A new tool for 3D segmentation of computed tomography data： *Drishti Paint* and its applications

Yuzhi Hu[1,2], Ajay Limaye[3], Jing Lu[4]*

[1]Department of Applied Mathematics, Research School of Physics, Australian National University, Canberra, ACT, Australia 2601

[2]Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia 2601

[3]National Computational Infrastructure, Building 143, Corner of Ward Road and Garran Road, Ward Rd, Canberra, ACT, Australia 2601

[4]Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China 100044

*Corresponding author: lujing@ivpp.ac.cn

Abstract

Computational tomography is more and more widely used in many fields for its non-destructive and high-resolution in detecting internal structures of the samples. 3D segmentation of computed tomography data, which sheds light into internal features of target objects, is increasingly gaining in importance. However, how to efficiently and precisely reconstruct computed tomography data and better represent the data remains a hassle. Here, using a set of scan data of a fossil fish as a case study, we present a new release of open-source volume exploration, rendering, and 3D segmentation software, *Drishti* v2.6.6, and its protocol for performing 3D segmentation and other advanced applications. We provide new toolsets and workflow to segment computed tomography data thus benefit the scientific community with more accurate and precise digital reconstruction, 3D modelling and 3D printing results. Our procedure is widely applicable not only in palaeontology, but also in biological, medical, and industrial researches, and can be used as a framework to segment computed tomography and other forms of volumetric data from any research field.

Keywords 3D Segmentation, *Drishti Paint*, computed tomography data, volumetric data

1 Introduction

Nowadays, computed tomography (CT) is widely used in many fields, such as medicine, science, industry and education [1-5]. To have a better understanding of the data generated from CT, 3D scientific visualization becomes more and more important for researchers to obtain better insights [6-9]. For the last four decades, 3D scientific visualization field have been developed with new ways to visualize and analyse data more accurately [10-19]. Two techniques have emerged to provide different visualizations: surface rendering, the method of interpreting data-sets by generating a set of polygons that represent the wanted feature; and volume rendering [10], a more direct way for the reconstruction of 3D structures, which represents 3D objects as a collection of cube-like building blocks called voxels, or volume elements. However, the importance of scientific visualization software along with their functionality was underestimated by the community due to lack of public exposure and communications between multidiscipline.

3D segmentation, segmenting the internal structures in sequences of images, is a key tool for investigating and understanding the internal structures of target objects [6, 20-22]. The 3D segmenting methods rely on thresholding, edge detection, clustering, or region growing to group pixels based on brightness, colour, or texture [21]. Compared with researches carried out in the image processing field, more requirements have to be met towards building and developing applications which require the use of more efficient and effective techniques to save time and resources.

Drishti, as an open-source volume exploration, rendering and 3D segmentation software [23], is well-known for its superb visualization outcomes [6, 24-26]. Here we present the latest released *Drishti* v2.6.6, and the last developed module *Drishti Paint* v2.6.6, as a new toolset for 3D segmentation (2D and 3D painters) of volumetric data (i.e. a 3D volume produced by a group of 2D images of a slice or section of the scanned object acquired by X-ray imaging and Magnetic resonance imaging, etc.) by using the CT scan data of a fossil fish as case study. We also suggest protocols for how to perform 3D segmentation using *Drishti Paint* v2.6.6 efficiently and precisely. New features in *Drishti*, such as mesh generation and simplification, allow 3D printing, model simulation, etc.) are also covered in this study.

2 Materials and Methods

2.1 Materials

The material used in this study, a Devonian unnamed placoderm fish (ANU V244) from Burrinjuck, near Canberra, south-eastern Australia, is held at Australian National University [3], Canberra, Australia. The whole specimen and the separated right anterior upper toothplate were scanned in 2015 [27, 28] at CT Lab, ANU [7] using a HeliScan MicroCT system with 1.2mm aluminium/ 0.35mm stainless steel for the whole specimen and 2mm aluminium filters for the upper toothplate to yield sharp images [18, 29] at a resolution of 21µm and 2µm respectively. CT data was reconstructed using an in-house software called *Mango* (https://physics.anu.edu.au/appmaths/capabilities/mango.php).

2.2 Methods

The CT datasets were explored and rendered using *Drishti* v2.6.6. The individual data sets were read at low resolution, and contrast was incremented with the help of histograms and slides were filtered. The information thus generated is written as *.pvl.nc for saved files (i.e. processed volume format) or *. xml (i.e. Extensible Markup Language format) for saved projects. The scan data was demonstrated by a protocol for segmenting the 3D volumetric data using *Drishti Paint* v2.6.6. The right check complex was segmented out of the whole dataset. The internal structure under the region-of-interest of its right anterior upper toothplate has been segmented as another case study.

3 Results and discussions

3D segmentation is often hampered by the time-intensive nature of extracting information from samples, the complexity of preparing fossils digitally, and the need for hardware. Here we highlight the workflow and key features of the *Paint* module for *Drishti* and the general applications of *Drishti* using CT data of an Early Devonian placoderm fish [27, 28] as an example. A suggested workflow of segmenting volumetric data in *Drishti* v2.6.6 is presented here (figure 1), which can generate good results in terms of segmentation, rendering and surface mesh generation outputs. Our protocols can be used as a baseline or starting point to practice accordingly in order to obtain an ideal result for a specified dataset. To help with a better understanding into other aspects of *Drishti*, we also provide additional information about *Drishti*, such as installation instructions, a summary of all *Drishti*-supported import formats, additional learning resources and background of the program (see supplemental information).

Three modules, *Drishti import*, *Drishti render* and *Drishti paint*, have their capacities and features, and can be used in combination with each other to ensure an accurate and precise segmentation along with volume rendering to help with visualize a region-of-interest and solve scientific problems. *Drishti Paint* uses a combination of discontinuity detection based and similarity detection-based image segmentation approaches. There are two modes in *Drishti Paint* v2.6.6, Graph Cut and Curve, which are designed specifically to consider 2D slices in volumetric data or 3D volume directly.

Two transformations in mathematical morphology (i.e. erosion and dilation) were implemented in *Drishti Paint* and we used a combination of these two transformations with 3D Freeform Painter to help with a faster segmentation process. The right cheek complex has been segmented from the original CT dataset of the whole specimen (figure 2). The internal canal networks of a selected region-of-interest on the right anterior upper toothplate have been segmented from the original dataset of the toothplate (figure 3). Processed data then exported as separate volumes by extracting the tagged volume after tagging the regions of interests using the tagging function. Both segmentations were carried out in 16-bits full resolution in alignment with their source data and used type 2 gradient thresholding with values thresholding to select the range of the histogram for segmenting.

We suggest that these two transforms are more useful when using clean and high contract dataset as a risk of changing the morphology of the input datasets by doing multiple transformations at once. Multiple-thresholding (i.e. use both values and gradient thresholding) in *Drishti Paint* v2.6.6 is very effective for volume segmentation and usually is the first step towards segmenting a volume (figures 2d and 3b), however, it is also very sensible to noise and intensity in homogeneities. In this case, to segment the internal canal networks of the selected region is tightly related to the selected thresholds, and any small changes in the thresholds values can lead to different segmented results, which is one of the key factors need to set up specifically and choose carefully per dataset (figures 2 and 3, supplementary figures 3 and 4).

The segmented right cheek unit has also been extracted as surface meshes (figure 4). The surface mesh data of the right cheek unit went through different stages of simplification process (figure 4b-d) to produce good quality surface models with relatively small file size allowing quicker physical analysing (e.g. finite element analysis) and 3D printing. Mesh simplification results show that the number of vertices affects the presentation of the information and the detection of details (figure 3). When more triangles have been decimated, fewer details from data are detected (i.e. loss of information) resulting in a reduction in file size which allows easier sharing of the digital 3D model [20] or uploading the model to open data repository for educating the public [21] without giving out details that are still under investigation. By looking at the amount of details lost/preserved pointed by the arrows (figure 4), we recommend a mesh smoothing factor of 2 and 50% decimation based on our segmented cheek 3D model (figure 4d) as it halves the data size but still preserves most of the information. 3D models can then be used to generate 3D printouts [30] or 3D portable documents [31] to test a previous hypothesis or help with functional morphology investigations.

4 Conclusions

Here we provide a new tool and workflow to segment volumetric data thus benefit the scientific community with more accurate and precise digital reconstruction, 3D modelling and 3D printing in *Drishti*. This procedure can be used as a framework to segment computed tomography and other forms of volumetric data and widely applicable in biological, medical and earth science researches. Our work will surely fuel further multiple cross-discipline collaborations between scientific visualization and many other fields.

Data accessibility

3D surface mesh data of the segmented right cheek complex with different levels of simplification, and a movie shows the segmented internal canal networks of the toothplate are available from the fig share repository: https://figshare.com/s/244e5f407d331a39b402.

Drishti v2.6.6 is available from: https://github.com/nci/Drishti

Authors' Contributions

J.L. and Y.H. designed the study. Y.H., J.L., A.L. performed the research and drafted the manuscript. Y.H. and J.L. prepared the figures. A.L. developed *Drishti* v2.6.6. All authors revised the manuscript. Y.H. and A.L. contributed equally.

Competing Interests

The authors declare no competing interests.

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References

1. Kingston AM, Myers GR, Latham SJ, Recur B, Li H, Sheppard AP. 2018 Space-filling X-ray source trajectories for efficient scanning in large-angle cone-beam computed tomography. *IEEE Transactions on Computational Imaging* **4**, 447-458. (doi: 10.1109/TCI.2018.2841202)

2. Zhu M, Ahlberg PE, Pan Z, Zhu Y, Qiao T, Zhao W, et al. 2016 A Silurian maxillate placoderm illuminates jaw evolution. *Science* **354**, 334-336. (doi: 10.1126/science.aah3764)

3. Geier B, Sogin EM, Michellod D, Janda M, Kompauer M, Spengler B, et al. 2020 Spatial metabolomics of in situ host-microbe interactions at the micrometre scale. *Nat. microbiol.* **5**: 498-510. (doi: 10.1038/s41564-019-0664-6)

4. O'Rourke JC, Smyth L, Webb AL, Valter K. 2020 How Can We Show You, If You Can't See It? Trialing the Use of an Interactive Three□Dimensional Micro□CT Model in Medical Education. *Anat. Sci. Educ.***13**: 206-217.(doi: 10.1002/ase.1890)

5. Taylor GJ, Hall SA, Gren JA, Baird E. 2020 Exploring the visual world of fossilized and modern fungus gnat eyes (Diptera: Keroplatidae) with X-ray microtomography. *J. R. Soc. Interface* **17**:20190750. (doi: 10.1098/rsif.2019.0750).

6. Lautenschlager S. 2016 Reconstructing the past: Methods and techniques for the digital restoration of fossils. *R. Soc. open sci.* **3**:160342. (doi: 10.1098/rsos.160342).

7. Davies TG, Rahman IA, Lautenschlager S, Cunningham JA, Asher RJ, Barrett PM, et al. 2017 Open data and digital morphology. Proc. R. Soc. B. 284: 20170194. (doi: 10.1098/rspb.2017.0194).

8. Hoffmann R, Lemanis RE, Falkenberg J, Schneider S, Wesendonk H, Zachow S, et al. 2018 Integrating 2D and 3D shell morphology to disentangle the palaeobiology of ammonoids: a virtual approach. *Palaeontology* **61**:89-104. (doi:10.1111/pala.12328)

9. Semple TL, Peakall R, Tatarnic NJ. 2019 A comprehensive and user□friendly framework for 3D□data visualisation in invertebrates and other organisms. *J. Morphol.* **280**:223-231. (doi: 10.1002/jmor.20938)

10. Drebin RA, Carpenter L, Hanrahan P. 1988 Volume rendering. *ACM Siggraph Computer Graphics* **22**:65-74.

11. Upson C, Faulhaber T, Kamins D, Laidlaw D, Schlegel D, Vroom J, et al. 1989 The application visualization system: A computational environment for scientific visualization. *IEEE Computer Graphics and Applications* **9**:30-42. (doi: 10.1109/38.31462)

12. Westover L. 1990 Footprint evaluation for volume rendering. *Proceedings of the 17th annual conference on Computer graphics and interactive techniques*. Dallas, TX, USA: Association for Computing Machinery; 1990. p.367–376. (doi: 10.1145/97879.97919)

13. Hall PM, Watt AH. 1991 Rapid volume rendering using a boundary-fill guided ray cast algorithm. In: *Patrikalakis N.M. (eds) Scientific Visualization of Physical Phenomena*. Springer, Tokyo. p. 235-249. (doi: 10.1007/978-4-431-68159-5_13)

14. Cabral B, Cam N, Foran J.1994 Accelerated volume rendering and tomographic reconstruction using texture mapping hardware. In: *Proceedings of the 1994 symposium on Volume visualization*. p. 91-98. (doi: 10.1145/197938.197972)

15. Lacroute P, Levoy M. 1994 Fast volume rendering using a shear-warp factorization of the viewing transformation. In: *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*. p.451-458. (doi: 10.1145/192161.192283)

16. Manssour IH, Furuie SS, Olabarriaga SD, Freitas CM. 2002 Visualizing inner structures in multimodal volume data. In: *Proceedings XV Brazilian Symposium on Computer Graphics and Image Processing IEEE*. (doi: 10.1109/SIBGRA.2002.1167123)

17. Johnson C. 2004 Top scientific visualization research problems. *IEEE Computer Graphics and Applications* **24**:13-17. (doi:10.1109/MCG.2004.20)

18. Latham SJ, Varslot T, Sheppard A.2008 Automated registration for augmenting micro-CT 3D images. *Anziam Journal* **50**:534-548.(doi: 10.21914/anziamj.v50i0.1389)

19. Brodlie KW, Carpenter LA, Earnshaw RA, Gallop JR, Hubbold RJ, Mumford AM, et al. 2012 Scientific visualization: techniques and applications. Springer Science & Business Media.

20. Lakare S, Kaufman A. 2000 3D segmentation techniques for medical volumes. Center for Visual Computing, Department of Computer Science, State University of New York. 2000:59-68.

21. Kaur D, Kaur Y. 2014 Various image segmentation techniques: a review. *International Journal of Computer Science and Mobile Computing* **3**:809-814.

22. Carvalho LE, Sobieranski AC, von Wangenheim A. 2018 3D Segmentation Algorithms for Computerized Tomographic Imaging: a Systematic Literature Review. *Journal of digital imaging* **31**:799-850. (doi: 10.1007/s10278-018-0101-z)

23. Limaye A. 2012 Drishti: a volume exploration and presentation tool. In: *Developments in X-ray Tomography* VIII 2012 Oct 17 (Vol. 8506, p. 85060X). International Society for Optics and Photonics. (doi: 10.1117/12.935640.short?SSO=1)

24. Cunningham JA, Rahman IA, Lautenschlager S, Rayfield EJ, Donoghue PCJ. 2014 A virtual world of paleontology. *Trends in Ecology & Evolution* **29**:347-357. (doi: 10.1016/j.tree.2014.04.004)

25. Johnson EH, Carter AM. 2019 Defossilization: A Review of 3D Printing in Experimental Paleontology. *Frontiers in Ecology and Evolution* **7**: 430. (doi: 10.3389/fevo.2019.00430)

26. Sutton M, Rahman I, Garwood R. 2017 VIRTUAL PALEONTOLOGY—AN OVERVIEW. *The Paleontological Society Papers* **22**:1-20. (doi:10.1017/scs.2017.5)

27. Hu Y-Z, Lu J, Young GC. 2017 New findings in a 400 million-year-old Devonian placoderm shed light on jaw structure and function in basal gnathostomes. *Scientific Reports* **7**:1-12. (doi:10.1038/s41598-017-07674-y)

28. Hu Y-Z, Young GC, Burrow C, Zhu Y-A, Lu J. 2019 High resolution XCT scanning reveals complex morphology of gnathal elements in an Early Devonian arthrodire. *Palaeoworld* **28**:525-534. (doi:10.1016/j.palwor.2018.12.003)

29. Myers GR, Kingston AM, Varslot TK, Turner ML, Sheppard AP. 2011 Dynamic tomography with a priori information. *Appl. Opt.* **50**:3685-3690. (doi: 10.1364/AO.50.003685)

30. Hu Y-Z, Young GC, Lu J. 2019 The Upper Devonian tetrapodomorph Gogonasus andrewsae from Western Australia: Reconstruction of the shoulder girdle and opercular series using X-ray Micro-Computed Tomography. *Palaeoworld* **28**:535-542. (doi:10.1016/j.palwor.2019.07.008)

31. Tesařová M, Heude E, Comai G, Zikmund T, Kaucká M, Adameyko I, et al. 2019 An interactive and intuitive visualisation method for X-ray computed tomography data of biological samples in 3D Portable Document Format. *Scientific Reports* **9**:1-8. (doi:10.1038/s41598-019-51180-2)

32. Cignoni P, Callieri M, Corsini M, Dellepiane M, Ganovelli F, Ranzuglia G. 2008 Meshlab: an open-source mesh processing tool. In: *Eurographics Italian chapter conference* 2008. p. 129-136.

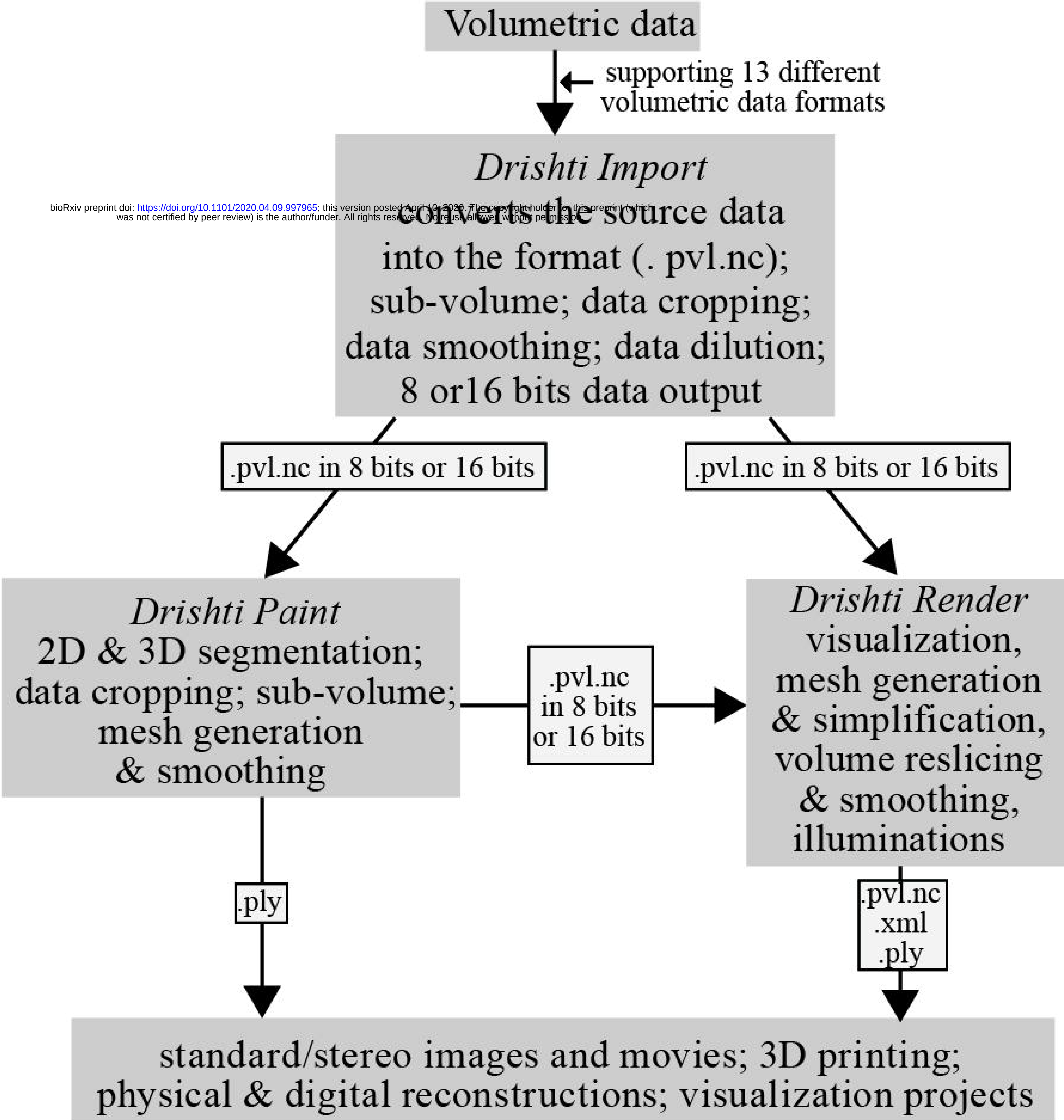
Figure legends

Figure 1. The general workflow for operating *Drishti* v2.6.6. Data formats in this figure are only abbreviations, for detailed information please refer to Supplementary Table 1.

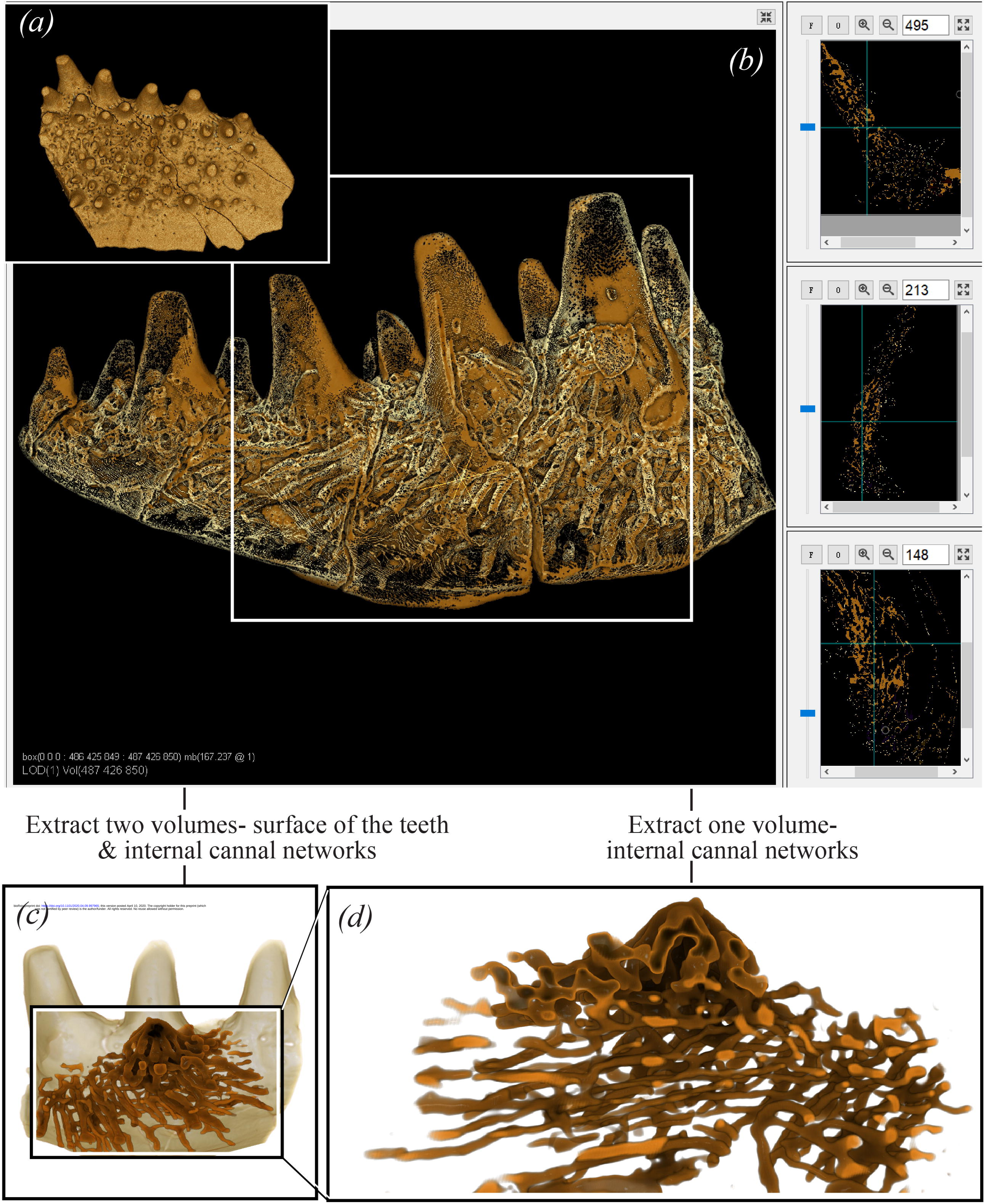
Figure 2. Extract a 3D virtual volumetric model in *Drishti*. A. Raw data of the right cheek complex of a Devonian placoderm fish (ANU V244) in *Drishti Import* v2.6.6. B. V244 in *Drishti Render* v2.6.6 in 16 bits full resolution (lateral view). C. Selected region-of-interest for segmentation. D. Selected region-of-interest in *Drishti Paint* v2.6.6 for segment the right cheek complex. E. Segmented right cheek complex in *Drishti Render* v2.6.6 (external view).

Figure 3. Segmenting internal structures of a toothplate (an Early Devonian placoderm fish, ANU V244) in *Drishti Paint*. A. Right upper anterior toothplate in *Drishti Render* v2.6.6 (external view). B. Raw data of the right upper anterior toothplate in *Drishti Paint* v2.6.6. The white-boxed area shows the selected region-of-interest on the right upper anterior toothplate for segmentation. C. Segmented outer surface of the region-of-interest on the right upper anterior toothplate and its internal canal networks underneath in *Drishti Render* v2.6.6. D. Segmented internal canal networks with a close-focus in *Drishti Render* v2.6.6.

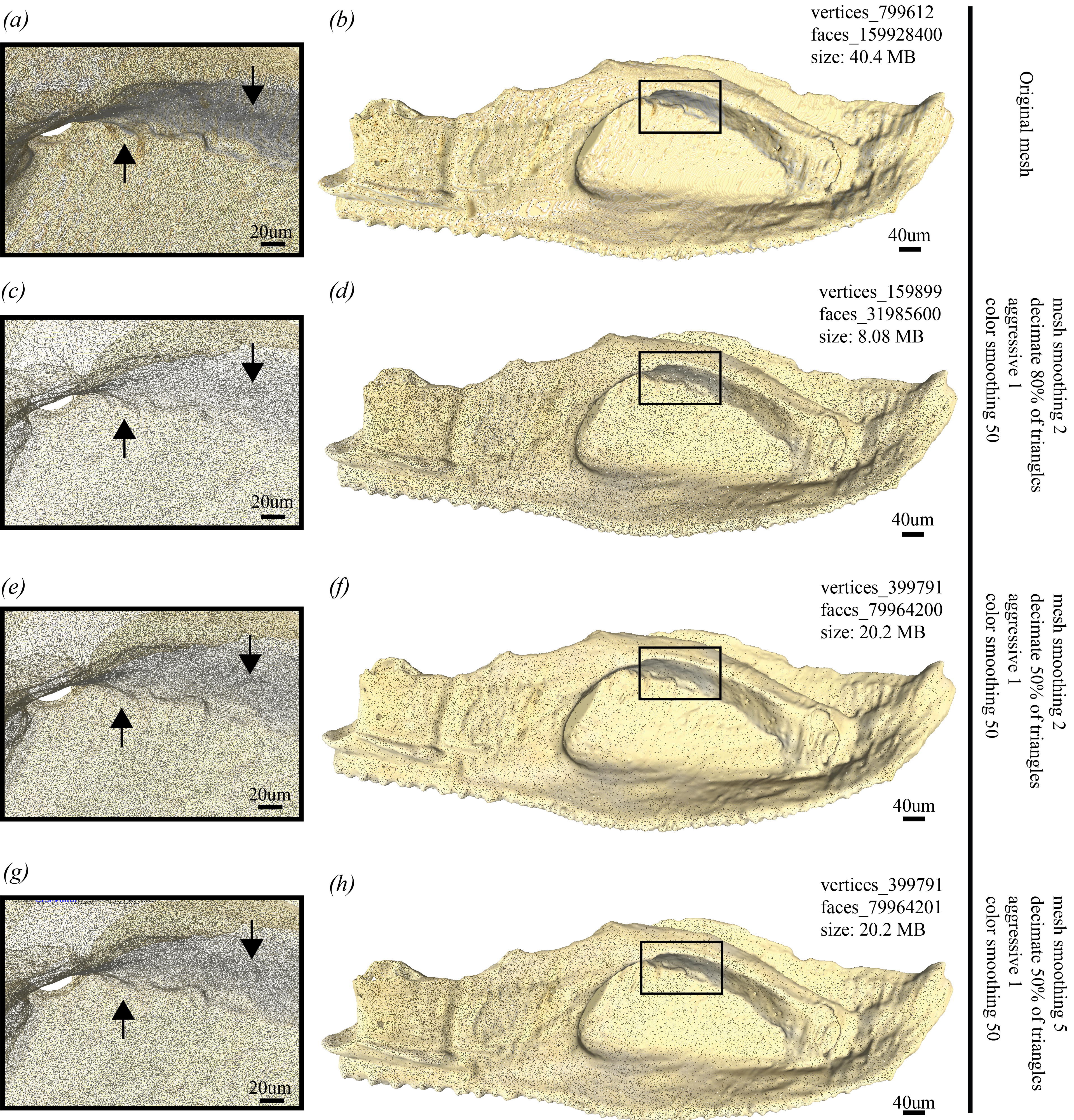
Figure 4. 3D surface meshes of the extracted right cheek unit (Devonian placoderm fish, ANU V244) with attached perichondral-ossified cartilages, showing the differences of vertex count and file sizes after different mesh simplification applications. The Vertex count was calculated in MeshLab v1.3.4 [32].


Volumetric data
supporting 13 different volumetric data formats
Drishti Import
converts the source data into the format (. pvl.nc); sub-volume; data cropping; data smoothing; data dilution; 8 or16 bits data output
.pvl.nc in 8 bits or 16 bits
.pvl.nc in 8 bits or 16 bits
Drishti Paint
2D & 3D segmentation; data cropping; sub-volume; mesh generation & smoothing
.pvl.nc in 8 bits or 16 bits
Drishti Render
visualization, mesh generation & simplification, volume reslicing & smoothing, illuminations
.ply
.pvl.nc .xml .ply
standard/stereo images and movies; 3D printing; physical & digital reconstructions; visualization projects


(a)
(b)
20mm
Select the Histogram
& Region of Interest
(c)
5mm
(d)
118
337
71
Segmentation
(e)
5mm



(a)
(b)
495
213
148
box(0 0 0 : 486 425 849 : 487 426 850) mb(167.237 @ 1)
LOD(1) Vol(487 426 850)
Extract two volumes- surface of the teeth
& internal cannal networks
Extract one volume-
internal cannal networks
(c)
(d)



(a)
20um
(b)
vertices_799612
faces_159928400
size: 40.4 MB
40um
Original mesh
(c)
20um
(d)
vertices_159899
faces_31985600
size: 8.08 MB
40um
mesh smoothing 2
decimate 80% of triangles
aggressive 1
color smoothing 50
(e)
20um
(f)
vertices_399791
faces_79964200
size: 20.2 MB
40um
mesh smoothing 2
decimate 50% of triangles
aggressive 1
color smoothing 50
(g)
20um
(h)
vertices_399791
faces_79964201
size: 20.2 MB
40um
mesh smoothing 5
decimate 50% of triangles
aggressive 1
color smoothing 50