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Smartphone-based photogrammetric 3D modelling assessment by comparison with radiological medical imaging for cranial deformation analysis

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Abstract

Cranial deformation in infants is a common problem in paediatric consultations. The most accurate medical diagnostic imaging methodologies are Computed Tomography (CT) and Magnetic Resonance Image (MRI). However, these radiological imaging technologies involve high costs and are invasive, especially for infants. Therefore, they are only used for severe cases, while milder cases are evaluated using less precise methodologies, such as callipers or measure tapes. The use of smartphone-based photogrammetric 3D models has been presented as a possible alternative to extracting accurate and complete external information in a low-cost, non-invasive manner but its accuracy is still to be tested. In this study, photogrammetric and radiological cranial 3D models have been obtained for a set of 10 patients. In order to compare them, the distances between model surfaces have been calculated. Results show an overestimation of the photogrammetric models up to 3.2 mm due to both hair and usage of caps. However, differences in shape, given by the standard deviation of the distances are below 1.5 mm for every patient. The accuracy of low-cost smartphone-based photogrammetric models has been found to be comparable to medical diagnostic imaging methodologies used for cranial deformation analysis.

Keywords: Computed Tomography, Evaluation, Magnetic Resonance Imaging, Structure from Motion.

1. Introduction

Medical diagnostic imaging techniques, particularly Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) are considered the “gold standard” for the collection of high-quality 3D information in medicine. These techniques have different advantages and limitations. On one hand, they are highly accurate and provide a high level of detail. On the other hand, they are invasive and expensive and CT involves an important dose of radiation. For the particular case of young infants, who would not be still during the test, the techniques are especially invasive since sedation is required.

Over the last years, photogrammetry and 3D scanning have emerged as powerful alternatives to obtain 3D models for medical purposes. These technologies are limited to the obtainment of the outer visible information but, on the other hand, they are non-invasive and, depending on the configurations and tools, photogrammetry can involve a significantly lower cost than traditional medical imaging techniques, as the equipment requirements can be reduced to a minimum (Salazar-Gamarra *et al.*, 2016; Kottner *et al.*, 2017). Traditional approaches include CT and/or MRI only for severe cases, when craniosynostosis is suspected and information on the state of bone sutures is needed as surgery is being considered. For milder cases, clinical assessment (consisting of visual evaluation and measurements taken with a calliper and measuring tape) is the common approach (Siegenthaler, 2015).

Some authors have studied the validity of models created by photogrammetry and 3D scanners in medicine. Comparison with CT/MRI has been carried out for different purposes, including different types of cranial deformation (Mendonca *et al.*, 2013; Ho *et al.*, 2017), orthodontics (Metzger *et al.*, 2013) and forensics (Kottner *et al.*, 2017), among others. Most studies involve the use of high-cost 3D camera solutions such as STARscanner (Orthomerica, Orlando, FL, USA) or 3D scanners such as 3dMD (3dMD, Atlanta, GA, USA) (Chong and Brownstein, 2010; Mendonca *et al.*, 2013; Metzger *et al.*, 2013; Beaumont *et al.*, 2017; Ho *et al.*, 2017; Meulstee *et al.*, 2017), while others include in-house solutions, such as the combination of several Single-Lens Reflex (SLR) cameras presented by Kottner (2017). The most common approach in these studies is the comparison of measurements taken on the 3D model and those taken directly on the patient. In other studies, the cranial volume is compared (McKay *et al.*, 2010). Only in some cases, model surfaces are the subject of the comparison (Kottner *et al.*, 2017) but not for cranial deformation analysis. The use of surfaces instead of single measurements provides a more complete comparison between methodologies. Moreover, the whole surface of the model provides a higher amount of information than a limited number of measurements. Different cranial deformation approaches can be used for analysis, such as ellipsoid fitting (Barbero-García *et al.*, 2017), principal components (Meulstee *et al.*, 2017) or global measurement (Skolnick *et al.*, 2015). The 3D model also allows the calculation of the cranial volume (McKay *et al.*, 2010).

Although the creation of 3D models using scanners, or setups of multiple cameras has been presented as a valid alternative, the equipment cost is high, especially for scanners and 3D cameras. As a consequence, the usage of these technologies is not common in the clinical practice and is limited to research projects. The use of a smartphone-based low-cost solution for the creation of 3D models for cranial deformation analysis has been introduced by the authors as preliminary tests (Barbero-García *et al.*, 2017). The image acquisition for this methodology is based on a slow-motion video camera, e.g. coming from a smartphone, and a fitted cap on the patient head. A slow-motion video is recorded in a small time frame during the standard medical consultation while the patient is being held by an accompanying person. Neither special lighting nor tripods are required for the data acquisition. The quality of the models was found to be comparable to that obtained using a full-frame SLR camera for the image acquisition (Lerma *et al.*, 2018).

In this study, 3D photogrammetric models are systematically compared with CT/MRI models. Image acquisition for the creation of photogrammetric 3D models is carried out using only a smartphone and a fitted special cap in real clinical conditions. Later, the models are compared with either CT or MRI data. The comparison is made, after registration of the different datasets, by computing the minimum distances between the registered photogrammetric and radiological 3D models surfaces.

The rest of the paper is structured as follows. Section 2 explains the methodology carried out for the creation of both models (radiological and photogrammetric) and the comparison between them. Section 3 presents the results, including distances between models and its significance, as well as the visualization of differences and explanation of error sources. Section 4 discusses the results with emphasis on the advantages and disadvantages of the low-cost photogrammetric solution. Finally, Section 5 draws some conclusions from the research on deformation analysis.

2. Methodology

A total of 10 patients were evaluated (2 females and 8 males). Their age varied between 1 month and 12 years, specifically 4, 5, 9 and 11 months; 1(two patients), 5, 6, 11 and 12 years. The patients were selected between those undergoing cranial CT or MRI regardless of the existence of cranial deformation to assess the performance of low-cost 3D imaging over CT/MRI. For older patients (over one year of age) long hair was considered an exclusion criterion, as it would affect the creation of the photogrammetric 3D models. The maximum data acquisition time difference between the two data collection approaches was two days; therefore, it can be stated that the data was taken in the same period of time.

For each patient a smartphone-based photogrammetric model and a radiological model (CT or MRI) was created. Fig. 1 summarises the main steps carried out for each approach, starting with data acquisition, then processing to build up the 3D models, and finally analysis and comparison after the 3D models are properly registered in the same reference system to determine the distances between them. Further details about the photogrammetric processing to create 3D models from slow-motion smartphone-based photogrammetry have been previously reported (Barbero-García *et al.*, 2017).

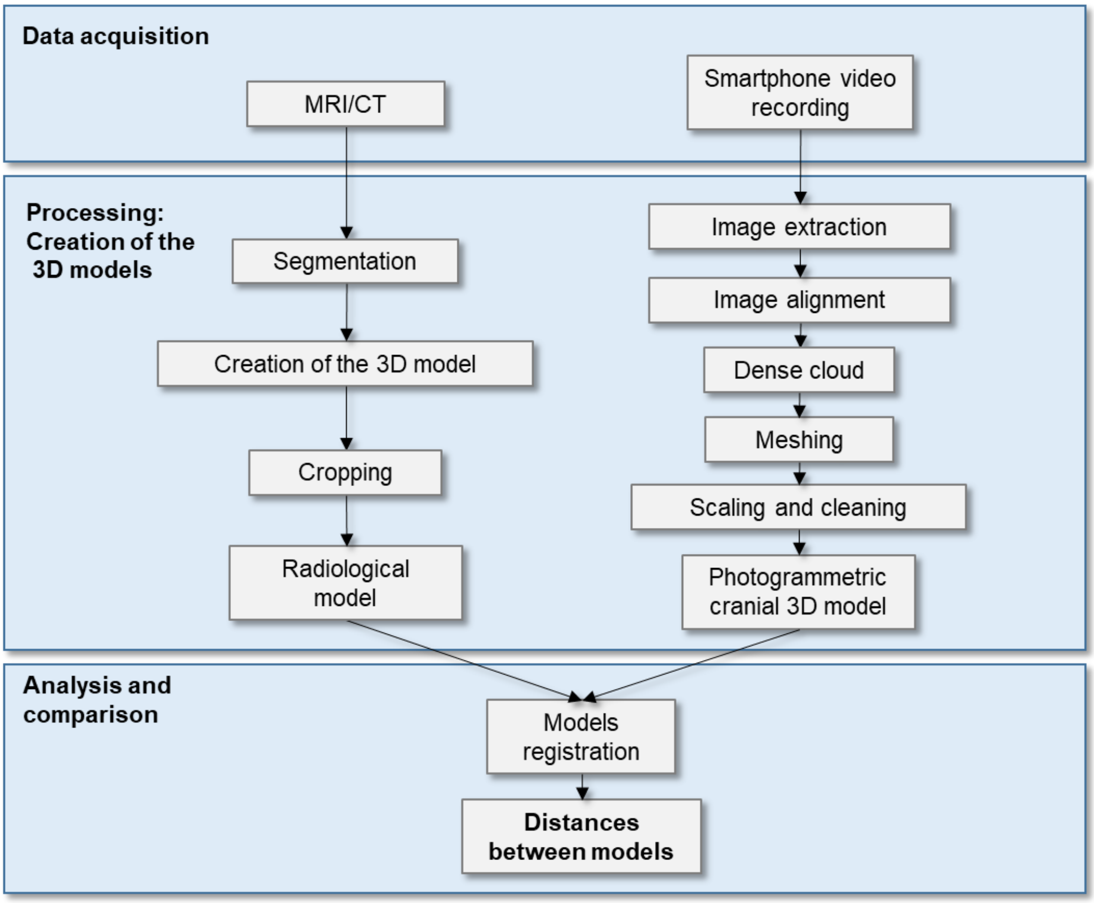


Figure 1. Flow diagram used to assess the differences between 3D models.

2.1. Radiological data processing

The cranial CT and MRI scans were performed at La Fe Hospital, Valencia, Spain. The purposes of the test varied for each patient. An important number of patients were under medical control for different types of cranial deformation (preoperative and postoperative stages). The rest of the patients suffered from different pathologies but were always studied with 3d CT or MR in their follow-up.

The data from radiological scans were provided using the Digital Imaging and Communications in Medicine (DICOM) format. The 3D model for each patient was reconstructed using the open-source software InVesalius 3.1.1 (CTI, Brazil). Incomplete models were discarded, although small uncovered areas on the top of the head were allowed. The model was manually segmented for the extraction of the skin and the output was exported to Polygon File Format (PLY). Lastly, the model was manually cleaned and cropped to ease its comparison with the photogrammetric 3D model.

2.2 Photogrammetry

The photogrammetric 3D models were carried out using two different smartphones in slow motion mode at the maximum frame rate allowed by each device: Samsung Galaxy S7 (Samsung, Seoul, South Korea) with a resolution of 1280x720 at a frame rate of 240 fps and Samsung Galaxy S5 at the same resolution and frame rate of 120 fps. The methodology developed can be found in Barbero-García et al. (2017). The video acquisition was carried out during the standard medical consultation. A fitted cap was placed on the patient’s head, it was required to avoid the effect of hair in the model and to ease the 3D reconstruction by adding texture (Fig.2).

A detailed study has been carried out to determine the smartphone performance for photogrammetric smartphone-based applications on spherical objects (Barbero-García et al., 2018). After testing two smartphones, one high-end Samsung Galaxy S7 (2017) and another Samsung Galaxy Trend Plus (2014), no special specifications were actually found as limiting factors other than high definition (HD, 1280 x 720 pixels) video and the slow-motion acquisition. In any case, recording taken in three rings with large overlap was found essential for automatic full 3D modelling without imperfections.

Image acquisition

The illumination conditions in the room were kept at a maximum to compensate for the lack of exposure of the slow motion video mode and assure the correct focusing of the mobile device. However, no special lighting was required. In case of early age patients, they were held upright by an adult. The patients were not asked to stay still, so normal movements occurred, especially in the case of younger infants. A video was recorded for each patient, lasting a maximum of 30 s. During the video recording, the operator moved around the patient’s head in three rings with the smartphone at different heights (viewpoints). This approach is based on the conclusions of previous studies carried out by the authors. Indeed, the optimal geometry of the image acquisition approach for near spherical objects (e.g. heads), using conventional, non-metric video cameras integrated in current smartphones can be found in Barbero-García et al. (2018). The whole image acquisition process required less than five minutes per patient and was carried out during a standard consultation.

Special care must be taken to conveniently cover the whole head surface in the video sequence, which can be hampered by the constant quick movements of the infants. It is worth noticing that this methodology requires the cap to be correctly fitted on the head to avoid imperfections during the eventual processing for 3D reconstruction and dense image matching.

Figure 2. Image used for the creation of the 3D model.

Processing

Firstly, the images were manually extracted from the video. Between 200 and 300 images were selected in each video file. The creation of the 3D models was carried out using PhotoScan (Agisoft, Russia). The 3D modelling process followed the usual pipeline in photogrammetric Structure-from-Motion (SfM) software, consisting of (i) Image alignment, (ii) Cloud densification, (iv) Meshing and (v) Texturing the mesh (optional, for visualisation purposes only). In case of failure, the process was completed using manually defined tie points. The model was then scaled using targets of known dimensions placed on the cap. Finally, areas outside the cap were cropped to avoid any measurements in those areas. The final 3D models obtained for each patient had between 100.000-200.000 points and 200.000-300.000 faces. The expected accuracy of the models was 1 mm (Lerma *et al.*, 2018).

A camera self-calibration was automatically done during the spatial orientation processing in the photogrammetric software as no previous camera calibration was available for each one of the sessions. Fig. 3 displays an image with the footprint of the geometric distortion pattern of the smartphone camera in one of the sessions. The self-calibration approach includes a comprehensive calibration to determine its interior orientation parameters, i.e. the principal distance, principal point offsets, radial/decentring lens distortion parameters and the affinity parameters (differential scaling and skewness). A calibration of the camera prior to the image acquisition was discarded as it would require a high amount of time and knowledge, making the methodology difficult to be applied in the clinical practice. Moreover, previous studies show that prior calibration of the camera does not have an important impact on the results for this particular application as far a large number of images are selected for the camera calibration (Barbero-García *et al.*, 2018).

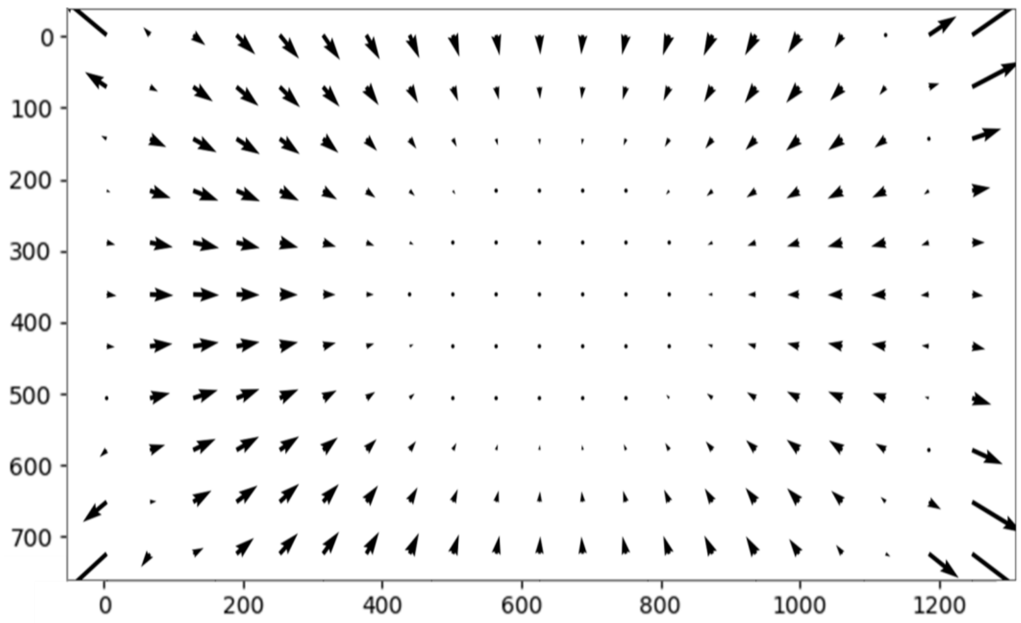


Figure 3. Calibration distortion pattern for Samsung Galaxy S5 (Scale: 2x).

Comparison

The software CloudCompare version 2.7.0 (http://cloudcompare.org/) was used to compare each pair of photogrammetric and radiological 3D models. In order to allow the comparison, the 3D models were manually registered to the same coordinate system. The registration was carried out by manual identification of cranial landmarks and posterior minimisation of the distance between models. The distance between models was computed for every point in the photogrammetric model (between 70.000 and 100.000 points) as the distance to the closest point of the radiological model. The tool "Compute cloud/mesh distance" in CloudCompare was used for this calculation, the option "signed distances" was chosen, as it is important for the evaluation; the radiological model was always used as a reference.

A small shift between two models (2 mm approx.) was expected due to the effect of the cap on top of the head pressing the hair, as pointed out by different authors (Schaaf *et al.*, 2010; Mendonca *et al.*, 2013).

3. Results

The differences between models can be found in Table 1 which contains the 10 patients ordered by age. The control radiological technique used for the comparison is specified in the fourth column with header CT/RMI. The maximum time shift between radiological imaging and photogrammetric data acquisition was less than 2 days. The average mean difference distance between pairs of models (Photogrammetry - CT/MRI) is 2.1 mm, being the minimum 0.5 mm and the maximum 3.2 mm. The standard deviation of the distance differences is constant across patients (0.7-1.4) with an average of 1.2 mm.

Table 1. Patients' information and distance difference parameters between radiological and photogrammetric models (differences in mm).

Patient number	Gender	Age (months)	CT/MRI	Time dif. (days)	Mean distance	Distance standard deviation

1	M	4.3	MRI	0.0	1.9	1.1
2	F	5.8	MRI	2.0	0.5	0.7
3	M	9.5	CT	0.0	1.5	0.7
4	F	11.1	CT	1.0	1.3	1.3
5	M	17.5	MRI	0.0	2.0	1.2
6	M	21.8	CT	0.0	2.4	1.4
7	M	70.4	CT	0.0	2.4	1.1
8	M	81.2	MRI	1.0	3.2	1.3
9	M	142.6	MRI	1.0	2.6	1.4
10	M	147.1	CT	0.0	1.1	1.4
				Average	2.1	1.2

The Student t-test was carried out for both the mean difference distance and the standard deviation. The 99% confidence interval for the mean difference distance is 1.1-2.7 mm. As for the standard deviation, the test confirms that the value is below 1.4 mm with a 99% confidence.

The mean difference distances and their standard deviations (Y axis) in relation to age (X axis) are presented in Figure 4. For patients younger than two years (n=6), the maximum difference distance is 2.4 mm and its average difference distance is 1.6 mm; this is the normal age range for cranial deformation assessment. Lower differences for this age range are possible, as hair does not affect the models.

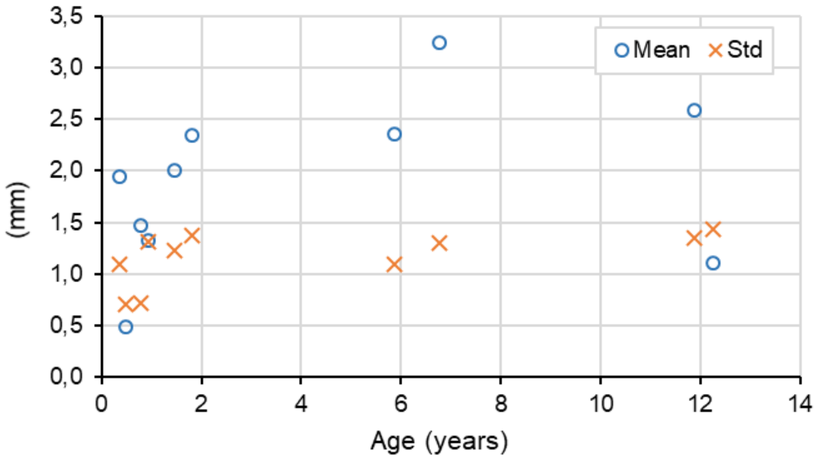
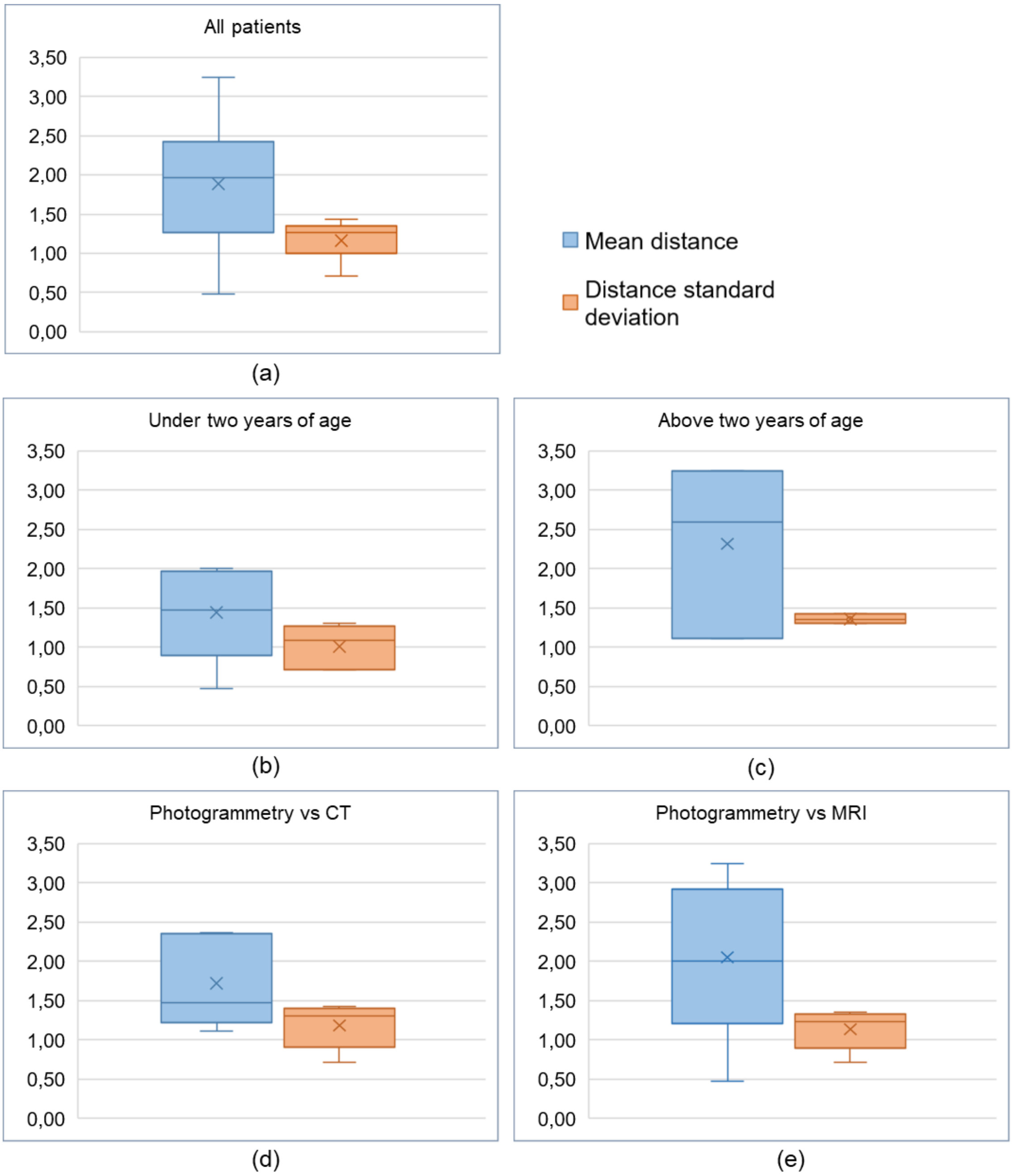


Figure 4. Mean distance differences and their standard deviations in relation to their patients’ age.

Figure 5 shows the mean distance and standard deviation for both age groups: up to two years of age (Fig.5 (b)) and above two years (Fig.5 (c)). Mean distance is considerably higher for the older patients group (Under two years: 1.6 mm, above two years: 2.3 mm). The comparison values are also shown for CT and MRI techniques separately, the mean difference is higher for MRI (MRI: 2.05 mm, CT: 1.72 mm) while the standard deviation is similar (MRI: 1.1 mm, CT: 1.2 mm).



(a)

(b) (c)

(d) (e)

Figure 5. Photogrammetry vs radiological test box-and-whisker plots showing the mean distance and the standard deviation results: a) all patients, b) under two years of age, c) older than two years, d) CT, and e) MRI.

Three-dimensional models of each patient’s head were delivered (Figs. 6 and 7). Fig. 6a,b shows the frontal and lateral views of one patient after CT, whereas Fig. 6a,c exhibits views after MRI. Colour maps were obtained for each patient showing the difference distances between 3D models delivered by CT and photogrammetry (Fig. 6c,d) and MRI and photogrammetry (Fig. 7b,d). Overall, no systematic errors were found as can be checked in Fig. 6. Areas of higher difference are located randomly around the head and particularly in the edge of the model.

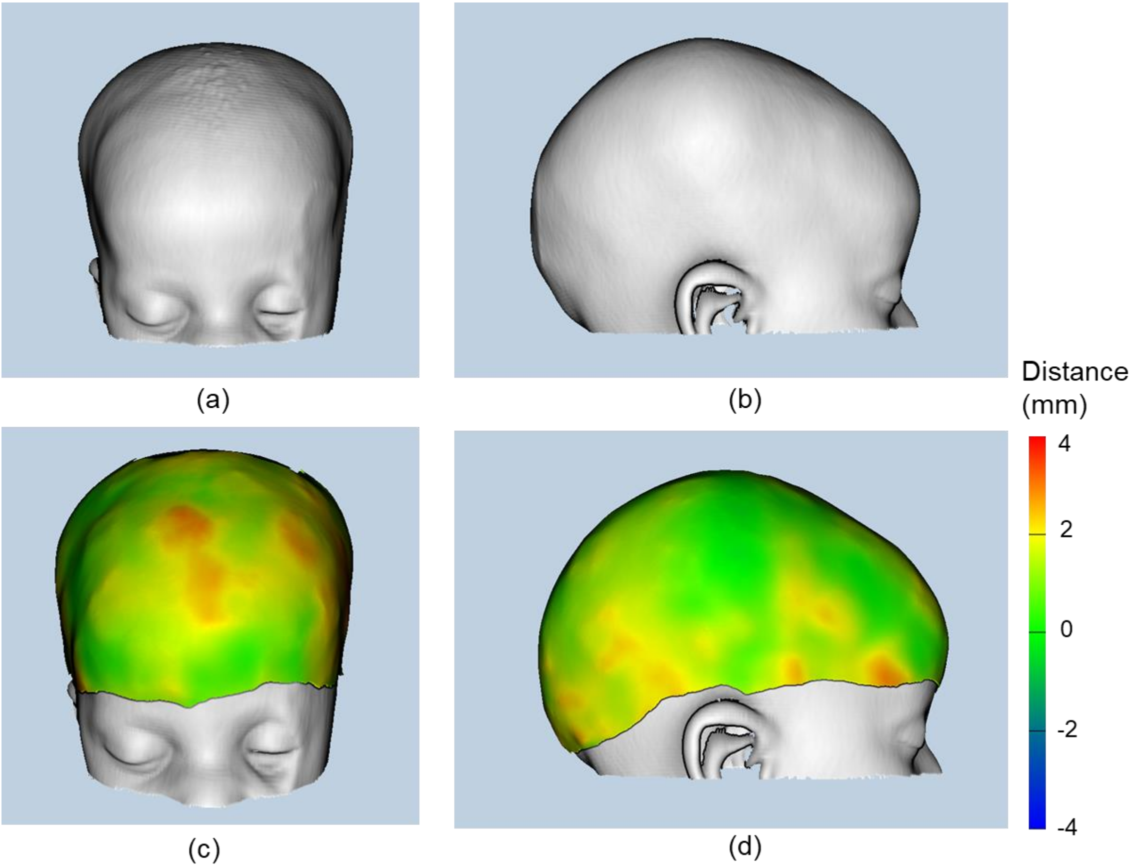


Figure 6. Derived models for the 3rd patient: a, b) CT; c, d) Difference distances in the 3D model between the photogrammetric solution and the registered CT.

The most important sources that yield a difference between radiological and photogrammetric 3D models were caused by the combined effect of the hair and the cap; and, in some cases, small inaccuracies of the photogrammetric model caused by low texture areas and edges. However, small errors were also found in some radiological 3D models (Fig.7a,b). Another source of error was given by the lying position of the patients that, in some cases, resulted in skin folds that were also detected as distance differences between models (Fig. 7c,d).

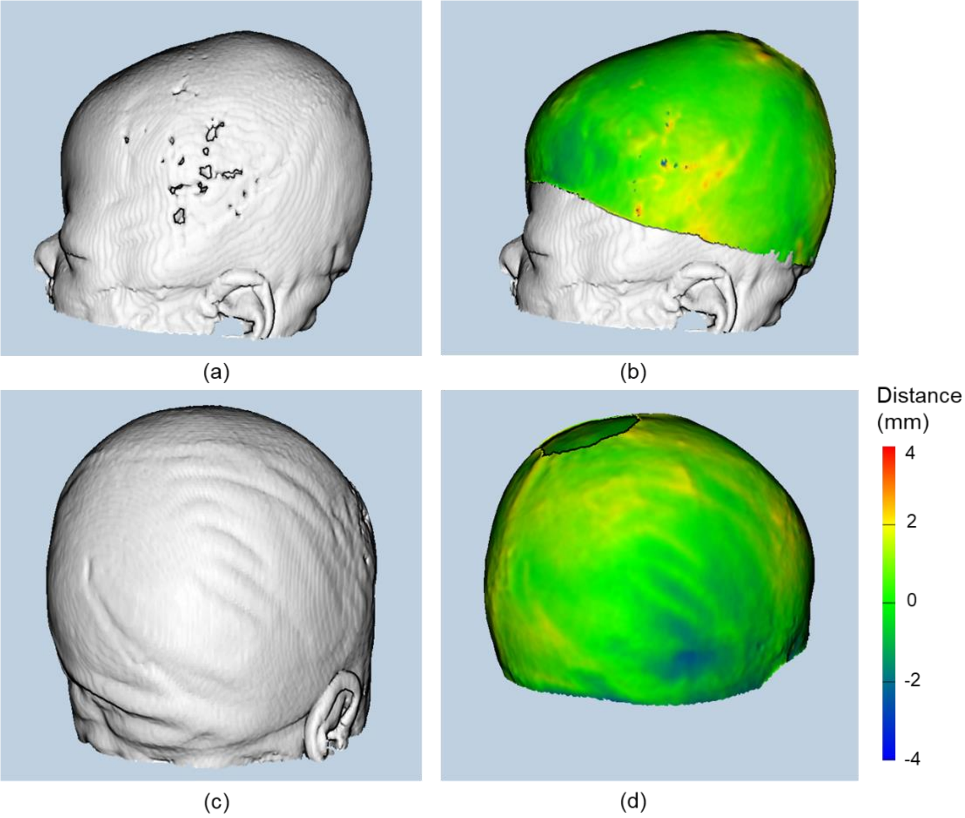


Figure 7. Examples of errors found in MRI 3D models due to holes (a) and lying position of the patient during the data acquisition (c). These errors affect the distance differences between photogrammetry and MRI (b, d), respectively.

4. Discussion

Cranial deformation is a pathology that presents high prevalence among infants. Consequently, the evaluation and monitoring of the deformation is a usual practice during paediatric consultations. However, the commonly used techniques, including visual assessment and the use of callipers and measuring tape, are strongly limited and experts do not agree on their reliability and capacity to represent adequately the deformation (Mortenson and Steinbok, 2006; Skolnick *et al.*, 2015).

Specifically designed 3D scanners and setups of 3D cameras have become an alternative for the evaluation of cranial deformation (such as STARscanner and 3dMD) (Skolnick *et al.*, 2015; Beaumont *et al.*, 2017; Kottner *et al.*, 2017). They are especially useful for the evaluation of cranial deformation as they provide highly accurate and complete information on the patient's head shape and they are non-invasive. However, due to the high cost of the metric devices the methodology is not implemented as part of the regular clinical practice. The methodology assessed in this study based on smartphone photogrammetry provides similar results to 3D scanners and multi-camera approaches. Moreover, it is low cost as only a smartphone is required for data acquisition. The simplicity of the setup would allow a real implementation of the methodology in routine clinical practice once a full automatic toolbox is developed.

Although some studies have evaluated the usability of 3D models for cranial deformation evaluation, the authors have not found references in the literature comparing the radiological and photogrammetric 3D models applying the surface distance differences method. This technique provides a significantly higher amount of information than the comparison of a limited number of manual measurements. The results showed an overestimation of 0.48-3.24 mm, although other authors reported that an overestimation of approximately 2 mm was to be expected (Mendonca *et al.*, 2013). However, distance differences in shape are low and constant, with standard deviations below 1.5 mm for all patients. Most distance differences in the 3D models are local and due to low texture areas, near the edges of the model or imperfections of the MRI/CT. Therefore, the imperfections in the 3D modelling will not be important enough to affect the assessment of the cranial deformation by the doctors and medical specialists.

It should be taken into account that higher distance differences happened only in older patients. The maximum mean distance difference for two-year-old infants is 2.35 mm. The reason for the older patients overestimation is surely the hair effect. Although patients with long hair were excluded from this study it was noticed that even thick, short hair can affect the results. This was not a problem with younger infants. Thus, hair has to be taken into account as a limiting factor for the effective application of this low-cost photogrammetric technology. However, infants subject to cranial deformation analysis in different stages, both pre and post-surgical, are usually under one year old. In fact, most cranial deformations appear during the first months of life (Persing et al., 2003). In addition, the ideal age for starting a correction is below 6 months according to some authors (Kelly et al., 1999), while others suggest that correction should start before four months (Sergueef, Nelson and Glonek, 2006). Besides, the use of helmets is considered especially useful in the age range of 4 to 12 months. Therefore, the presented methodology is expected to cover the right age frame when both diagnosis and monitoring are found essential. Nevertheless, the only known constraint for applying this low-cost methodology is the presence of short hair, but it is not usually a problem in infants up to 1-year-old.

The usage of a perfectly fitted cap is totally necessary to obtain accurate results. As a consequence of this, any patient with head bandages that could not be removed or any other unremovable devices, such as cranial distractors, would need adequate customization of the reference cap or otherwise would not be eligible for this low cost smartphone-based photogrammetric methodology. The movement of patients during the data acquisition is also an issue for younger infants, however, no inaccuracies were found as a consequence of movement.

The main limitation of the methodology is the impossibility to extract non-visible information such as those on the bone. However, most common cranial deformation types, such as positional plagiocephaly, are measured using the surface information only. For severe cases of deformation, such as craniosynostosis, this methodology could not be used as a diagnostic tool but it could be combined with radiological tests for monitoring purposes, especially for patients following a treatment such as cranial orthosis.

Currently, the main tools for the measurement of cranial deformation are the metric tape and the calliper. These tools are intended to acquire isolated craniometric indexes. Although clinically useful, these indexes do not provide a 3D representation of the addressed deformity. Besides, in optimal conditions, the precision of this methodology is 1 mm. However, in real clinical conditions (including infants moving, hampering the identification of cranial landmarks) accuracy is worse than 2 mm and shows a significant interobserver and intraobserver variability. The human tolerance for the perception of mild head asymmetry is also considered 2 mm (Kreutz *et al.*, 2018). As the presented results show differences in shape compared to radiological tests below 1.5 mm we consider that the methodology can provide at leastsimilar accuracy to traditional clinical measurements, but with the advantage of having a complete 3D objective model as output and in a totally non-invasive and low-cost manner. The implementation of the methodology could mean an easier and more detailed evaluation of infants from early ages, allowing better monitoring of the patient's evolution and the results of the treatments.

5. Conclusions

Photogrammetric 3D models obtained from smartphone-based slow-motion videos have been found to provide valuable information for the assessment of cranial deformation in infants under 2 years of age. The differences with the "gold standard" represented by CT and MRI show an overestimation of the photogrammetric caused, by the effect of the hair and the cap. The average difference distance in shape determined from the 10 full 3D models of the patients' heads was 2.1 mm; and 1.6 mm for infants under 2 years of age. The standard deviation of differences is below 1.5 mm for all patients. These values clearly validate the proposed smartphone-based photogrammetric solution as it has a similar accuracy to other commonly used methodologies such as callipers or measure tape, but with higher reliability and repeatability and in a comprehensive way. i.e. covering the whole patient's head.

The main disadvantage of the presented methodology is its limitation to extracting outer visible information only. As a consequence, it can replace radiological tests as far outer anomalies are presented in infant's patients. Nevertheless, the value of the presented methodology is bounded by the possibility to include it in the regular clinical practice as a routine monitoring, non-invasive technique. Therefore, future research should focus on the development of a fully automatic tool able to deliver ready-to-use 3D models and reports to doctors and medical staff.

The availability of cranial 3D models would allows the development of new deformation assessment parameters adapted to detailed and comprehensive 3D data. The possibilities in this area have been partially explored and more development is foreseen in the near future.

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7. References

Barbero-García, I., Cabrelles, M., Lerma, J. L. and Marqués-Mateu, Á. (2018) 'Smartphone-based close-range photogrammetric assessment of spherical objects', The Photogrammetric Record, 33(162), pp. 283–299. doi: 10.1111/phor.12243.

Barbero-García, I., Lerma, J. L., Marqués-Mateu, Á. and Miranda, P. (2017) 'Low-Cost Smartphone-Based Photogrammetry for the Analysis of Cranial Deformation in Infants', World Neurosurgery, 102, pp. 545–554. doi: 10.1016/j.wneu.2017.03.015.

Beaumont, C. A. A., Knoops, P. G. M., Borghi, A., Jeelani, N. U. O., Koudstaal, M. J., Schievano, S., Dunaway, D. J. and Rodriguez-Florez, N. (2017) ‘Three-dimensional surface scanners compared with standard anthropometric measurements for head shape.’, Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery, 45(6), pp. 921–927. doi: 10.1016/j.jcms.2017.03.003.

Chong, A. K. and Brownstein, G. (2010) ‘A technique for improving webcam precision in biological plant measurement’, Photogrammetric Record, 25(130), pp. 180–196. doi: 10.1111/j.1477-9730.2010.00578.x.

Ho, O. A., Saber, N., Stephens, D., Clausen, A., Drake, J., Forrest, C. and Phillips, J. (2017) ‘Comparing the Use of 3D Photogrammetry and Computed Tomography in Assessing the Severity of Single-Suture Nonsyndromic Craniosynostosis’, Plastic Surgery, 25(2), pp. 78–83. doi: 10.1177/2292550317694845.

Kelly, D. K. M., Littlefield, M. T. R., Pomatto, M. J. K., Ripley, M. C. E., Beals, D. S. P. and Joganic, D. E. F. (1999) ‘Importance of Early Recognition and Treatment of Deformational Plagiocephaly with Orthotic Cranioplasty’:, The Cleft Palate-Craniofacial Journal, 36(2), pp. 127–130. doi: 10.1597/1545-1569_1999_036_0127_IOERAT_2.3.CO_2.

Kottner, S., Ebert, L. C., Ampanozi, G., Braun, M., Thali, M. J. and Gascho, D. (2017) ‘VirtoScan - a mobile, low-cost photogrammetry setup for fast post-mortem 3D full-body documentations in x-ray computed tomography and autopsy suites’, Forensic Science, Medicine, and Pathology, 13(1), pp. 34–43. doi: 10.1007/s12024-016-9837-2.

Kreutz, M., Fitze, B., Blecher, C., Marcello, A., Simon, R., Cremer, R., Zeilhofer, H.-F., Kunz, C. and Mayr, J. (2018) ‘Facial asymmetry correction with moulded helmet therapy in infants with deformational skull base plagiocephaly.’, Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery, 46(1), pp. 28–34. doi: 10.1016/j.jcms.2017.10.013.

Lerma, J. L., Barbero-García, I., Marqués-Mateu, Á. and Miranda, P. (2018) ‘Smartphone-based video for 3D modelling: Application to infant’s cranial deformation analysis’, Measurement, 116, pp. 299–306. doi: 10.1016/j.measurement.2017.11.019.

McKay, D. R., Davidge, K. M., Williams, S. K., Ellis, L. A., Chong, D. K., Teixeira, R. P., Greensmith, A. L. and Holmes, A. D. (2010) ‘Measuring cranial vault volume with three-dimensional photography: A method of measurement comparable to the gold standard’, Journal of Craniofacial Surgery, 21(5), pp. 1419–1422. doi: 10.1097/SCS.0b013e3181ebe92a.

Mendonca, D. A., Naidoo, S. D., Skolnick, G., Skladman, R. and Woo, A. S. (2013) ‘Comparative study of cranial anthropometric measurement by traditional calipers to computed tomography and three-dimensional photogrammetry’, Journal of Craniofacial Surgery, 24(4), pp. 1106–1110. doi: 10.1097/SCS.0b013e31828dcdcb.

Metzger, T. E., Kula, K. S., Eckert, G. J. and Ghoneima, A. A. (2013) ‘Orthodontic soft-tissue parameters: A comparison of cone-beam computed tomography and the 3dMD imaging system’, American Journal of Orthodontics and Dentofacial Orthopedics, 144(5), pp. 672–681. doi: 10.1016/j.ajodo.2013.07.007.

Meulstee, J. W., Verhamme, L. M., Borstlap, W. A., Van der Heijden, F., De Jong, G. A., Xi, T., Bergé, S. J., Delye, H. and Maal, T. J. J. (2017) 'A new method for three-dimensional evaluation of the cranial shape and the automatic identification of craniosynostosis using 3D stereophotogrammetry', International Journal of Oral and Maxillofacial Surgery, 46(7), pp. 819–826. doi: 10.1016/j.ijom.2017.03.017.

Mortenson, P. A. and Steinbok, P. (2006) 'Quantifying Positional Plagiocephaly', Journal of Craniofacial Surgery, 17(3), pp. 413–419. doi: 10.1097/00001665-200605000-00005.

Persing, J., James, H., Swanson, J., Kattwinkel, J. and Commitee on Practice and Ambulatory Medicine (2003) 'Prevention and Management of Positional Skull Deformities in Infants', 112(1), pp. 199–202.

Salazar-Gamarra, R., Seelaus, R., da Silva, J. V. L., da Silva, A. M. and Dib, L. L. (2016) 'Monoscopic photogrammetry to obtain 3D models by a mobile device: a method for making facial prostheses.', Journal of otolaryngology - head & neck surgery = Le Journal d'oto-rhino-laryngologie et de chirurgie cervico-faciale, 45(1), p. 33. doi: 10.1186/s40463-016-0145-3.

Schaaf, H., Pons-Kuehnemann, J., Malik, C. Y., Streckbein, P., Preuss, M., Howaldt, H. P. and Wilbrand, J. F. (2010) 'Accuracy of three-dimensional photogrammetric images in non-synostotic cranial deformities', Neuropediatrics, 41(1), pp. 24–29. doi: 10.1055/s-0030-1255060.

Sergueef, N., Nelson, K. E. and Glonek, T. (2006) 'Palpatory diagnosis of plagiocephaly', Complementary Therapies in Clinical Practice, 12(2), pp. 101–110. doi: 10.1016/J.CTCP.2005.11.001.

Siegenthaler, M. H. (2015) 'Methods to Diagnose, Classify, and Monitor Infantile Deformational Plagiocephaly and Brachycephaly: A Narrative Review', Journal of Chiropractic Medicine, 14(3), pp. 191–204. doi: 10.1016/j.jcm.2015.05.003.

Skolnick, G. B., Naidoo, S. D., Nguyen, D. C., Patel, K. B. and Woo, A. S. (2015) 'Comparison of Direct and Digital Measures of Cranial Vault Asymmetry for Assessment of Plagiocephaly.', The Journal of craniofacial surgery, 26(6), pp. 1900–1903. doi: 10.1097/SCS.0000000000002019.