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A Review of the Issues Surrounding Three-Dimensional Computed Tomography for Medical Modelling using Rapid Prototyping Techniques

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Abstract

This technical note aims to raise awareness amongst radiographers of the application of Computed Tomography data in the production of models using Rapid Prototyping technologies. It also aims to provide radiographers with recommendations that will assist them in providing three-dimensional Computed Tomography data that can fulfil the requirements of medical modelling. Potential problem areas in data acquisition and transfer are discussed and suggestions are given for methods that aim to avoid these.

Keywords

3D modelling, medical rapid prototyping, anatomical models, computed tomography

Introduction

Medical modelling is the term for the production of highly accurate physical models of anatomy directly from 3D medical image data utilising computer-controlled manufacturing machines commonly referred to as Rapid Prototyping (RP). Medical modelling involves acquiring three-dimensional image data of human anatomy, processing the data to isolate individual tissues or organs of interest, optimising the data for the RP technology and finally building the physical model in an RP machine. These machines have been primarily developed to enable designers and engineers to build exact models of products that they have designed using computer-aided design software (CAD). Consequently, RP technologies have developed to produce models of very high accuracy as rapidly as possible.

Medical modelling has many applications and the most common has been in head and neck reconstruction including neurosurgery, craniofacial / maxillofacial surgery and manufacturing prosthetics and implants. Medical models are routinely used for diagnosis, communication and pre-surgical planning but also they are increasingly used in the design and manufacture of implants and prosthesis[1-9], creating surgical guides[10-15], making imaging phantoms and teaching. Clear demonstration of benefits published in case studies and review articles has led to increasing interest in medical modelling[16-18]. Hundreds of medical models are produced in the UK each year and the numbers are growing rapidly making it increasingly likely that radiographers will be asked to provide CT images for medical modelling.

Usually, a surgeon or clinician who requires a medical model will request a 3D scan of the area of interest. The medical modelling process requires the relevant anatomy to be captured in a three-dimensional format and although a number of medical imaging technologies have been successfully employed to make models, including MRI[19] and Ultrasound[20], volumetric Computed Tomography (3D CT) is by far the commonest imaging modality. The 3D medical image data is processed, mathematically modelled and subsequently transferred to a rapid prototype model provider for manufacture. Useful reviews of the rapid prototyping methods and clinical applications are available[21, 22]. After acquisition and transfer, the images are imported into specialist RP software and techniques such as image thresholding and region growing are used to isolate the desired anatomical structure[23]. This data is then exported in a format called STL (Standard Triangulation Language) that can be utilised by RP machines. The steps from CT image to 3D reconstruction as an STL file is illustrated in Figure 1.

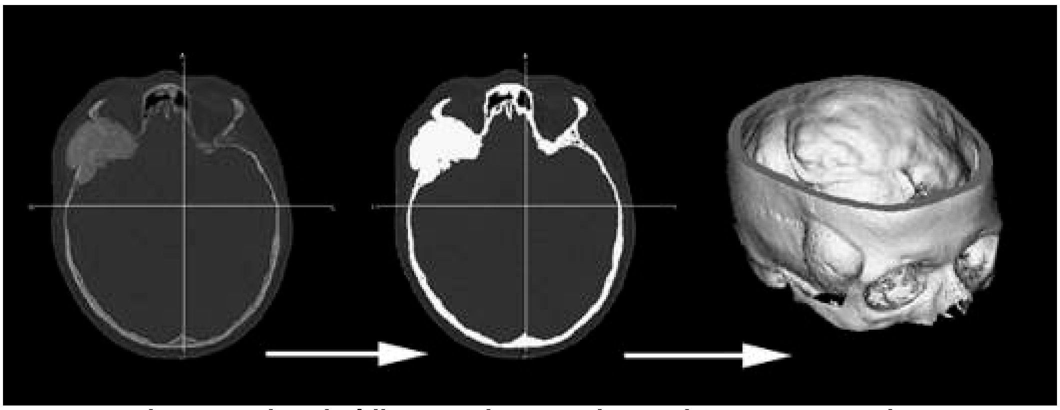

Figure 1: Thresholding, Region growing and 3D reconstruction

The software for the RP machine then slices the three-dimensional data to produce a cross-section for each layer the machine will build. It is not possible to describe each RP technology in detail here but more information can be found in reference texts[21]. A typical medical model of the mid-face and mandible is shown in Figure 2. The model is multicoloured to help the clinician distinguish between different tissue types identified within the CT images.

Figure 2: A typical medical model made by stereolithography.

A good quality medical model would be defined as a model that is fit for purpose. Specifically, it should include all of the anatomy of interest, be free from any artefacts that result in the physical model deviating from the anatomy and be sufficiently dimensionally accurate. This technical note aims to provide radiographers with recommendations that will enable them to provide 3D CT images that can fulfil the requirements of medical modelling quickly and efficiently. There have been many case studies describing the use of medical models and but comparatively few have addressed the issues encountered when attempting to utilise medical modelling[24, 25]. Potential problem areas in data acquisition and transfer are addressed in this note and suggestions are given for methods that can be applied to limit or avoid these errors.

CT Considerations for Medical Modelling

Anatomical Coverage

An ideal CT acquisition should be free from image artefacts, have isotropic voxel resolution, high image contrast between the anatomy of interest and neighbouring tissues and low noise. It is clear that the series of axial images must begin and end either side of the anatomy of interest but it is important to begin and end the scan some distance either side of the region/anatomy of interest. It is better to include anatomy above and below the area of interest, the amount being dependent on the region being scanned and the purpose of the model. For example when constructing medical models of cranial defects to facilitate the manufacture of a cranioplasty plate, it is helpful to include a margin of 20 mm around the defect so that the prosthetist can shape the titanium plate to fit the patient correctly. In some cases, anatomy well beyond the area of direct interest is used to help form or shape a repair to a bone of soft tissue defect[4, 5, 26-28]. For example, a model may include the left side of a body part so that symmetry can be used to assist the construction of a prosthesis on the right side. The data volume should be continuous as non-continuous data may contain areas where the patient has shifted position slightly and the separate series will not align perfectly.

Patient Arrangement, Positioning and Support

Movement during the CT acquisition will result in movement artefact and distort the image data, which will translate directly through to the finished model. In maxillofacial surgery anything greater than one-millimetre of movement may render a model unusable[29]. Involuntary movement of the chest, neck, head or mouth can occur through breathing or swallowing. Multislice CT is capable of imaging the chest or abdomen within 15 seconds, which is achievable in a single breath-hold. Although medical modelling is most commonly undertaken for bone structures, there is increasing interest in modelling soft-tissue structures including the heart and arteries[30]. Therefore, gated acquisition for cardiac compensation using multislice CT scanning[31] would lead to significant movement artefact reduction. The image data may be acquired during systole or diastole but the choice of which to use would depend on the model application and should be clarified before scanning. Other sources of movement like swallowing or talking should be minimised as far as possible.

It is increasingly common for 3D CT scans to be utilised in the multi-disciplinary management of a patient, where the image data is not only used for diagnosis but also for surgical planning, computer guided surgery, medical modelling and prostheses design. The 3D CT data may be used to represent both hard and soft tissue internally but may also find subsequent application in tissue reconstruction or prosthetic rehabilitation. It is therefore important to consider the positioning and support of soft tissues to eliminate or reduce unwanted deformation of soft tissue. The use of positioning pads should be considered so that the anatomy of interest does not become distorted prior to scanning. Patient immobilisation techniques such as vacuum pillows or simple foam pads may be used to support the patient, even to the extent that the surgical position of the patient may be replicated within the scanner. Examples of unwanted soft tissue deformations caused during CT acquisition can be seen in Figure 3 where the images were acquired for the soft tissue information. Note the use of a hand in supporting a child’s chin in Figure 3. The use of the data should be clarified with the referring clinician to ensure appropriate positioning and support is used.

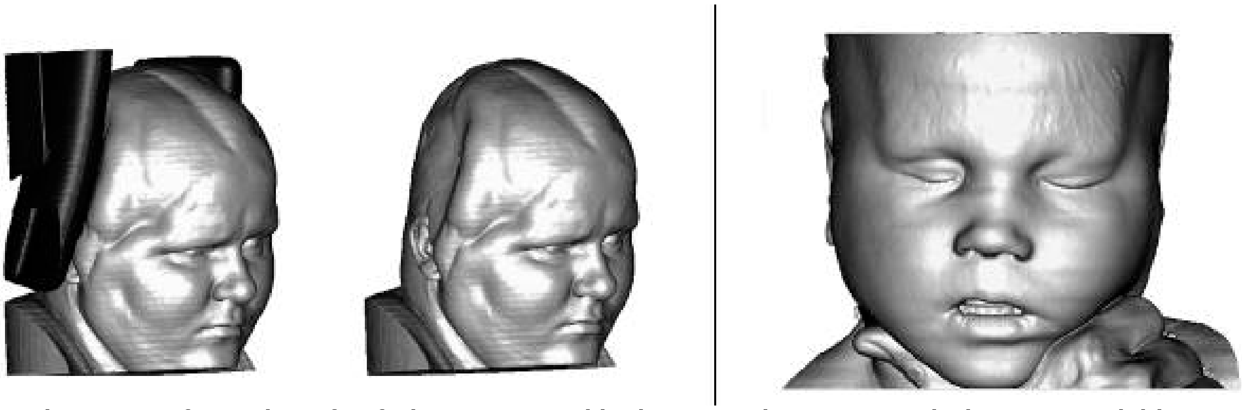

Figure 3: Deformation of soft tissues caused by inappropriate support during CT acquisition.

When using CT data for surgical planning it is often necessary for different bones to be manufactured individually so that they can be moved independently to simulate surgical techniques. It is common for example when planning maxillofacial surgery to perform osteotomies and move parts of the mandible or maxilla. Often the patient is scanned with a closed bite, which causes the data for upper and lower teeth to merge. This makes subsequent separation of the mandible and maxilla using image-processing techniques very difficult. The effect of this overlap can be seen in Figure 4. For maxillofacial cases it is recommended that a slightly open bite or spacer be used that will enable the different jaws to be separately segmented.

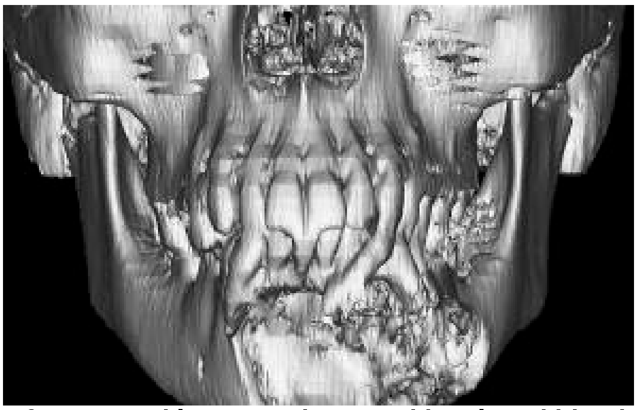

Figure 4: Joining of upper and lower teeth caused by closed bite during acquisition.

CT Parameters

There is a very wide range of CT technology available in the health service (from single slice helical to 64 slices or greater) and the variation in clinical practice throughout the UK and Ireland is very wide. It would not be appropriate for us to provide a definitive CT scanning protocol for any or all regions of the body, given that different centres will have different technology and imaging protocols depending on local needs. It is recommended that radiographers use their routine 3D volumetric protocol for the given anatomical area also taking into consideration some of the issues below.

Slice Thickness

To maximise the data acquired the reconstructed slice thickness should be minimised. Some scanners can produce 0.5 mm slices, which gives excellent results but this must be balanced against increased radiation dose. For example in maxillofacial surgery a slice thicknesses of 0.5 to 1 mm will be required to ensure the resulting model is sufficiently accurate. A slice thickness of 2 mm may be adequate for larger structures such as the long bones or pelvis. Using a slice thickness that is greater than 2 mm will result in a loss of data and a stepped artefact and is therefore not recommended for rapid prototype models.

Consideration should also be given to slice reconstruction and overlap. In single helical and multislice CT, the reconstruction of axial slices may be performed with a significant overlap. This feature is especially useful where thin bones are present or 3D surface rendering of small blood vessels is required[30]. For example, images were reconstructed from 1.0 mm slices with 0.5 mm increment (50% overlap) to aid the manufacture of titanium implant of the orbit[7]. The 50% overlap had a significant effect on the visualisation of the orbital floor and on the surface quality of the medical model providing very smooth surfaces.

Gantry Tilt

Gantry tilt is commonly used it CT to provide the appropriate angle of slice relative to the anatomy of interest and also to reduce the radiation dose to the orbits in head scanning. However, for the purposes of medical modelling, gantry tilt should be set to zero (0^0) as it does not significantly improve the quality of the acquired data and provides an opportunity for error when the service provider imports the images. Large gantry tilt angles are clearly apparent on visual inspection of the data and may be corrected. However, small angles may not be easy to check visually and may remain undetected or be compensated for incorrectly. Even the use of automatic import of the medical image standard DICOM is no guarantee as although the size of angle is included in the format, the direction is not. Failure to compensate for the direction correctly will lead to a distorted model, wasting time and money and potentially leading to errors in surgery or prosthesis manufacture.

X-Ray Scatter

Dense objects such as amalgam or gold fillings, braces, bridges, screws, plates and implants scatter X-rays resulting in a streaked appearance in the image. It is common practice in radiography to remove all metal to reduce artefacts where possible. However, where metal implants cannot be removed the effects of these can be manually edited using medical imaging software to produce a better medical model. However, this does depend on the expertise of the service provider and consequently the accuracy of the model in the affected areas cannot be guaranteed.

Noise and Image reconstruction kernels

Noise is a fundamental component of a CT image and is especially prevalent in dense tissues. Medical modelling depends on identifying well-defined boundaries between different tissues, which is achieved by using pixel thresholding. Noise interrupts the boundary, resulting in incomplete surfaces in 3D reconstructions that typically appear rough or porous as illustrated in Figure 5. Efforts could be made to reduce noise by increasing mA where medical models are required. However, any increase in dose would need to be clinically justified by the benefits of the medical model.

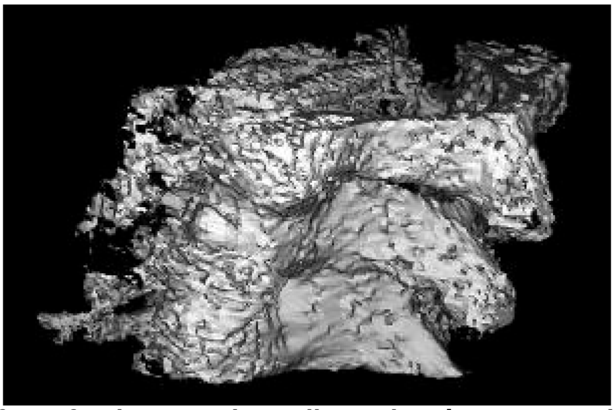

Figure 5: The effect of noise on a three-dimensional reconstruction of vertebrae.

During the reconstruction, digital filters (kernels) are applied which enhance or smooth the image depending on the clinical application. Typically, the options will range from “sharp” to “smooth”. Sharpening filters increase edge sharpness but at a cost of increasing image noise. Smoothing filters reduce noise content in images but also decrease edge sharpness. In general, when building medical models, smooth filters tend to give better results and are easier to work with. Although the smooth image contrast appears poor on screen (Windows computers can only display 256 shades of grey and the human eye can only perceive about 70 grey levels), density profiles show that the actual contrast is good and allows a lower threshold to be used.

Data Transfer

3D medical image processing and medical RP software (e.g. Mimics, Materialise N.V, Technologielaan 15, 3001 Leuven, Belgium, AnalyzeDirect, Inc. 7380 W 161st Street, Overland Park, KS, 66085 USA) require DICOM V3.0 data format and are usually sent to a medical modelling service provider on CD-ROM. In nearly all cases, only the reconstructed axial/transverse images are required as further image processing and modelling will be carried out by the service provider. CT images should be written without image compression or the automated viewing software. From a patient confidentiality point of view, the exclusion of the manufacturer's viewing software means that images on a lost or misplaced CD cannot be easily viewed without specialist knowledge and software. The images do not need to be "windowed" prior to storage or transfer as access to the original DICOM images allows the service provider to view them with their own settings. Careful consideration should be given to patient confidentiality and data security and procedures should be agreed with the service provider to ensure all data is securely and ethically treated. For example, data should be sent by registered post, the service provider should be requested to store data in a locked cabinet, and access to any data should be password protected. Arrangements should also be made to return or destroy the CD on completion of the model.

Conclusion

A consideration of the issues described above will help to improve the source volumetric CT image data used for medical rapid prototyping and subsequently improve model quality.

Acknowledgements

Figure 2 is reproduced with the permission of Queen Elizabeth Hospital Birmingham, United Kingdom, Figure 3a was kindly provided by Dr. Jules Poukens, University Hospital Maastricht, The Netherlands. Figures 3b and 4 were kindly provided by Carol Voigt, Brånemark Institute, South Africa.

Conflicts of Interest

The authors have no conflicts of interest to declare.

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