SUMMARY

AM offers possibilities to fabricate different types of patient-specific constructs such as anatomical models, surgical guides and implants. Such constructs can improve the surgeon's dexterity, decrease operation time and improve accuracy of surgical procedures. As demonstrated in **Chapter 2**, AM can be combined with virtual planning to create accurate and low-cost individualised orbital floor implants. A virtual 3D model of a patient with an orbital floor fracture was generated from CT images of the patient. The fracture was virtually closed using spline interpolation. The resulting 3D model was used to design and manufacture a mould of the defect site using an inkjet printer. This tangible mould was subsequently used during surgery to sculpture an individualised autologous orbital floor implant. This novel treatment method enhanced the overall accuracy and efficiency of the surgical procedure. The sculptured autologous orbital floor implant showed an excellent fit in vivo and reduced the operation time by approximately 40%.

Despite recent advances and promising case studies involving medical AM, notable scientific, technological and regulatory challenges remain. Each step in the medical AM process, i.e., imaging (step 1), image processing (step 2) and manufacturing (step 3) can introduce inaccuracies in the resulting construct. However, since the aforementioned AM constructs can be fabricated with great accuracy (< 0.1 mm) using current printing technologies, their design is currently limited by the accuracy of the imaging and image processing steps. Therefore, the general aim of this thesis was to provide an insight into the current scientific and technological challenges faced in medical additive manufacturing with respect to imaging and image processing. More specifically, the different parameters that influence the accuracy of patient-specific AM constructs were identified.

In **Chapter 3**, the image quality and the accuracy of STL models acquired using different CT scanners and acquisition parameters is assessed. Images of three dry human skulls were acquired using different scanning protocols on two multi-detector row computed tomography (MDCT) scanners, a dual energy computed tomography (DECT) scanner and one cone beam computed tomography (CBCT) scanner. All images were ranked according to their image quality and converted into STL models. These STL models were subsequently compared with corresponding gold standard models acquired using an optical 3D surface scanner. It was found that the image quality differed between the MDCT, DECT and CBCT scanners. Images acquired using low-dose MDCT protocols were preferred over images acquired using routine protocols. All CT-based STL models demonstrated non-uniform geometrical deviations of up to +0.9 mm. The largest deviations were observed in CBCT-derived STL models. Therefore, it can be concluded that CT imaging technologies and their acquisition parameters can markedly affect the accuracy of medical AM constructs.

In **Chapter 4**, the impact of head positioning on CBCT image quality is evaluated. The impact of supine, prone and oblique patient imaging positions on the image quality, contrast-to-noise ratio and figure of merit value in the maxillofacial region of a fresh frozen cadaver head was assessed using a CBCT scanner. In addition, the CBCT supine images

were compared with supine MSCT images. The best CBCT image quality was achieved in the prone imaging position for sinus, mandible and maxilla, followed by the supine and oblique imaging positions. The MSCT scanner offered similar image qualities to the 7.5-mA supine images acquired using the mobile CBCT scanner. The prone imaging position offered the best CNR and FOM values on the mobile CBCT scanner. These findings can help to improve CBCT image quality in the maxillofacial region, which, in turn, may improve the overall accuracy of CBCT-derived AM constructs.

In addition to the CT imaging step, the accuracy of medical AM constructs is affected by errors introduced during image processing, particularly during the image segmentation process. Therefore, in **Chapter 5**, thirty-two publications that reported on the accuracy of different CT image segmentation methods for bone used in medical AM are reviewed. The advantages and disadvantages of the different image segmentation methods used in these studies were evaluated and the reported accuracies were compared. The spread between the reported accuracies was large (0.04 mm to 1.9 mm). Global thresholding was the most commonly used segmentation method with accuracies under 0.6 mm. The disadvantage of this method is the extensive manual post-processing required. Advanced thresholding methods could improve the accuracy to under 0.38 mm. However, such methods are currently not included in commercial software packages. Statistical shape model methods resulted in accuracies from 0.25 mm to 1.9 mm but they are only suitable for anatomical structures with moderate anatomical variations. To improve the accuracy and reduce the cost of patient-specific AM constructs, more advanced image segmentation methods are required.

Chapter 6 provides more insight into the most commonly used image segmentation method in medical AM, namely global thresholding. The impact of manual and default threshold selection on the reliability and accuracy of skull STL models acquired using different CT technologies was evaluated. One female and one male human cadaver head were imaged using MDCT, DECT and two CBCT scanners. Four medical engineers manually thresholded the bony structures on all CT images. The lowest and highest selected mean threshold values and the default threshold value were used to generate skull STL models. Geometric variations between all manually thresholded STL models were calculated. Additionally, in order to calculate the accuracy of the manually and default thresholded STL models, all STL models were superimposed on an optical scan of the dry female and male skulls ("gold standard"). The intra- and inter-observer variability of the manual threshold selection was good (intra-class correlation coefficients >0.9). All engineers selected grey values closer to soft tissue to compensate for bone voids. Geometric variations between the manually thresholded STL models were 0.13 mm (MDCT), 0.59 mm (DECT) and 0.55 mm (CBCT). All STL models demonstrated inaccuracies ranging from −0.8 mm to +1.1 mm (MDCT), −0.7 mm to +2.0 mm (DECT) and −2.3 mm to +4.8 mm (CBCT). The findings of this study demonstrate that manual threshold selection results in better STL models than default thresholding.

In **Chapter 7**, a novel method was developed to assess the accuracy and reliability of CT scanners and software packages. To this end, an anthropomorphic phantom that provided ground truth measurements for the evaluation of the oropharynx morphology was 3D printed. This phantom was used to assess the accuracy of two multi-detector row computed tomography (MDCT) scanners (GE Discovery CT750 HD, Siemens Somatom Sensation) and three CBCT scanners (NewTom 5G, 3D Accuitomo 170, Vatech PaX Zenith 3D). All CT images were segmented by two observers and converted into standard tessellation language (STL) models. The volume and the cross-sectional area of the oropharynx were measured on the acquired STL models. Finally, all STL models were registered and compared with the gold standard. Significant differences were observed in the volume and cross-sectional area measurements of the oropharynx acquired using the different MDCT and CBCT scanners. The Siemens MDCT and the Vatech CBCT scanners were more accurate than the GE MDCT, NewTom 5G, and Accuitomo CBCT scanners.

AM medical models, implants and drill guides are becoming increasingly popular amongst maxillofacial surgeons and dentists. This rise in popularity has subsequently increased the number of CT and CBCT scans performed worldwide. However, all X-ray based imaging modalities induce harmful ionizing radiation to the patient. Therefore, **Chapter 8** assesses the feasibility of using radiation-free UTE MRI sequences for medical AM. Three morphologically different dry human mandibles were scanned using a CT and MRI scanner. All CT and MRI scans were converted into STL models and geometrically compared with a corresponding gold standard STL model acquired using an optical 3D scanner. To quantify the accuracy of the AM process, the CT, MRI and gold-standard STL models of one of the mandibles were additively manufactured, optically scanned and compared with the original gold standard STL model. Geometric differences between all three CT-derived STL models and the gold standard were < 1.0 mm. All three MRI-derived STL models generally presented deviations < 1.5 mm in the symphyseal and mandibular area. It should be noted that the AM process only introduced minor deviations of < 0.5 mm. Hence, UTE MRI sequences offer an alternative to CT in generating STL models of the mandible and could be suitable for surgical planning and AM.