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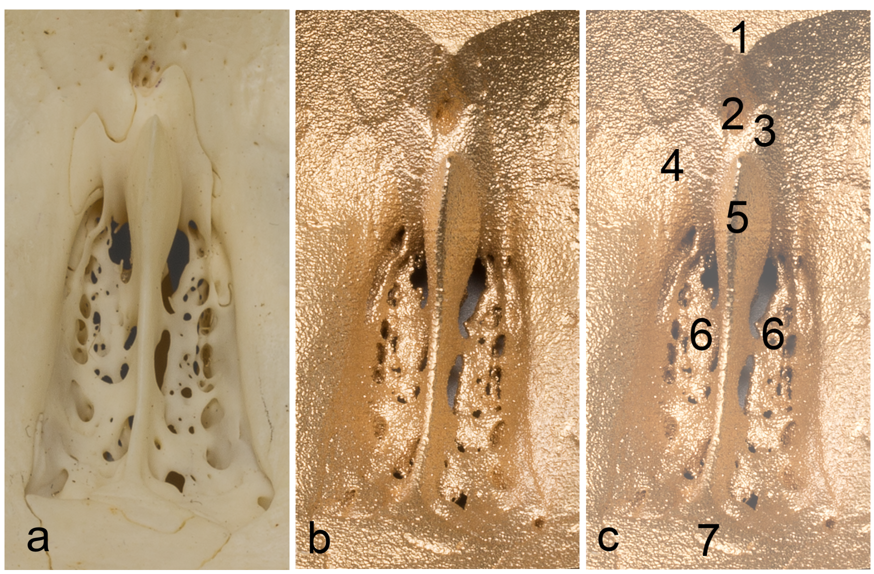
«Triple-A Study»



Jean H.D. Fasel

Printing Gold in 3D: An Anatomical Accuracy Analysis («Triple-A Study»)

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Abstract

Three-dimensional gold printing is driving major innovations in many areas. Additive technologies are also being used increasingly in medicine. However, little scientific work has been published to date on the 3D printing of biocompatible precious metals, such as gold. The aim of this study is to evaluate the accuracy of gold-printed biomedical items. An 18 kt replica of the *lamina cribrosa ossis ethmoidalis* of a patient was compared qualitatively and quantitatively with the original. Two methods were used: surface scanning and neutron tomography (Polymetric, Darmstadt, Germany; Geomagic Studio, Rockhill, SC, USA; Paul Scherrer Institute PSI, Villigen, Switzerland; Volume Graphics, Heidelberg, Germany). The qualitative comparison showed a very good match. The anatomic structures were reproduced correctly, including the *foramina laminae cribrosae* and the *sutura sphenoethmoidalis*. The quantitative results also converged irrespective of the investigative method: the deviations showed a narrow Gaussian distribution with an average value of 53.1 µm and 61.6 µm, respectively. The corresponding maximum deviations were 0.500 mm and 0.499 mm. This study therefore documents that 3D printing enables even a complex area of the human skull, such as the *lamina cribrosa*, to be replicated in gold with high anatomic accuracy, where accuracy is defined in deviations from the original well into the submillimeter range. Optical surface scanning can be recommended as a methodology for future evaluation studies.

Keywords additive manufacturing, human skull, accuracy, nominal/actual comparisona

Introduction

Three-dimensional gold printing (3DP) is driving major innovations in many areas, especially in the design, jewellery and clock-making industries. Additive manufacturing technologies are also arousing considerable interest in medicine [1-5]. However, little scientific work has been published to date on the 3D printing of biocompatible precious metals, such as gold [6,7].

This study aims to contribute to the scientific evaluation of accuracy of gold-printed biomedical replicas. The article presents the results on a particularly complicated area of the human skull, the *lamina cribrosa ossis ethmoidalis*, which is especially difficult to reproduce. Methodological conclusions are drawn for corresponding future comparative studies based on the results.

Materials and Methods

The region under investigation is the human *lamina cribrosa*, a part of the ethmoidal bone visible in the anterior cranial fossa (Fig. 1). Qualitative and quantitative investigations of the replica of this item printed in 18 kt gold were carried out and compared with the original, as follows:

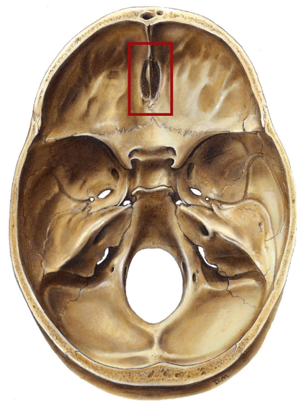

Fig. 1 Top view on the internal surface of a human cranial base. The area investigated in this study, the *lamina cribrosa ossis ethmoidalis*, lies in the anterior cranial fossa and is circled in red.

1. Qualitative investigation

For the qualitative evaluation, structures visible to the naked eye on the surface of the *lamina cribrosa* region in the original were compared with those in the replica (Fig. 2).

2. Quantitative investigation

Two methods were used to compare the gold replica with the original: white light surface scanning and high resolution neutron tomography.

2.1. Optical surface scanning

The item was first scanned using white lighting scanning (PT-M4c scanner, Polymetric, Darmstadt, Germany). The quantitative comparison with the original was carried out using the Geomagic Studio software (edition 2014.0.1.1671, 3DSystems Rock Hill, SC, USA). The deviations of the replica from the original were colour-coded using the deviation control tool.

2.2. Neutron computed tomography

The *lamina cribrosa* was also examined using high resolution neutron tomography with cold neutrons at the ICON beamline (Paul Scherrer Institut PSI, Villigen, Switzerland) [8]. The data obtained was compared using the nominal/actual comparison module of the 3D analysis software VG studio max (version 2.2.6, Volume Graphics GmbH, Heidelberg, Germany).

Results

The *lamina cribrosa* of the investigated skull is shown in Fig. 2, first on the original (a), second on the replica made from 18 kt gold (b). The qualitative comparison of the two with the naked eye revealed a very good match of the structural elements (*crista frontalis, foramen coecum, ala cristae galli, impressio digitata, crista galli, foramina laminae cribrosae and sutura sphenoethmoidalis*; Fig. 2c).

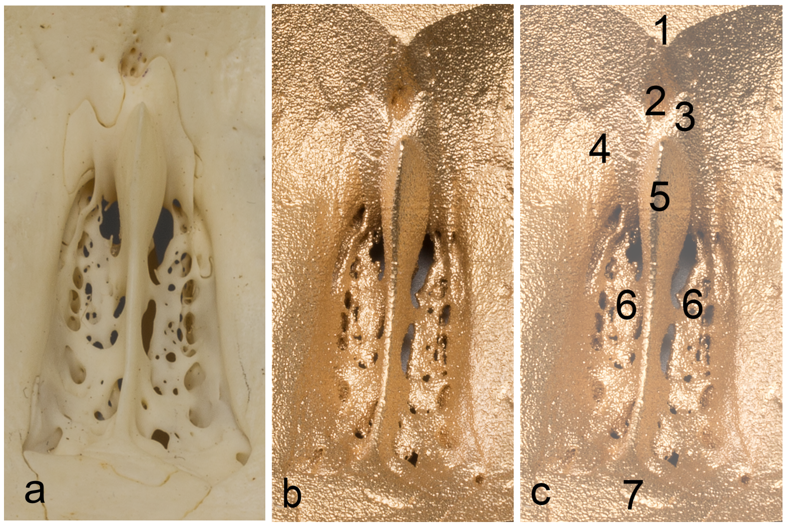

Fig. 2 Region of the *lamina cribrosa* on the original skull (a) and as a replica in 18 kt gold (b). Note the good qualitative match of the anatomic structures (c).
1 Crista frontalis, 2 Foramen coecum, 3 Ala cristae galli, 4 Impressio digitata, 5 Crista galli, 6 Foramina laminae cribrosae, 7 Sutura sphenoethmoidalis.

The quantitative comparison of the replica with the original revealed the following deviations, based on the surface scanning approach: average deviation 53.1 µm, standard deviation 123.5 µm, root mean square estimate 134.4 µm, maximum deviation 0.5000 mm. These results are represented colour-coded in Fig. 3.

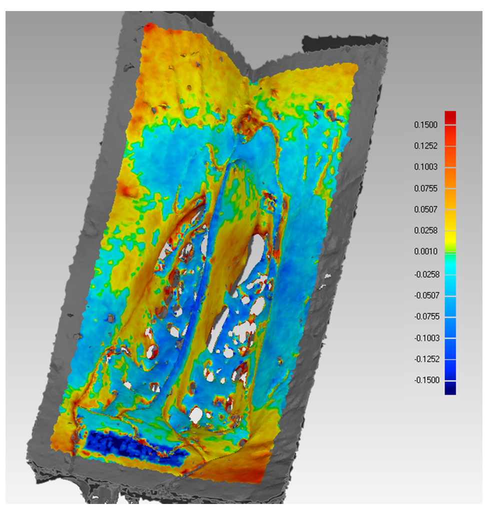

Fig. 3 Colour-coded deviation analysis of the replica compared with the original (in mm), based on optical surface scanning. The deviations are well into the submillimeter range; more than 95% of the surface is below 0.150 mm.

The neutron tomography-based comparison also showed high conformity of the gold replica and the original bone. The histogram of the deviations revealed a narrow Gaussian distribution with a median value of 61.7 µm (Fig. 4). The deviation of 85.8% of the sample surface was less than 100 µm compared with the reference, and 95% of its surface showed deviations of less than 136 µm (Fig. 5). The maximum deviation was 0.499 mm (Fig. 6).

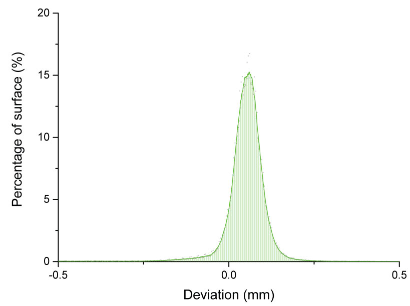

Fig. 4 Histogram of the differences (in mm) between the gold replica and the reference object based on the neutron tomography approach. The deviations occur in a narrow Gaussian distribution with a median value of 0.0617 mm.

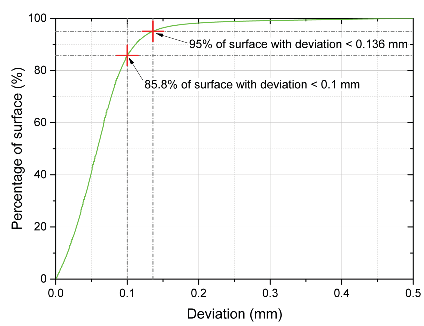

Fig. 5 Cumulative curve of the gold replica‘s deviation from the authentic cribriform plate based on neutron tomography. The graph indicates that 85.8% of the sample surface show a difference of less than 0.100 mm, and 95% less than 0.136 mm.

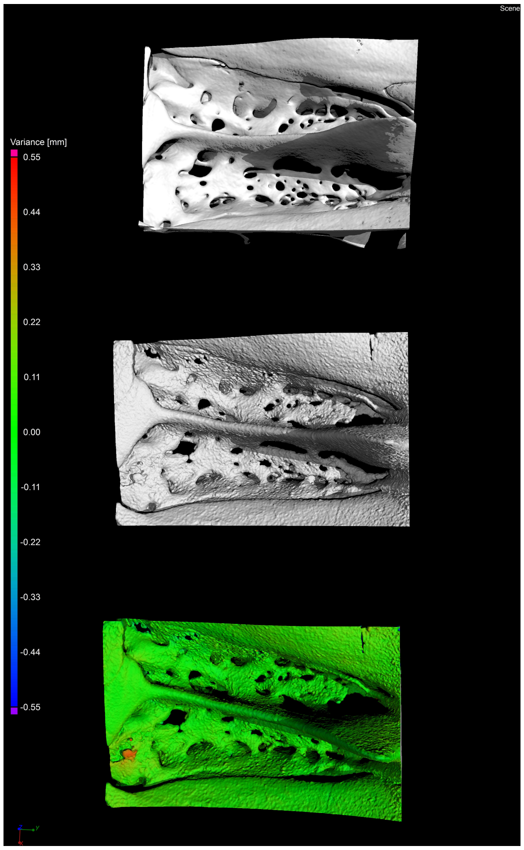

Fig. 6 Colour-coded comparison (bottom) of the gold replica (middle) and the original bone (top) based on the neutron tomography approach. The majority of the differences are within a band of ±0.100 mm (green) from the reference.

Discussion

Graspable models of the human skull and parts of it, obtained through additive manufacturing, are being met with increased interest in surgery [9-12]. One of the areas particularly difficult to replicate is the region of the cribriform plate of the ethmoid bone [13], owing to its complex shape. This region was therefore the focus of investigation for this study, to establish the limits of 3D printing in gold on one of the most demanding parts of the human skull. Figure 2 documents that a very good qualitative match may be achieved between replica and original. All anatomic structures, even the *foramina laminae cribrosae* and the *sutura sphenoethmoidalis*, were reproduced correctly. This result is in stark contrast to the models of the human skull currently on the market, in which only approximate reproductions of the *lamina cribrosa* are presented.

The qualitative observations are confirmed by the quantitative results determined in this study: the dimensional deviation of the gold replica from the original was less than 0.1 mm on average. Ninety-five percent of the surface showed a deviation of less than 0.14 mm, while the maximum deviation did not exceed 0.5 mm.

The region of interest was investigated with two independent methods: white light surface scanning and high resolution neutron tomography with cold neutrons. The fact that both techniques gave converging results increases the credibility of the finding, on the one hand, and allowed the following conclusion to be drawn with respect to future investigations, on the other hand: neutron tomography is the method of choice for analysing the internal structure of metallic components, because X-rays are generally more greatly attenuated than neutrons and therefore provide less information about the internal structure of the sample [14]. If, however, the surfaces of items in gold are to be investigated, whose wall thickness cannot be penetrated even with neutrons, surface scanning may be recommended as a valid investigative method.

Conclusions

This study shows that cutting-edge additive manufacturing technologies enable even such a complex area as the human *lamina cribrosa ossis ethmoidalis* to be replicated in gold with high anatomic accuracy, where the accuracy of deviations from the original is defined well in the submillimeter range. Optical surface scanning can be recommended as a method for future comparative studies.

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