Comparison of Plaster Casting With Three-Dimensional Cranial Imaging

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Objective: **The development of a new cranial imaging system to capture a three-dimensional (3D) model of an infant's head has been previously reported. The accuracy of this new system has been independently established. However, before replacing the traditional plaster casting technique, the two methods require a comparison to ensure that the models they produce are equivalent.**

Methods: **Ten sequential infants were digitized by the 3D imaging system and the plaster casting technique following previously reported protocols. The cast models were also digitized so they could be compared with the digitized images. The two models (3dImage and Cast) were then imported into dimensional analysis software and aligned and registered with well-established registration algorithms. Difference maps that identified the variation between the two surfaces were generated for each pair, and descriptive statistics of these differences were recorded.**

Results: **The mean difference between the cast and the digitized models was 0.052 mm (standard deviation = 0.988), with a root mean square (RMS) difference of 1.028 mm. Two-dimensional slices obtained from the registered 3D surfaces demonstrated excellent agreement between the cranial contours.**

Conclusions: **In this investigation, the 3D models created by the new imaging system were found to be within 1.0 mm RMS of the models created by the plaster casting technique. Two-dimensional cranial contours demonstrated excellent agreement between the two methods. The results of this investigation confirmed that the new cranial imaging system and the traditional plaster casting technique yield equivalent models.**

KEY WORDS: *deformational plagiocephaly, imaging, plaster casting, three-dimensional*

In 1996, development began on a new cranial imaging system designed to capture accurate three-dimensional (3D) models of infant crania. This system was initially conceived to replace the traditional plaster casting technique currently used in fabrication of cranial remodeling bands (Ripley et al., 1994). The casting process, though able to produce an accurate 3D model of an infant's cranium, is labor intensive and requires a considerable amount of training and experience. Additionally, this process does not allow one to cast the infant's face, which is often desirable considering the significant amount of facial asymmetry that may be present.

The new technology would provide the ability to record more detailed information about the infant's initial deformity, which is important for clinical investigations as well as the creation of custom-made cranial bands. In addition, this technology has the potential to advance clinical care by allowing one to closely monitor patients in treatment and provide specific feedback to practitioners providing care. This technology can also be used for clinical research, including investigations on both the natural history and the treatment outcomes of deformational plagiocephaly.

The imaging system, developed in conjunction with 3dMD (Atlanta, GA), can capture a digital image of an infant head within 0.008 seconds with an accuracy of ±0.250 mm (Littlefield et al., 2004). Images acquired from the system can be

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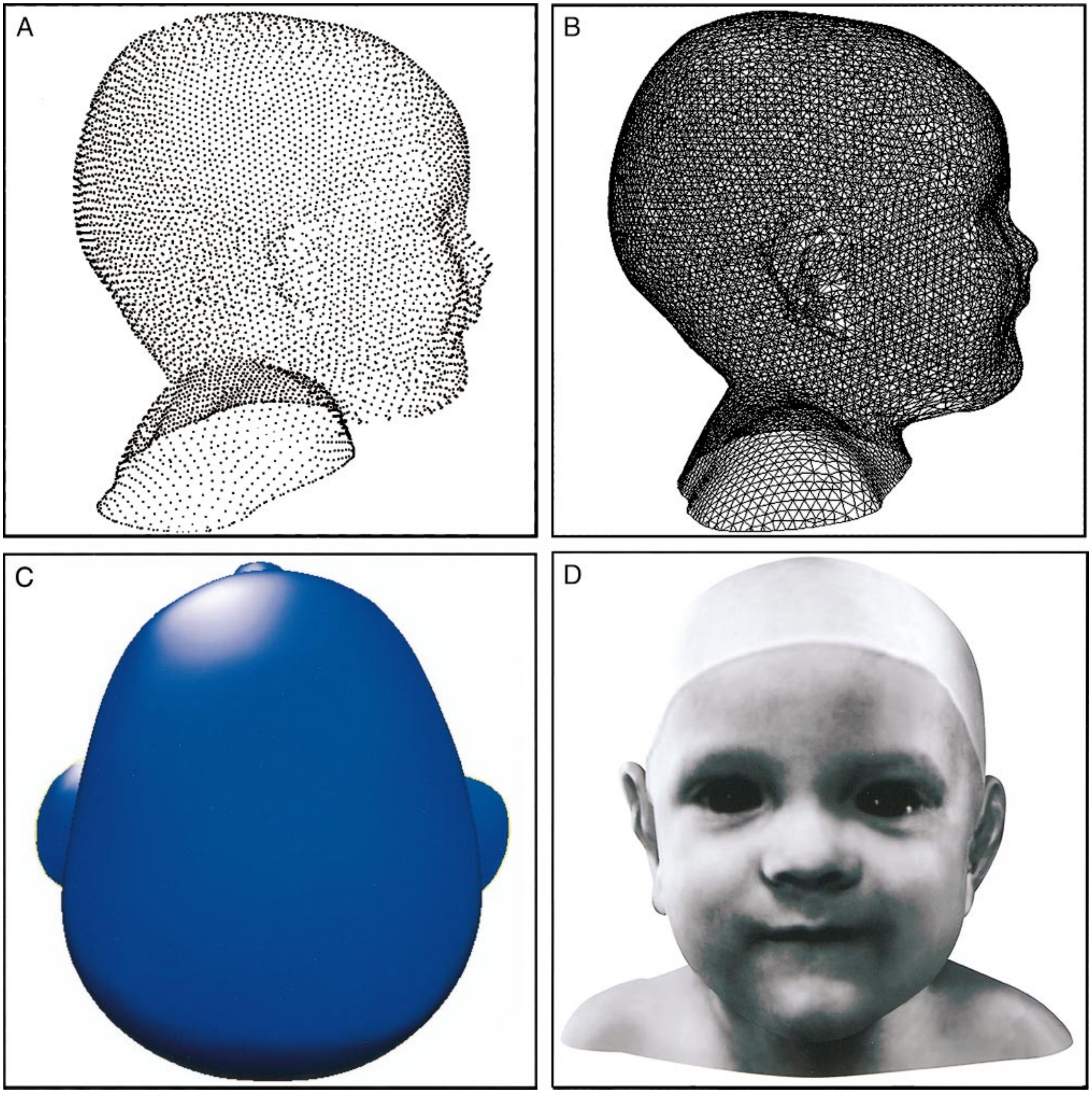

FIGURE 1 **Images acquired in the new imaging system presented in various formats. A: Point cloud. B: Wire frame. C: Surface. D: Texture.**

viewed in various formats, including point cloud, wire frame, and surface rendering (Fig. 1A through C). A digital photograph of the infant (referred to as texture) is also captured and directly overlaid to ensure proper patient identification (Fig. 1D). This system received final approval by the Food and Drug Administration (FDA) in 2002 (K014012).

Although the accuracy of this new imaging system has been independently established (Littlefield et al., 2004), an investigation on how closely 3D digitization compared with the time-tested plaster casting technique needed to be performed before introducing this technology into our practice. The objective of this study was to compare the models produced by these two vastly different methods.

Materials and Methods

Ten infants seen sequentially in one clinical practice were digitized by the new cranial imaging system and then cast following previously reported protocols (Fig. 2A) (Ripley et al., 1994). The casting process created a negative cast impression (Fig. 2B) of the infant's head, from which a positive model was created by filling it with a plaster-based slurry (Fig. 2C). The positive models created from filling the negative impression were then digitized (Fig. 2D) so they could be compared directly with the digitized image of the infant.

Data from both the digitized infant (3dImage) and the digitized positive model (Cast) were imported into analysis soft-

FIGURE 2 A: Infant undergoing plaster casting technique. B: Negative cast impression when removed from the infant's head. C: Positive plaster model created from cast impression. D: Digitization of plaster model.

ware (3dMD) for comparison. The two models were aligned and registered with well-established registration algorithms based upon a minimization of the sum of squared differences (least squares approach) and iterated closest-point algorithms (Fig. 3) (Arun et al., 1987; Besl and McKay, 1992). The image acquired from the direct digitization of the infant was used as the reference surface for registration in all cases.

Once registered, a difference map was generated that demonstrated the overall deviation between the two surfaces (Fig. 4). The difference between these surfaces is presented both qualitatively as a colored topographic map and quantitatively as a set of descriptive statistics (e.g., the mean, standard deviation, and root mean square [RMS] deviation). Because the 3dImage was used as the reference surface, areas toward the red side of the spectrum corresponded to sections where the cast model was larger, whereas areas toward the green side of the spectrum represented areas where the cast model was smaller. Because the casting process does not capture facial information, large negative deviations (green) would be expected in this region.

Another result of the casting process not capturing facial information is that the facial region must be excluded in the

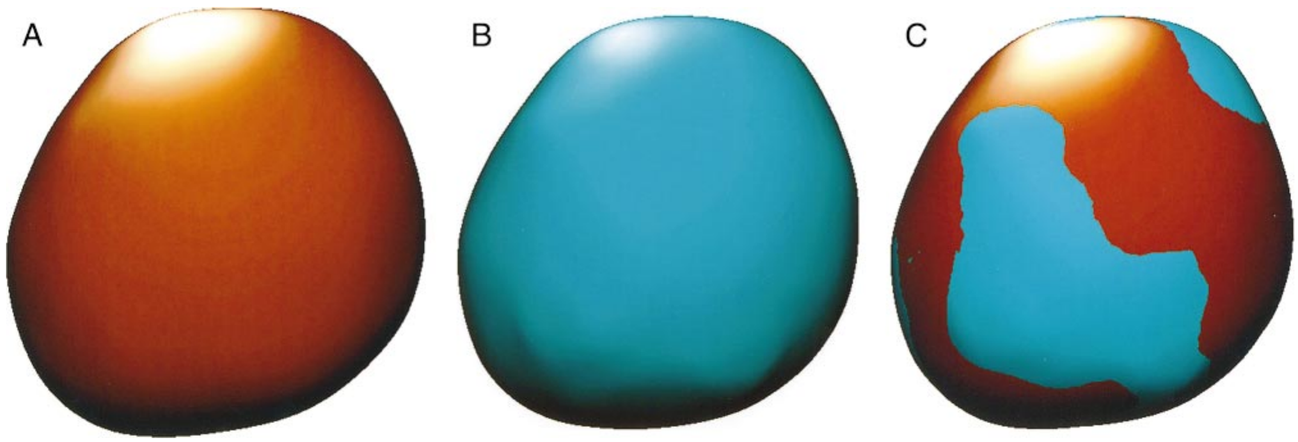

FIGURE 3 **Vertex views. A: Digitized plaster model. B: Digitized infant. C: Models aligned and registered.**

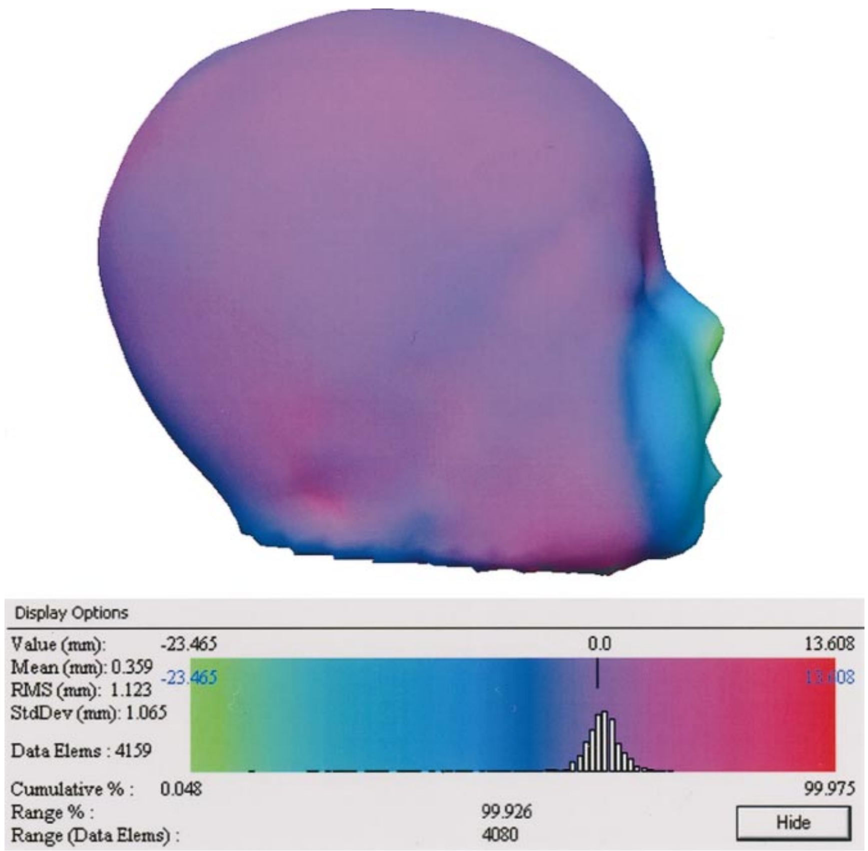

FIGURE 4 **The differences between models calculated and presented as colored difference map and descriptive statistics.**

final comparison of the two surfaces. This was accomplished in the software by dragging the cursor on either end of the distribution until the facial region was excluded (indicated in black, Fig. 5). This process was performed carefully so that only the facial data were eliminated and no data were removed from the surface of the cranium. After eliminating the facial data, the color topographic map yielded a more detailed visual representation of the deviation between the two surfaces of the rest of the cranium (Fig. 5). The program then automatically recalculated statistics describing the difference between these two cranial surfaces.

Accuracy is often reported as a mean or average difference between surfaces. However, in this situation, reporting an average is inaccurate because the surface created from one data set may have components that lay both above (+) and below (−) the reference surface. These positive and negative values offset each other, resulting in a mean value close to zero (Table 1). In situations where this cancellation can occur, it is nec-

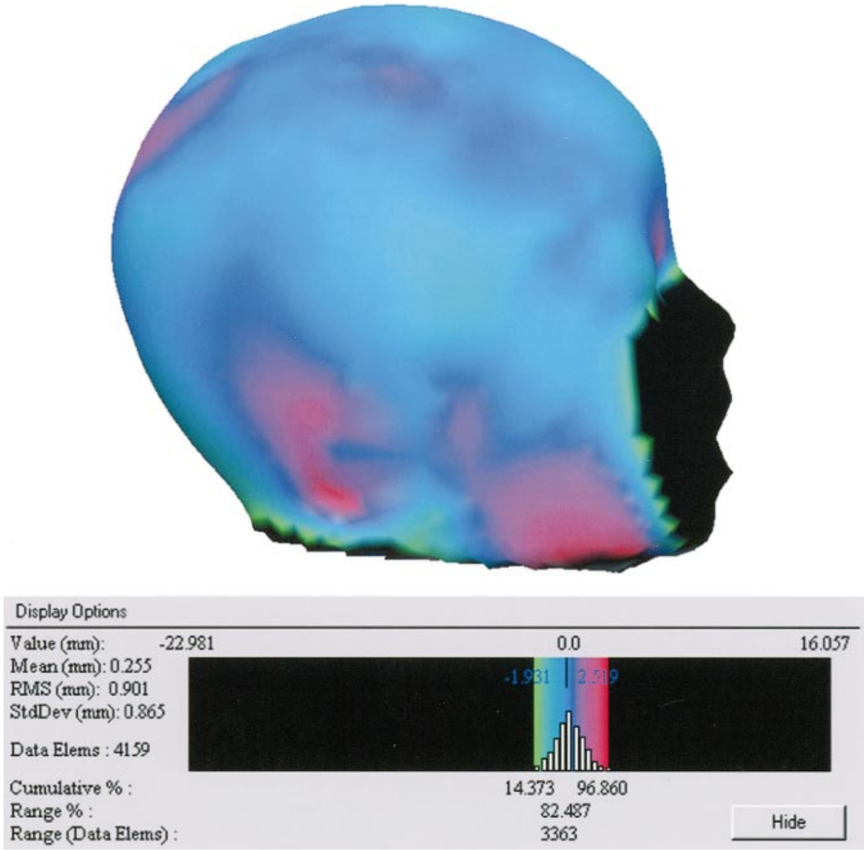

FIGURE 5 Adjusted difference map demonstrating exclusion of facial region from comparison and revised descriptive statistics.

essary to report the mean difference as an RMS. Unlike the arithmetic mean, the RMS statistic more accurately reflects the magnitude of deviation between the two surfaces (Freund and Williams, 1991).

Results

The results of this study are summarized in Table 1. For the 10 sequential comparisons, cast models were within 1.028 mm RMS of the 3dImage. The difference between the two techniques was tightly distributed, with a mean maximum deviation of 1.581 mm and a minimum deviation of 0.587 mm.

TABLE 1 Mean Difference, Standard Deviation (SD), and Root Mean Square (RMS) Difference Between Direct Digitization (3dImage) of Infant and Model Created From Plaster Casting Technique (Cast).

Patient	*Mean (mm)*	*SD*	*RMS Difference (mm)*
1	0.255	0.865	0.901
2	0.082	1.579	1.581
3	0.177	0.950	0.966
4	−0.327	1.000	1.052
5	−0.163	0.850	0.865
6	0.411	1.151	1.222
7	0.006	0.587	0.587
8	0.468	1.012	1.115
9	−0.473	1.023	1.127
10	0.088	0.867	0.867
Average	0.052	0.988	1.028

To visualize these relationships in a different way, we can obtain cross sections of the registered models that allow us to see the data in two-dimensional (2D) slices. The location and orientation of the cross section can be changed, allowing for an infinite number of ways to examine the agreement between these two surfaces. To obtain a 2D slice, a plane is dropped through the cranium and the data above that plane are removed. The resulting image, when viewed from above, is a cross section of the registered surfaces similar to 2D computed tomography slices (Fig. 6). The line in blue represents the cast model and the line in red corresponds to the digitized infant. Overall, excellent agreement exists between these two contours. The exact difference at any point along this contour can be determined directly from the color topographic map. An additional example of this cross-sectional analysis is presented in Figure 7.

Discussion

At the beginning of this investigation, observation of some systematic difference between models created by plaster casting and those obtained with optical digitization was expected. If for no other reason, these differences were expected simply because of the extremely different methods of obtaining phys-

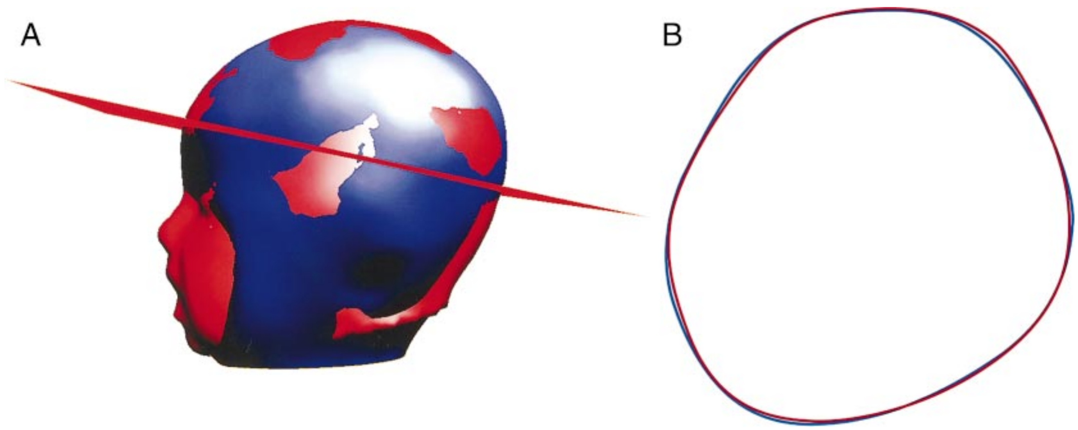

FIGURE 6 Case 1—A 4.5-month-old boy with severe plagiocephaly. A: Models were aligned and registered and a cross section taken through upper cranium. B: Two-dimensional cross-sectional contour demonstrating difference between these models. The blue line represents the cast model and the red line corresponds to the digitized infant.

ical models; one relies on professional skill and experience, the other on technology. The results of this investigation, however, demonstrated an excellent agreement between these two methods. This was confirmed both quantitatively through the use of statistics and qualitatively through the use of color topographic maps and cross-sectional contours.

Although confirmation of the accuracy of the plaster casting technique was not surprising, it is natural to question how this manual approach can produce models rivaling a sophisticated piece of technology. To understand this, one must appreciate the significant amount of effort that has been invested in developing specific protocols for the casting procedure. To begin with, a detailed written procedure has been created that outlines the exact step-by-step process used to obtain an accurate cast; deviations from this procedure are not tolerated. Additionally, clinicians undergo 4 weeks of hands-on training and must pass a written and practical test on casting before being authorized to treat patients. These same clinicians have regular review of their casting skills during annual audits, and every cast that comes into our manufacturing facility undergoes a rigorous inspection procedure as required by the FDA (Trautman, 1997). All the steps outlined above have been designed to ensure the quality of the original cast. However, as indicated earlier, this is a very labor-intensive process and requires a significant amount of training, experience, and quality control to guarantee that an accurate cast has been achieved.

It should also be recognized that the plaster casting technique is currently the gold standard and the method by which the majority of cranial molding devices have been made since the late 1970s (Clarren and Smith, 1979; Clarren, 1981; Nichter et al., 1986; Pattisapu et al., 1989; Ripley et al., 1994; Pollack et al., 1997; Littlefield et al., 1998; Mulliken et al., 1999). Therefore, before introducing new technology into clinical practice, the new system needed to be compared with this gold standard. The objectives of this investigation were to identify global differences between these two methods (e.g., casting produces a model 5% larger than digitization) and also to determine if there were any regional differences (e.g., digitization better defines the forehead curvature). Understanding these differences is critical, as it will certainly affect both the fit and function of a cranial remodeling band.

From a global perspective, the two techniques produced re-

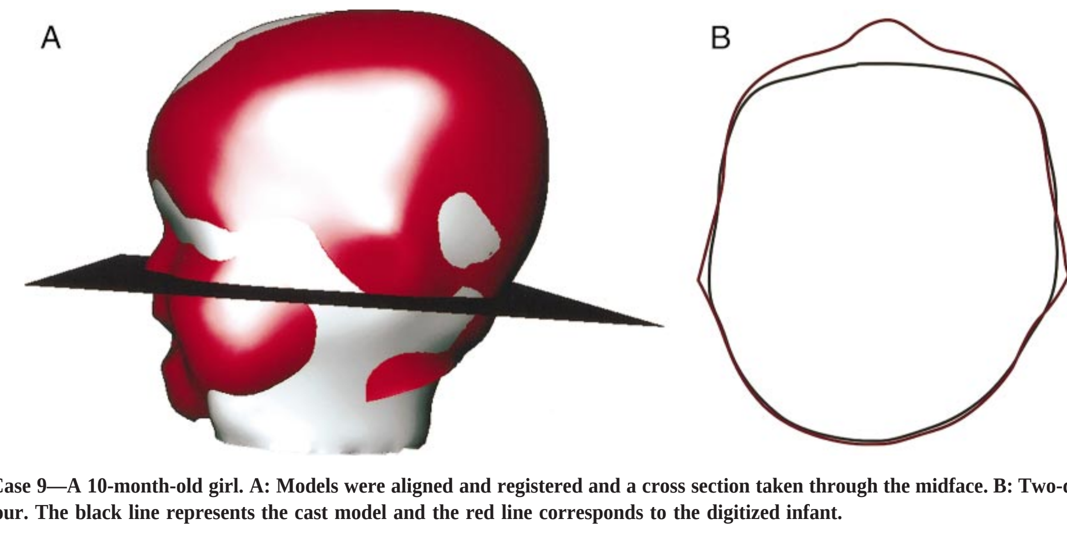

FIGURE 7 Case 9—A 10-month-old girl. A: Models were aligned and registered and a cross section taken through the midface. B: Two-dimensional cross-sectional contour. The black line represents the cast model and the red line corresponds to the digitized infant.

markably similar models, with differences on the order of 1 mm RMS. Likewise, no significant regional differences were found, as confirmed by the excellent agreement between the cranial contours. As such, we conclude that the new imaging system could be introduced into clinical practices with confidence.

Although the two different methods produced comparable models, there are a number of reasons to incorporate the new 3D imaging technology. As previously discussed, advantages regarding patient care and production and clinical research can now be realized with this new technology (Vannier et al., 1993; Galdino et al., 1999; Hurwitz et al., 1999; Da Silveira et al., 2003; Duffy et al., 2003). Parents will likely more readily accept the digitization process, thereby increasing the likelihood of obtaining both pre- and posttreatment 3D models for outcome studies. More sophisticated analysis of the changes in head shape can be performed (e.g., curvature, volume, center of mass), and researchers will no longer be limited to linear, 2D anthropometric measurements. In addition, changes in cranial configuration can be presented visually as incremental changes over an entire surface, as shown in the color difference maps of Figures 4 and 5, where areas with the most correction are presented in red and areas with least the improvement are presented in green. Because facial information is also recorded, analysis of changes in facial and skull-base asymmetry may also be investigated.

A considerable amount of work still needs to be accomplished before many of the benefits described earlier will be realized. The new digitizer is a one-of-a-kind system that is still undergoing rigorous validation and verification procedures. This is the first published study using this new technology in the treatment of plagiocephaly. The sample, though relatively small, represented a broad range of infants with respect to age (3.5 to 11 months), gender (6 boys, 4 girls), and head configurations (plagiocephaly, brachycephaly, dolichocephaly, brachycephaly with asymmetry). No differences as a function of infant age, gender, or head configuration were observed. No restrictions were placed on who qualified for participation; if they were cast, they were digitized. Once safety and efficacy have been demonstrated, incorporation of this technology into clinical practices may allow us to perform additional multi-institutional trials that would lend further validity to the assessment.

In addition, significant challenges still exist with respect to how one can measure differences between two surfaces that have changed not only in size but also in shape. Also, methods for accurate landmark identification (Yoon et al., 1992; Kohn et al., 1995; Hurwitz et al., 1999; Ayoub et al., 2003), registration of complex 3D surfaces (Arun et al., 1987; Lorensen and Cline, 1987; Besl and McKay, 1992; Schroeder, 1997), and development of standards for measurement of these 3D surfaces still need to be completed. Nonetheless, a number of researchers continue to make significant advances in the field of 3D medical digitization (Cutting et al., 1988; Vannier et al., 1993; Bhatia et al., 1994; Ras et al., 1994; Galdino et al., 1999; Duffy et al., 2000; Da Silveira et al., 2003), and it is only a matter of time before many of the hurdles we face today are behind us.

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