Low-Cost Smartphone-Based Photogrammetry for the Analysis of Cranial Deformation in Infants

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■ BACKGROUND: **Cranial deformation, including deformational plagiocephaly, brachycephaly, and craniosynostosis, is a condition that affects a large number of infants. Despite its prevalence, there are no standards for the systematic evaluation of the cranial deformation. Usually, the deformation is measured manually by the use of calipers. Experts, however, do not agree on the suitability of these measurements to correctly represent the deformation. Other methodologies for evaluation include 3-dimensional (3D) photography and radiologic scanners. These techniques require either patient's sedation and ionizing radiation or high investment. The aim of this study is to develop a novel, low-cost, and minimally invasive methodology to correctly evaluate the cranial deformation using 3D imagery.**

■ METHODS: **A smart phone was used to record a slow motion video sequence on 5 different patients. Then, the videos were processed to create accurate 3D models of the patients' head, and the results were compared with the measurements obtained by the manual caliper.**

■ RESULTS: **The correspondence between the manual and the photogrammetric 3D model measurements was high as far as head marks are available, with differences of 2 mm ± 0.9 mm; without marks, measurement results differed up to 20 mm.**

■ CONCLUSIONS: **Smartphone-based photogrammetry is a low-cost, highly useful methodology to evaluate cranial deformation. This technique provides a much larger quantity of information than linear measurements with a similar accuracy as far as head marks exist. In addition, a new approach for the evaluation is pointed out: the comparison between the head 3D model and an ideal head, represented by a 3-axis ellipsoid.**

Key words
- 3D modeling
- 3D photography
- Brachycephaly
- Plagiocephaly
- Slow-motion video

Abbreviations and Acronyms
3D: 3-dimensional
CT: Computed tomography
DP: Deformational plagiocephaly
RMSE: Root mean square error
SLR: Single-lens reflex

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INTRODUCTION

Cranial deformation is one of the most common problems in pediatric neurosurgery. Although most cases are related to positional deformations, true craniosynostosis is always a concern and has to be ruled out based on clinical assessment. Radiologic studies may be obtained either in patients in whom physical examination cannot confidently establish a diagnosis or when surgical treatment is taken into consideration.

Deformational plagiocephaly and brachycephaly have become common problems that can affect, according to some investigations, up to 48% of newborns.[1] This problem has greatly increased since 1992 as a consequence of the recommendation of a supine sleep position to prevent infant death syndrome.[2] Deformational plagiocephaly is an asymmetry of the skull that appears at birth or shortly after, and it is believed to be caused by extrinsic forces on the infant's malleable cranium.[3] This lack of symmetry usually is caused by supine sleeping and the preference to turn the head to one side, in many cases due to torticollis.[2] Other factors, however, such as intrauterine constraints or birth trauma also are known causes.[4] Positional brachycephaly typically consists of a symmetrical occipital flattening with a compensatory parietal widening. It usually is caused by the supine positioning while sleeping when there is not a preferred turning side.[4] In most cases, cranial deformation is associated only with cosmetic problems, although severe cases may involve a greater risk of strabismus, mandibular, auditory problems,[5] and even hindbrain herniation.[6]

Therapies for deformational plagiocephaly (DP) and brachycephaly include active repositioning, physiotherapy, and in some cases the use of orthotic helmets.[2,4,7] The effectiveness of many of these therapies, however, is a topic of discussion among experts.[8,9] The correct evaluation of the treatments requires durable, reproducible, and rapid methods to quantify asymmetry.[9,10]

At present, there are no standards for diagnosing and monitoring DP. Instead, multiple ways to measure deformation have been developed by different authors, including visual assessment/clinical classification, anthropometric caliper measurements, flexicurve, plagiocephalometry/molding devices, 3-dimensional (3D) photography, and radiologic imaging.[4]

In contrast, craniosynostosis is a much less common cause of cranial deformation than positional plagiocephaly or brachycephaly. The global prevalence of craniosynostosis ranges from 3.1 to 6.4 in 10,000 live births.[11,12] In infants with craniosynostosis, the premature fusion of one or more cranial sutures results in a distorted head shape and the risk of increased pressure. Most cases require surgical correction, and computed tomography (CT) scans usually are required before and after the surgery. These scans involve an important dose of radiation on infants, which may elevate the risk of malignant tumor development.[13]

3D photography has important advantages over other methods to evaluate cranial deformation. It allows experts to measure angles and surfaces, the results are independent from the examiner, the marks are selected on a static surface, and the measurements can be repeated and archived.[2] Moreover, it can be used to measure every type of cranial deformation.[13]

Some 3D products currently are being used,[2] but the cost of the equipment is still high. Moreover, this methodology is focused on the extraction of the 3D models, but it does not include the posterior evaluation of the deformation.

At present, the advances in 3D techniques allow users to create accurate 3D models using nonspecific technology such as consumer-grade cameras, single-lens reflex (SLR) cameras, video cameras, or even smart phones. This methodology can be undertaken with very low investment, depending on the camera, large/medium/small/mini frame camera, ultra-high/high speed video camera, etc. Without a doubt, image-based 3D photography is a low-cost approach compared with other highly sophisticated 3D measurement techniques such as active laser scanning and CT.

In the postprocessing step, 3D models allow a much more complex asymmetry evaluation than clinical examination. 3D cranial models can be fitted into geometrical models representing a so-called ideal cranial shape, such as an ellipsoid. Using this methodology, it is possible to evaluate the deformation in terms of the well-known root mean square error (RMSE). The RMSE already has been used by some authors to calculate the differences in shape and volume between 2 surfaces. These authors used RMSE to evaluate asymmetry by superposing left and right side of the head and calculating differences between them. Although the estimation of cranial volume with the assumption that it fits an ellipsoid dates back to the 1950s, as pointed out by several studies[14,15] reported by Manjunath,[16] no studies have focused in comparing the true cranial shape with an ideal mathematical model such as an ellipsoid. The aim of this study is to extend the diagnosis of cranial deformation by 3D modeling via the use of simple, automatic, low-cost, and minimally invasive techniques.

METHODOLOGY

The evaluation of the cranial deformation of patients was carried out with the use of different methodologies. First, the deformation measures were taken by a pediatric neurosurgeon during a medical consultation using a caliper. Afterwards, a 3D cranial model was created via the use of image-based 3D modeling, namely photogrammetry, the science and technology of extracting measurements from photographs. The 3D model was analyzed to measure the cranial deformation with both traditional clinical measurements (matching the measurements taken with the caliper) and automatic 3D image-based methodologies (**Figure 1**).

Planning

Photography sessions with infants create several problems that can be solved with a suitable setup and session planning. Infants (in the range of 3–8 months) are very active during medical consultations, and it is extremely difficult to keep them calm during the image survey. Imagery acquisition with the use of conventional cameras usually results in poorly focused images as the result of movement; however, the use of anesthesia to put the patient to sleep is a highly invasive methodology and is avoided.

Lighting conditions do need to be specifically set up for the image acquisition process in case normal indoor illumination is not enough. On the one hand, for digital photography in the patient examination room, additional lighting in the form of halogen (or better LED) lamps is required to guarantee low ISO values on the camera systems with our digital SLR camera (Canon EOS 1 Ds Mark III; Canon, Tokyo, Japan). On the other hand, the use of videos, and specifically, slow-motion videos (Samsung S7 Edge smart phone; Samsung, Seoul, South Korea) was found to be a good alternative to obtain high-resolution, well-focused images even with movement. Neither special lighting lamps nor photographic devices such as tripods were required. In addition, it was found to be a quick method compared with taking pictures with an SLR camera.

A second problem is posed by the movement, specifically, the head and the background changing position in relation to each other. This issue can be solved by using a setup of multiple synchronized cameras that take images at the same exact moment, each one from a different location around the head. This setup works well for moving targets; however, it is expensive and complex. The preprocessing step of creating digital masks can solve this problem in a simpler way, making use of just one camera. A mask delimitates the area of the image that will be used for the 3D modeling and the background is, therefore, excluded. Manual masking is a time-consuming process, but it can be automated to some extent. To avoid the effect of the hair on the quality of the model, a cap was used. Targets were placed on the cap to improve the quality of the model and facilitate its creation with well-defined marks.