

Comparison of STL skull models produced using open-source software versus commercial software

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Abstract

Purpose – This paper aims to compare the automatic segmentation of medical data and conversion to stereolithography (STL) skull models using open-source software versus commercial software.

Design/methodology/approach – Both open-source and commercial software used automatic segmentation and post-processing of the data without user intervention, thus avoiding human error. Detailed steps were provided for comparisons and easier to be repeated by other researchers. The results of segmentation, which were converted to STL format were compared using geometric analysis.

Findings – STL skull models produced using open-source software are comparable with the one produced using commercial software. A comparison of STL skull model produced using InVesalius with STL skull model produced using MIMICS resulted in an average dice similarity coefficient (DSC) of 97.6 ± 0.04 per cent and Hausdorff distance (HD) of 0.01 ± 0.005 mm. Inter-rater study for repeatability on MIMICS software yielded an average DSC of 100 per cent and HD of 0.

Social implications – The application of open-source software will benefit the small research institutions or hospitals to produce and virtualise three-dimensional model of the skulls for teaching or clinical purposes without having to purchase expensive commercial software. It is also easily reproduceable by other researchers.

Originality/value – This study is one of the first comparative evaluations of an open-source software with propriety commercial software in producing accurate STL skull models. Inaccurate STL models can lead to inaccurate pre-operative planning or unfit implant.

Keyword Rapid prototyping

Paper type Research paper

Introduction

Advances in craniofacial imaging have allowed the three-dimensional reconstruction of complex anatomical structures for medical applications. This technology has provided new possibilities to visualise complex medical data through generation of three-dimensional physical models that can be used to assist in diagnosis, pre-operative planning, disease visualisation, implant design, surgical guide, surgical simulation, medical education and patient management.

The technology is known as rapid prototyping (RP) because its main use is to rapidly create cost-effective prototypes during the design process. RP is also known as additive manufacturing

(AM) (Mika *et al.*, 2012; Tsai and Wu, 2014) as the three-dimensional printing process was through successive material layering. This technique refers to the process of using a machine to additively assemble a three-dimensional object layer by layer, using a digital design as a blueprint (Chen *et al.*, 2017).

Three-dimensional model of the skulls can be produced by converting digital imaging and communications in medicine (DICOM) data, obtained during the acquisition of computed tomography (CT) radiographs, into a digital design in stereolithography (STL) format. This three-dimensional model in STL format could be sent to three-dimensional printer for printing. The printed three-dimensional anatomical models are important in clinical and surgical planning and in medical imaging research (Bucking *et al.*, 2017). Segmentation of medical images is the method of partitioning related regions by combining the homogenous pixel (Timon and Diethard, 2009).

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Recent advances in segmentation software have made it easy to automatically or semi-automatically extracting the region of interest from the DICOM data. The three-dimensional printers, traditionally used in industrial applications, are now available for medical applications. The advancement in this technology has led to an increase in the use of three-dimensional printing in medicine, which enables fast creation of three-dimensional models without the need for manufacturing expertise (Trace *et al.*, 2016).

Most of the published articles used commercial software (Volpe *et al.*, 2018; Yu *et al.*, 2018; Zeng *et al.*, 2019; Zhang *et al.*, 2018) for processing of DICOM data, where the raw medical data were segmented, processed and saved into STL format, which can be sent to three-dimensional printer for printing physical models. One of the most commonly used software is MIMICS (Ghai *et al.*, 2018). However, there is an increasing trend of the usage of open-source software (Ganry *et al.*, 2017; Sander *et al.*, 2017). The key advantage of open-source software is that it is available for free, which significantly lowers the entry barrier to using it.

In comparative studies involving open source software, Wallner *et al.* (2018) applied “GrowCut” open-source algorithm using three-dimensional Slicer software to segment the mandible of 10 CT images, and later, compared with slice-by-slice segmentation on the same data sets using MeVisLab software as ground truth. After segmentation, the accuracy was assessed by certain parameters such as segmentation volume, dice similarity coefficient (DSC) and Hausdorff distance (HD) (voxel value). According to their results, average DSC values were over 85 per cent, HD below 33.5 voxels, and no significant different was observed on segmentation volumes.

Similarly, Abdullah *et al.* (2016) compared the three-dimensional reconstruction of mandible segmented using MIMICS and open-source medical imaging interaction toolkit (MITK) software on five CT images. Results of the geometric differences showed average errors of two three-dimensional models were less than 1 per cent using HD and no significant differences in the measurement of the landmarks. However, these comparisons were performed on mandible, not the whole skull.

Most of the studies reported in the literature used commercial software for three-dimensional reconstruction of skulls. There are a few studies using open source software for the three-dimensional reconstruction of the skulls (Egger *et al.*, 2017; Naftulin *et al.*, 2015), but these were not a comparative study. Therefore, this study was performed to compare two three-dimensional virtual models of the skull reconstructed using commercial and open-source software, which could provide more economical options for clinicians or researchers in patient management.

Materials and methods

CT head scans of patients were randomly collected from the picture archiving and communication system (PACS) server at the radiology department, Hospital USM. They were scanned using the Siemens Somatom Definition AS+ 128-slice (Siemens Medical Solutions, Erlangen, Germany). Ethical application was approved by the Ethics and Research Committee USM, reference number USMKG/PPP/JEPeM (246.3[13]).

Head CT images with a slice thickness of 1 mm and a matrix of 512×512 pixels each were retrieved from the PACS Server to a Dell Precision T7500 workstation in DICOM format. In total, 50 scans were processed using both commercial MIMICS software, version 17.0 (Materialise NV, Belgium) and open-source InVesalius software, version 3.1 (Renato Archer Information Technology Centre, Brazil). Both MIMICS and InVesalius uses the existing axial view to create cross-sections in the sagittal and frontal views for the three-dimensional image segmentation.

The sequence of the CT images, representing the various sections of the anatomical structures can be identified based on the gray scale of the image pixels. The Hounsfield unit, which expresses the gray scale, was adjusted accordingly using threshold method to segment hard tissues and soft tissues in both software. After segmentation and post-processing, the virtual three-dimensional model of the skull was saved in STL format.

The STL format of the skulls produced using InVesalius software were compared with the STL format produced using MIMICS software, which is used as “gold standard”. For repeatability, the segmentation process was repeated by the authors using similar methodology on five skulls using MIMICS software. Both STL formats were compared using DSC and HD (Egger *et al.*, 2013).

Computed tomography image segmentation

An automatic segmentation and reconstruction of the skull were applied using MIMICS and InVesalius software. Post-processing was conducted using automatic process to clear the noises or objects not related to skulls such as tubes or gantry. Both segmentation and post-processing of the images used automatic process without manual intervention to prevent human errors. The final three-dimensional model of the skull was converted to STL format for three-dimensional analysis as shown in Figure 1.

The step-by-step segmentation, post-processing and three-dimensional reconstruction process for MIMICS v17.0 (Figure 2) software are as the following:

- 1 *Loading file*
 - file – new project wizard;
 - select files that contain Dicom data to import;
 - reading file;
 - click convert;
 - converting file
 - verify the proposed orientation – click ok; and
 - file loaded.
- 2 *Segmentation*
 - segmentation – thresholding;
 - predefined thresholds set – bone (CT) – click apply;
 - green mask created;

Figure 1 Image segmentation process. The STL format of the skulls was used for three-dimensional analysis

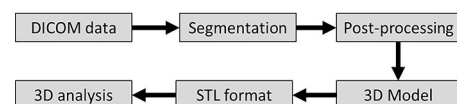
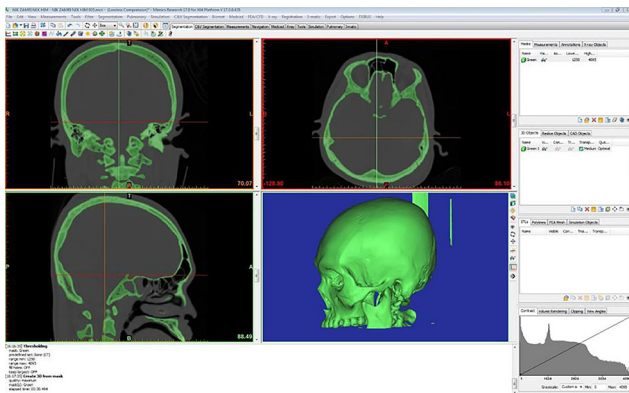


Figure 2 Graphical user interface of MIMICS v17.0 software

- right-click on green mask – calculate three-dimensional;
- choose optimal quality – click calculate; and
- three-dimensional model created (create three-dimensional from mask).

3 Post-processing

- Segmentation – region growing;
- click on the two-dimensional skull area (axial/sagittal/coronal);
- right-click on yellow mask – calculate three-dimensional;
- three-dimensional model created (create three-dimensional from mask);
- right-click on three-dimensional objects – yellow – STL+;
- click yellow 2 – click Add;
- choose output directory – click finish; and
- three-dimensional model is saved in STL format.

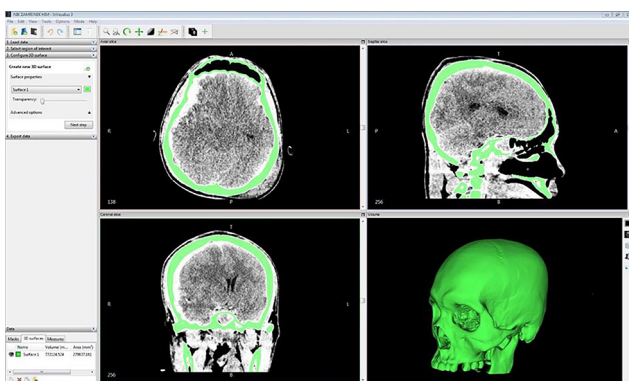
The step-by-step segmentation, post-processing and three-dimensional reconstruction process for In Vesalius v3.1 software are as the following (Figure 3):

1 Loading file:

- file – import DICOM – select folder – click import.

2 Segmentation:

- mask automatically segmented by bone threshold (226) default – click create surface; and
- three-dimensional model created.

Figure 3 Graphical user interface of InVesalius v3.1 software

3 Post-processing:

- advance options (click triangle) – select the largest surface – click next step;
- click save tool – choose segmented-data.vtk – save file format to STL – click save; and
- three-dimensional model is saved in STL format.

Three-dimensional analyses

The accuracies of the three-dimensional reconstruction of skull produced using InVesalius versus MIMICS software as gold standard was evaluated using metrics based on three-dimensional geometry such as HD and DSC applying open-source Cloud Compare software.

Hausdorff distance

Steps involved in computing HD using Cloud Compare are as the following (Figure 4):

- Load two STL files of the skull;
- Register two skull objects: tools – registration – match bounding – box centers;
- If the skull facing different direction: edit – translate/rotate;
- Fine registration: tools – registration – fine registration (ICP); and
- Compute HD: tools – distances – cloud/mesh dist.

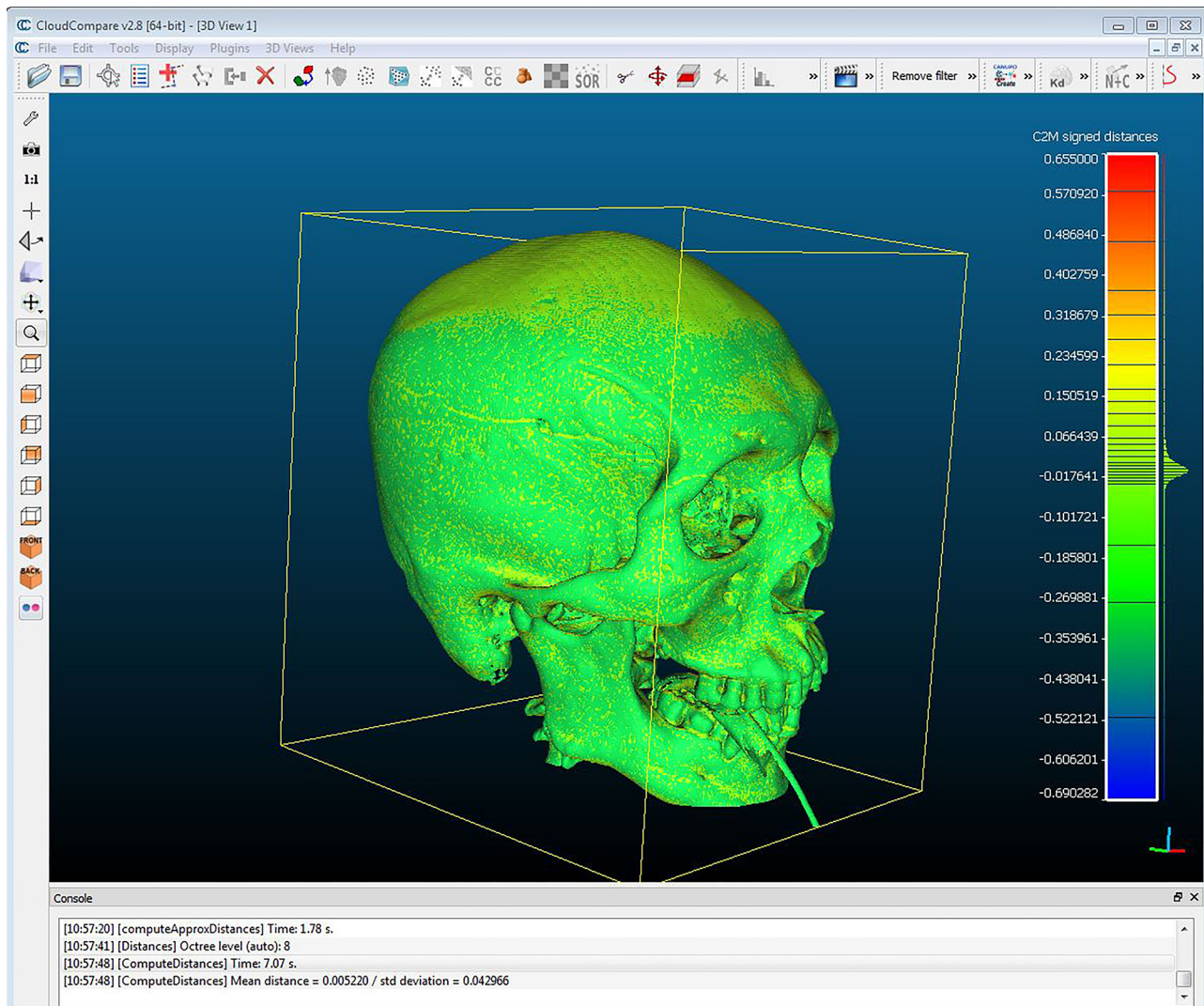
Dice similarity coefficient

Steps involved in computing DSC using Cloud Compare are as the following:

- load two STL files of the skull;
- click on the first skull to measure volume (cube units);
- edit – mesh – measure volume (Volume A);
- click on another skull and repeat the measure volume process (Volume B);
- register two skull objects: tools – registration – match bounding – box centers;
- if the skull facing different direction: edit – translate/rotate;
- fine registration: tools – registration – fine registration (ICP);
- to get overlapping volume: plugins – mesh boolean operations;
- click “intersection A $\cap$ B” (computation process will take a while);
- if computation failed, import data to meshlab to reduce number of triangles (remesh);
- repeat process from Step 1;
- measure overlapped volume: edit – mesh – measure volume (overlapped volume); and
- result of DSC between 0 (No overlap) to 1 (complete overlap).

Results

The aim of this study was to compare two three-dimensional models of the skull reconstructed using MIMICS v17.0 and InVesalius v3.1 software. All segmented images were converted into STL format using an automated process in the

Figure 4 HD computed using Cloud Compare software

software. The resulting STL format from InVesalius open-source software were compared to the gold standard STL formats from MIMICS software. A comparison was performed using DSC and HD. The results are summarised in [Table I](#). For repeatability study, the results are shown in [Table II](#).

The goal of this study was to evaluate the segmentation of DICOM data into three-dimensional model using InVesalius open-source software compared to commercial MIMICS software. Three-dimensional geometric analyses were used for this evaluation for 50 different skulls. Five skulls were randomly selected for the repeatability test.

The results of the study are detailed in [Table I](#). The primary conclusion is that the segmentation of the skulls using InVesalius open-source software can be performed in fewer steps than MIMICS software, as shown in the methodology and with good agreement (DSC: 97.64 ± 0.04 per cent, HD: 0.01 ± 0.01 mm). The columns DSC and HD show the agreement between the two segmentations using DSC and HD, respectively.

The segmentation process using MIMICS software were repeated twice on five different skulls at a different time using the same software installed in the same machine, thus having two results, MIMICS (A) and MIMIC (B) for the repeatability assessment of the segmentation. The results in [Table II](#) showed perfect agreement of 100 per cent DSC and 0 mm HD. As the process of segmentation was fully automated, the segmentation of the skulls could be repeated even by different users if it follows the same methodology.

Discussion

Research in the medical imaging field has become more complex over the years. The availability and variety of modalities have grown; for example, the advancement in CT images offers more options for further research to improve patient management but at the same time the researchers will be faced with more challenges. These are in the form of cost and expertise to deal with the medical imaging software. The

Table I This table presents the three-dimensional analyses between the two three-dimensional models segmented using mimics vs InVesalius software on 50 different skulls. The columns DSC and HD show the agreement between the two segmentations using a DSC and HD

Case no.	Mimics (M) volume (mm ³)	InVesalius (IV) volume (mm ³)	IV/M volume	Max distance (mm)	Max error (%)	DSC*	HD* (mm)
1	779,523	788,511	1.012	1.494	0.747	0.986	0.006
2	655,150	668,728	1.021	1.506	0.753	0.988	0.005
3	529,677	535,321	1.011	1.498	0.749	0.995	0.006
4	594,506	605,421	1.018	1.541	0.770	0.987	0.006
5	478,540	485,397	1.014	1.413	0.706	0.912	0.008
6	524,016	527,740	1.007	1.497	0.748	0.992	0.007
7	705,464	714,561	1.013	1.661	0.831	0.965	0.008
8	597,343	601,252	1.007	1.606	0.803	0.979	0.007
9	614,512	616,520	1.003	1.538	0.769	0.995	0.003
10	663,646	667,800	1.006	1.617	0.808	0.991	0.005
11	656,762	660,315	1.005	1.521	0.760	0.993	0.008
12	474,793	479,338	1.010	1.642	0.821	0.990	0.008
13	569,972	572,823	1.005	1.507	0.754	0.995	0.005
14	577,271	586,887	1.017	1.439	0.720	0.997	0.009
15	690,084	695,051	1.007	1.659	0.830	0.996	0.008
16	521,869	526,635	1.009	1.407	0.704	0.998	0.011
17	492,118	495,639	1.007	1.464	0.732	0.991	0.010
18	475,706	479,055	1.007	1.509	0.754	0.991	0.008
19	644,100	654,344	1.016	1.608	0.804	0.962	0.008
20	604,217	610,324	1.010	1.545	0.772	0.991	0.006
21	598,786	620,143	1.036	1.497	0.748	0.891	0.006
22	604,217	610,324	1.010	1.545	0.772	0.991	0.006
23	573,962	581,828	1.014	1.556	0.778	0.983	0.006
24	544,742	549,127	1.008	1.482	0.741	0.992	0.006
25	547,628	551,057	1.006	1.552	0.761	0.996	0.007
26	526,945	519,856	0.987	1.490	0.745	0.883	0.006
27	690,892	696,783	1.009	1.598	0.799	0.971	0.009
28	617,882	624,338	1.010	1.601	0.800	0.991	0.006
29	547,917	554,252	1.011	1.569	0.785	0.988	0.005
30	614,387	627,784	1.022	1.566	0.783	0.962	0.009
31	648,315	656,458	1.013	2.016	1.001	0.994	0.015
32	580,976	587,758	1.012	1.446	0.723	0.837	0.006
33	504,859	510,617	1.011	1.479	0.739	0.996	0.015
34	563,583	574,605	1.020	1.680	0.840	0.992	0.033
35	586,547	591,756	1.009	1.490	0.745	0.982	0.007
36	820,674	822,977	1.003	1.384	0.692	0.995	0.006
37	784,248	787,430	1.004	1.783	0.892	0.994	0.015
38	519,288	514,112	0.990	1.774	0.887	0.805	0.015
39	669,529	677,397	1.012	1.730	0.865	0.99	0.007
40	522,769	529,248	1.012	1.514	0.757	0.988	0.015
41	601,157	610,301	1.015	1.822	0.911	0.989	0.011
42	607,437	615,449	1.013	1.675	0.837	0.988	0.025
43	521,414	527,088	1.011	1.464	0.732	0.988	0.014
44	635,862	639,561	1.006	1.384	0.692	0.995	0.008
45	606,228	608,171	1.003	1.453	0.727	0.996	0.010
46	645,687	652,085	1.010	1.361	0.680	0.994	0.019
47	442,307	446,034	1.008	1.450	0.725	0.984	0.017
48	464,377	469,777	1.012	1.760	0.880	0.996	0.015
49	643,664	647,132	1.005	1.431	0.715	0.994	0.008
50	656,470	663,274	1.010	1.556	0.778	0.983	0.006
Mean	594,840	600,768	1.010	1.556	0.778	0.976	0.010

Notes: *DSC = dice similarity coefficient (0 = no overlap, 1 = complete overlap); HD = Hausdorff distance

Table II Five skulls were randomly selected, and the segmentation performed twice using MIMICS software to test for the repeatability of the method (MIMICS a vs MIMICS B). The columns DSC and HD show the agreement between the two segmentations using a DSC and HD

Case no.	MIMICS(A) volume (mm ³)	MIMICS(B) volume (mm ³)	B/A volume	Max distance (mm)	Max error (%)	DSC*	HD* (mm)
1	779,523	779,523	1	0	0.746	1	0
2	655,150	655,152	1	0	0.751	1	0
3	529,677	529,677	1	0	0.748	1	0
4	594,506	594,506	1	0	0.767	1	0
5	478,540	478,546	1	0	0.706	1	0

Notes: * DSC = dice similarity coefficient (0 = no overlap, 1 = complete overlap); HD = Hausdorff distance

commercial medical imaging software is costly and normally out of reach for a small research institution or clinical setting.

Open-source software could be used to solve these challenges. They have penetrated the medical market and have proven to be more robust and cost-effective than their commercial counterparts (Ratib *et al.*, 2011). The software may provide manual, semi-automatic or automatic segmentation capability, but they tend to be either very broad or very specific in the scope of functionality that they provide (Abdullah *et al.*, 2016). For example, three-dimensional Slicer (Scanlan *et al.*, 2018) and MIPAV (<https://mipav.cit.nih.gov/>) software provide large-scale packages/functionality; however, due to the large number of features that they provide, they carry a steep learning curve.

For reproducibility and to reduce human error, the InVesalius software was chosen based on the ability to conduct the automatic segmentation in every step, similar to MIMICS software. Manual editing may result in over or under segmentation by the observer. Semi-automatic segmentation refers to the process, whereby this automatic segmentation is followed by manual checking and editing of the segment boundaries.

Semi-automatic segmentation also requires more time as it involves manual checking and editing, which involves many slices of two-dimensional data. This time factor is the main drawback of semi-automatic segmentation in the routine clinical setting, let alone the steep learning curve to learn how to use that particular software.

In this study, the DICOM data from CT scans were segmented and reconstructed into three-dimensional model using both MIMICS and InVesalius software. The segmentation, post-processing, and three-dimensional reconstruction process were automated without manual editing from users for both software. The same methodology and step-by-step guide were given to users to follow. Therefore, human errors were minimised.

The steps involved in segmentation the skulls using InVesalius software were less compared to MIMICS software, where it involved six versus 19 steps using InVesalius software and MIMICS software, respectively. This showed that open-source software may provide faster process compared to commercial software.

One of the key features of the InVesalius software is easy to understand user interface allowing new users to quickly adapt with the interface and start using it without having to look at the user's manual. Users who are not experts in image processing can easily learn the process as the segmentation flow is very straight forward.

Many research studies applied open-source software, however, no comparisons were made to verify with other commercial software for the accuracy of the output. In this

study, 50 CT scans were used for image reconstruction from DICOM raw data to three-dimensional model of the skull in STL format. All cases were compared one by one and results showed that they are similar by 97.6 per cent with average distance of 0.01 mm.

In another study, pre-operative model was created using three-dimensional modelling and AM for clinical application (Mika *et al.*, 2012). The three-dimensional model of the skull from the CT images was reconstructed using Osirix 2.7.5 software, which is also an open-source software. However, the Osirix software is only available for Apple operating system. On the other hand, InVesalius software is available for the Microsoft Windows, GNU/Linux and Apple Mac OS X platforms (<https://invesalius.github.io/>).

The virtual three-dimensional model of internal structures of the human body, in this case, the skull, is needed for final production of a three-dimensional physical model. It requires a very good segmentation with a high resolution and pixels of a small size to maintain its accuracy (Jardini *et al.*, 2014). This study proved that open-source software can be robust and yet user-friendly with the advantage of minimal cost to use.

This study compared the STL models of skulls produced by InVesalius and MIMICS, which showed comparable results. Segmentation and obtaining the STL files are a step towards AM for medical applications such as creating implant design. MIMICS has the strength and good capability for computer-aided design modelling and implant design, which is the key for AM applications. Therefore, other third-party software could be proposed for post-processing of STL models in combination with InVesalius to design the implant in future.

Conclusion

In total, 50 different three-dimensional models of the skulls in STL format were successfully segmented from the CT scan images using MIMICS v17.0 and InVesalius v3.1 software and converted into STL format for analysis using DSC and HD. Three-dimensional models produced by InVesalius software are comparable with the three-dimensional models produced by MIMICS Software, it could potentially be used for pre-operative planning and patient management with minimum cost especially for the clinical setting in the developing countries.

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