri</i>	-	-	22	ZMH E7356
	<i>Parapneustes cordatus</i>	-	-	13.91	ZMH E7358