Comparing the Use of 3D Photogrammetry and Computed Tomography in Assessing the Severity of Single-Suture Nonsyndromic Craniosynostosis

La comparaison de la photogrammétrie tridimensionnelle et de la tomodensitométrie pour évaluer la gravité d'une craniosténose non syndromique simple

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Abstract

Purpose: Single-suture nonsyndromic craniosynostosis is diagnosed using clinical assessment and computed tomography (CT). With increasing awareness of the associated risks of radiation exposure, the use of CT is particularly concerning in patients with craniosynostosis since they are exposed at a younger age and more frequently than the average child. Three-dimensional (3D) photogrammetry is advantageous—it involves no radiation, is conveniently obtainable within clinic, and does not require general anaesthesia. This study aims to assess how 3D photogrammetry compares to CT in the assessment of craniosynostosis severity, to quantify surgical outcomes, and analyze the validity of 3D photogrammetry in craniosynostosis. **Methods:** Computed tomography images and 3D photographs of patients who underwent craniosynostosis surgery were assessed and aligned to best fit. The intervening area between the CT and 3D photogrammetry curves at the supraorbital bar (bandeau) level in axial view was calculated. Statistical analysis was performed using Student *t* test. Ninety-five percent confidence intervals were determined and equivalence margins were applied. **Results:** In total, 41 pairs of CTs and 3D photographs were analyzed. The 95% confidence interval was 198.16 to 264.18 mm² and the mean was 231.17 mm². When comparisons were made in the same bandeau region omitting the temporalis muscle, the 95% confidence interval was 108.94 to 147.38 mm², and the mean was 128.16 mm². Although statistically significant difference between the modalities was found, they can be attributable to the dampening effect of soft tissue. **Conclusion:** Within certain error margins, 3D photogrammetry is comparable to CT in assessing the severity of single-suture nonsyndromic craniosynostosis. However, a dampening effect can be attributable to the soft tissue. Three-dimensional photogrammetry may be more applicable for severe cases of craniosynostosis but not milder deformity. It may also be beneficial for assessing the overall appearance and aesthetics but not for determining underlying bony severity.

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Résumé

Objectif : La craniosténose non syndromique simple est diagnostiquée par une évaluation clinique et une tomodensitométrie. Étant donné la plus grande sensibilisation aux risques d'exposition aux radiations, la tomodensitométrie est particulièrement inquiétante chez les patients ayant une craniosténose, qui y sont exposés plus jeunes et plus souvent que les enfants moyens. La photogrammétrie tridimensionnelle (3D) est avantageuse : elle ne nécessite ni radiation ni anesthésie générale et est facile à obtenir en clinique. La présente étude vise à comparer la photogrammétrie 3D à la tomodensitométrie pour évaluer la gravité de la craniosténose, quantifier les résultats de l'opération et analyser la validité de la photogrammétrie 3D en cas de craniosténose.

Méthodologie : Les chercheurs ont évalué et mesuré les images tomodensitométriques et les photos 3D des patients qui ont subi une opération de craniosténose pour en déterminer le meilleur ajustement. Ils ont calculé la zone conjointe entre les courbes de tomodensitométrie et de photogrammétrie 3D au niveau de la ligne (bandeau) sus-orbitaire en vue axiale. Ils ont effectué une analyse statistique à l'aide du test de Student, déterminé les intervalles de confiance à 95 % et appliqué les marges d'équivalence.

Résultats : Au total, 41 paires d'images tomodensitométriques et de photos 3D ont été analysées. L'intervalle de confiance à 95 % était de 198,16 mm² à 264,18 mm² et la moyenne, de 231,17 mm². Si l'on comparait la même zone de bandeau en excluant le muscle temporal, l'intervalle de confiance à 95 % se situait entre 108,94 mm² et 147,38 mm², et la moyenne était de 128,16 mm². La différence statistiquement significative observée entre les modalités pourrait être attribuable à l'effet modérateur des tissus mous. **Conclusion :** Sous réserve de certaines marges d'erreur, la photogrammétrie 3D est comparable à la tomodensitométrie pour évaluer la gravité de la craniosténose non syndromique simple. Cependant, un effet modérateur peut être attribuable aux tissus mous. La photogrammétrie 3D s'applique peut-être mieux aux cas graves de craniosténose qu'aux anomalies plus bénignes. Elle peut également être bénéfique pour évaluer l'esthétisme global, mais non pour déterminer la gravité des déformations osseuses sous-jacentes.

Keywords

craniosynostosis, 3D photogrammetry, computed tomography, single-suture, nonsyndromic

Introduction

Craniosynostosis is a condition where premature closure of cranial vault sutures leads to suture-specific deformity of the cranial vault and cranial base. It is traditionally diagnosed with clinical assessment and confirmed using computed tomography (CT) scan of the skull. The treatment is complex and requires surgical intervention for correction, at 3 to 12 months of age. Computed tomography imaging is well established for assessing the premature fusion of cranial sutures. Recently, there has been increased public awareness of risks associated with radiation exposure due to CT scans such as development of leukemia and malignant tumours.¹⁻⁴ It is particularly concerning in the craniosynostosis population, as the patients receive this exposure at a younger age and more frequently than the average child. Children in general are at greater risk than adults to the negative effects of radiation exposure since they have greater organ sensitivity and have a larger number of projected remaining life years during which pathology can develop.

Over the last several years, there has been growing interest and continued technological advancement in three-dimensional (3D) photogrammetry as an imaging modality. Three-dimensional photogrammetry is rapid, easy to apply, noninvasive, and does not require an additional visit to the hospital (ie, it can be performed on the same day as the clinic appointment; Figure 1). With recent CT data methods in the literature to objectively quantitate the severity of the craniosynostosis and degree of correction,^{5,6} 3D photos may be considered as a

possible substitution for CT data to quantify results. Some studies have assessed the use of 3D photography in craniosynostosis alone, comparing various 3D photography imaging systems to each other or comparing 3D photogrammetry to direct anthropometry.⁷⁻⁹ This study compared 3D photogrammetry to CT imaging, considered to be the gold standard. This makes it particularly applicable to the current need to objectively assess craniosynostosis without subjecting this paediatric population to unnecessary additional radiation exposure. The purpose of this study is 2-fold—(1) to assess how 3D photogrammetry compares to CT in the quantitative assessment of craniosynostosis and (2) to assess whether 3D photogrammetry is equivalent to CT data in quantifying surgical outcomes.

Research Design and Methods

This was a research ethics board-approved study. All paediatric patients who had single-suture nonsyndromic craniosynostosis assessment and treatment by 2 experienced paediatric craniofacial surgeons at The Hospital for Sick Children, Toronto, between 2004 and 2012 were considered for the study. The patients' demographic information, CT head imaging, and 3D photographs were collected from the hospital electronic medical records, the hospital picture archiving and communication systems (PACS), and the 3D photogrammetry studio, respectively.

The inclusion criteria included all patients with single-suture nonsyndromic craniosynostosis who were assessed and

Figure 1. Demonstration of three-dimensional (3D) photogrammetry images anterior view of 2 patients with craniosynostosis.

treated at The Hospital for Sick Children. The exclusion criteria excluded any patient who did not have CT imaging performed, who did not have 3D photographs taken, and/or patients who had poor quality or incomplete CT images. These latter were usually obtained from outside hospitals and transferred on a compact disc (CD).

Data were collected retrospectively. The 3D photographs were taken using the 3dMDface System (Atlanta, California) by a specially trained technician, resulting in a 3D external surface description of all patients' heads data sets ($n = 41$). The bony tissue was segmented in the CT images, which were obtained from The Hospital for Sick Children Radiology Department or from outside CDs loaded into the PACS in Digital Imaging and Communications in Medicine format. These were then used to generate 3D computer images of the patient skulls using the multipurpose software program Mimics (Materialise, Leuven, Belgium).

After collecting 3D photographs and CT skull images for all patients included in the study, each preoperative 3D photograph was paired to the corresponding preoperative CT skull model for the same patient. The same process was performed to match the postoperative 3D photographs to their corresponding CT models. As a result, of the total 41 patient data sets, some sets were obtained from the same patient but are an independent data set given that one is taken preoperatively and another is taken postoperatively.

Even though the surface used to obtain the curvatures of 3D images is theoretically comparable to CT soft tissue rather than CT bone, it was decided to compare it to CT bone as this is the window use by most craniofacial surgeons in assessing craniosynostosis. Thus, in comparing the 3D photographs to what is considered the gold standard, we would be able to best assess validity and feasibility of using 3D photogrammetry. Furthermore, it was originally hypothesized that the layer of soft tissue overlying skull would either be thin enough to be insignificant or can be accounted for in the third step explained below where the temporalis muscle is excluded from each side.

The initial step was to register and align (to best fit) the 2 different imaging modalities (CT and 3D photographs) in all orientation planes in the coordinate frame—axial, sagittal, and

coronal (Figure 2). The Mimics software program was used for this purpose. The second step was to extract the bandeau-level (just above the supraorbital rim) curves for both CT-derived skull model and 3D photograph (Figure 3). This was achieved by passing a cross-sectional plane at the level of the supraorbital bar in the axial orientation through both CT skull model and 3D photograph and then taking the overlying curvature that resulted from the intersection of this plane and the 2 models. The supraorbital bar was selected in order to obtain the axial curvature at the same standardized level for each patient and for each imaging modality. The third step involved setting lateral limits to exclude temporalis muscles from each side (Figure 4). This was done to eliminate excessive soft tissue bulk and to focus on the skull shape. The zygomatico-frontal suture was used as the landmark, and lateral limits were set on each side for excluding the temporalis muscle. The fourth step was calculation of the area contained within the 2 curves—extracted from the CT skull model and the 3D photograph for each patient—to determine the “area under the curve” (AUC; the shaded green area shown in Figure 5). Computer-aided design (Mimics, Materialise, Leuven, Belgium and Matlab by Mathworks, MA, USA) software was utilized to calculate the AUC, defined as the surface area bordered by the 3D photograph curvature and the CT-derived curvature of the frontal bandeau. Area calculations were performed both with and without the underlying soft tissue (ie, temporalis muscle).

Statistics

Student *t* test was used to perform an equivalence study. An error margin was applied and a confidence interval of 95% was set. The error margin was set at 51.1 mm^2 , calculated as 10% AUC change of the *least* severe case. This was determined by experts consensus in paediatric craniofacial surgery as the amount of deviation from the ideal shape (based on the template) to be considered clinically acceptable.

Results

The demographics of each patient data set (pairs of 3D photographs with their associated CT skull) were collected. The types of craniosynostosis included 18 metopic, 19 unicoronal, 4 multiple suture (frontal sphenoidal, bicoronal and metopic, and bicoronal) craniosynostosis (Table 1). The age of patients ranged from 8.4 to 21.1 months. Eighteen sets of imaging were taken preoperatively and 23 were taken postoperatively.

Both CT and 3D photogrammetry documented the morphology of single-suture nonsyndromic craniosynostosis. The AUC represents the difference between the head shape deformity between the curvature of the supraorbital bandeau on the 3D photograph and on the CT skull. This calculation provided a quantitative measure to compare the 2 modalities in assessing severity of patients with craniosynostosis. The 95% confidence interval for the AUC was 108.94 to 147.38 mm^2 . The mean AUC was 128.16 mm^2 . Equivalence was not established with the set error margin of 51.1 mm^2 (Figure 6).

Figure 2. The images from the patient's computed tomography (CT) skull and three-dimensional (3D) photographs were superimposed onto each other and aligned to best fit in the axial, coronal, and sagittal planes using the Mimics software program.

Figure 3. The level where the axial curvature was taken was at the supraorbital bandeau demonstrated from frontal and bird's eye views of the three-dimensional (3D) reconstruction of a computed tomography (CT) skull. The curvature obtained at this level for the 3D photograph (purple line) is compared to the curve of the CT skull (blue outline). The area under the curve (AUC) was then calculated as the space between the purple curve and the blue curve.

Figure 4. The lateral limits were set to exclude temporalis muscles from each side in order to eliminate excessive soft tissue bulk and to focus on the skull shape pertinent to the craniosynostosis skull deformity.

In order to further assess this soft tissue dampening effect, a small sample of patient sets was selected ($n = 5$), and the CT-derived skull (bony tissue) and soft tissue models for each patient, from the same CT acquisition, were obtained and loaded in the CAD software. The AUC at the bandeau level was calculated between CT soft tissue and CT bone. The average AUC for metopic and unicoronal craniosynostosis was 170.13 mm^2 and 230.92 mm^2 , respectively. The average AUC for both synostosis types was 194.45 mm^2 . The authors of this article plan to gather a larger sample size in order to further investigate this soft tissue dampening effect in a full study.

Figure 5. The shaded green area represents the calculated area under the curve (AUC) between the curvature of the three-dimensional (3D) photograph curve and the computed tomography (CT) skull curve.

Discussion

Changes in practice are usually difficult to implement, especially in the field of paediatrics. Paediatric craniofacial surgeons traditionally diagnose craniosynostosis using clinical assessment and CT imaging. This very reliable method has been used for an extensive number of years. However, when new research findings present results showing possible disadvantages and dangers of our current clinical practices, a need arises to develop new methods to diagnose and treat patients with less risk involved. The question that emerges with any new technology is whether it is as good as, if not better than, its older gold-standard counterpart, thereby prompting scientific discussion and research to compare modalities. Three-dimensional photography is relatively young compared to its older and more reliable CT counterpart. However, the technology is advancing rapidly and 3D photogrammetry is showing its usefulness and applicability in a multitude of manners. One major caveat is that 3D photographs are unable to give direct visualization neither of cranial vault sutures nor of the brain itself. In situations where an atypical or more challenging presentation of craniosynostosis arises and clinical assessment of head shape cannot reliably provide the diagnosis of which suture is fused, CT scans are able to give direct visualization of the suture that is fused. Furthermore, when there is concern for increased intracranial pressure or a cerebrospinal fluid leak postoperatively, CT scans are able to provide information to confirm or deny the suspicion while showing the exact appearance of the cranial vault osteotomies and their newly placed positions postoperatively. At present, surgeons may feel that 3D photogrammetry is inadequate in presurgical planning and may not feel comfortable taking a patient to surgery based solely on 3D photography. Additionally, concerns of litigation may also be an issue, as 3D photography has not been established as a “standard of care” yet. This being said, the modality of 3D photogrammetry is showing great promise for the future.

There were several limitations to this study. This was a retrospective study with a small sample size. Furthermore, during the alignment of the 3D photographs with the CT skull images to best fit, there is an aspect of subjectivity even though

Table 1. Demographics of Patient Data Sets.^a

Patient Data Set	Type of Synostosis	Age at Time of Surgery, Months	Timing From Surgery
1	Metopic	9.6	Preoperative
2	Metopic	15.5	Preoperative
3	Metopic	8.9	Postoperative
4	Metopic	11.1	Preoperative
5	Metopic	8.7	Preoperative
6	Metopic	8.7	Postoperative
7	Right unicoronal	10.7	Preoperative
8	Left unicoronal	21.1	Preoperative
9	Right unicoronal	12.2	Preoperative
10	Left unicoronal	11.5	Preoperative
11	Left unicoronal	9.8	Preoperative
12	Right frontal sphenoidal	10.4	Preoperative
13	Right frontal sphenoidal	10.4	Postoperative
14	Bicoronal and metopic synostosis	10.1	Preoperative
15	Bicoronal and metopic synostosis	10.1	Postoperative
16	Metopic	12.0	Preoperative
17	Metopic	12.0	Postoperative
18	Metopic	13.3	Preoperative
19	Metopic	13.3	Postoperative
20	Metopic	10.0	Postoperative
21	Metopic	10.4	Postoperative
22	Metopic	10.8	Postoperative
23	Metopic	10.4	Postoperative
24	Metopic	9.6	Postoperative
25	Metopic	11.2	Postoperative
26	Metopic	8.4	Postoperative
27	Metopic	9.1	Postoperative
28	Left unicoronal	10.6	Preoperative
29	Left unicoronal	10.6	Postoperative
30	Right unicoronal	10.7	Preoperative
31	Right unicoronal	10.7	Postoperative
32	Right unicoronal	9.7	Postoperative
33	Right unicoronal	8.6	Preoperative
34	Right unicoronal	8.6	Postoperative
35	Right unicoronal	10.6	Preoperative
36	Right unicoronal	10.6	Postoperative
37	Right unicoronal	10.6	Preoperative
38	Right unicoronal	10.6	Postoperative
39	Right unicoronal	8.8	Postoperative
40	Left unicoronal	9.6	Postoperative
41	Right unicoronal	10.7	Postoperative

Abbreviations: CT, computed tomography; 3D, three-dimensional.

^aPairs of 3D photographs with their associated CT skull.

a small scale grid was used and consensus between 2 reviewers was required to accept an alignment. Comparing the 3D photographs that use the surface of the soft tissues with the CT skull which is the surface area of the bone is not the most direct comparison. However, the authors chose not to compare the 3D photographs with CT soft tissue because most craniofacial surgeons currently look at the CT bone rather than the CT soft tissue when they obtain a CT on their patients with craniosynostosis. Thus, in comparing the 3D photograph with the CT imaging considered to be the gold standard, it is most

Figure 6. In order to determine equivalence, the 95% confidence interval should straddle the error margin represented by H_0 . The H_0 was determined to be 51.1mm². This was calculated as 10% area under the curve change of the *least* severe case determined by experts consensus in paediatric craniofacial surgery as the amount of deviation from the ideal shape (based on the template) to be considered clinically acceptable. Equivalence was not demonstrated but can be accounted for by the soft tissue dampening effect.

applicable in determining whether equivalence exists. Comparing 3D photographs with CT soft tissue may be a more direct comparison but would not be relevant to current clinical practice. It was suspected that a dampening effect of soft tissue would be a contributing factor in 3D photographs but not in CT bone. This phenomenon can be seen intraoperatively for a metopic craniosynostosis remodeling case.⁶ When the patient is lying supine on the operating table and a bird's eye view is adopted, the deformity is visible and a prefabricated template of a normative bandeau shape⁵ placed over the supraorbital bar shows the AUC required for correction to a more "normal" appearing skull shape. However, when the soft tissue has been stripped away, and the same prefabricated template is placed over the supraorbital bar area, the AUC is larger. Finally, there are limitations that are inherent to 3D photographs. In the paediatric population, patients are generally sedated with the assistance of anaesthesiologists during CT scanning. In contrast, when 3D photographs are obtained, paediatric patients are usually awake, expressive, and mobile. Slight variations such as the position of thin fabric toque placed over the head, the amount of hair the patient has (which varies with age and gender), whether the child is crying or has a neutral facial expression, or the presence of postoperative swelling can all affect the curvature of the 3D photograph but will not affect the CT bony image.

Despite these limitations in this study, the advantages of 3D photogrammetry still remain. An imaging modality that involves no radiation, is conveniently obtainable within clinic, and does not require general anaesthesia still has significant potential to alleviate the disadvantages associated with CT scans. However, with considerations of the soft tissue dampening effect and nonequivalence of 3D photogrammetry and CT

scans of the skull in this patient population, 3D photographs may need to be reserved for more severe cases of craniosynostosis but not milder deformity.

Conclusion

Cranial shape evaluation via 3D photogrammetry is comparable to CT scanning but not equivalent. It is important to account for the dampening effect of soft tissue overlay on the underlying bony contour when using 3D photogrammetry. The use of 3D photographs may be useful for assessing craniosynostosis for severe deformities but not for mild deformities. It may also be beneficial for assessing the overall appearance and aesthetics but not for determining underlying bony severity at the present time.

Declaration of Conflicting Interests

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