MATLAB® tool for evaluating temporal hollowing before and after surgery in patients with metopic synostosis

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Metopic synostosis is a congenital condition where the metopic suture has fused prematurely resulting in a triangular forehead and ocular hypotelorism. The diagnosis is surgically treated with a cranioplasty before the age of one year for both functional and cosmetic reasons with the aim to enlarge the intracranial volume and reshape the forehead.

Temporal hollowing is the most often seen postoperative abnormality. To be able to evaluate the degree of temporal hollowing before and after surgery an objective method is desired.

The aim of the project is to define a quantitative measure of the surgical success rate of metopic synostosis. For this aim a MATLAB tool was constructed, able to calculate how successful the surgery is with respect to temporal hollowing. The program segments the outer bone contour of the skull of a patient and an age and gender matched control. The final result is given as a percentage of the differing area in the temporal region between the patient and the control, divided by the total frontal area of the patient.

14 patients, 7 patients operated with a spring assisted cranioplasty and 7 with bone graft, with matched controls were measured. The mean improvement of temporal hollowing for spring assisted cranioplasty was 91 % and 63 % for surgery using bone graft.

A useful tool for comparing different surgical techniques has been constructed. The intra-user variability is 0.08 % and inter-user variability is 3.0 %.
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1. **INTRODUCTION**

The skull of a newborn child consists of several different bones separated by sutures. Craniosynostosis is a congenital condition in which one or several of the skulls sutures has fused prematurely. There are five main sutures; the metopic, cranial, sagittal, lambdoid and squamosal suture (Fig.1). As the brain grows rapidly during the first year stretching the bones apart, the sutures works as growth sites allowing the skull to expand. When growth decreases as the brain reaches its full size the sutures fuse. When closed prematurely the suture prevents growth perpendicular to itself forcing a compensating growth at the other sutures which leads to characteristic deformities depending on the affected suture (1). Craniosynostosis leads to deformation of the skull and a restricted growth of the skull which might lead to intracranial pressure.

![Image of the five main sutures separating the bones of the skull of a newborn child. Image from the department of Plastic Surgery at Sahlgrenska University Hospital.](image)

Metopic synostosis is the second most common type of craniosynostosis (2) and is caused by premature fusion of the frontal, metopic, suture (3). The condition is characterized by a triangular forehead (Fig.2) caused by the restricted growth of the frontal bones, an increased interparietal width, a midline bony ridge and ocular hypotelorism (4) which involves a decreased distance between the eyes and deformation of the orbital shape.
The diagnosis is surgically treated with a cranioplasty before the age of one year for both functional and cosmetic reasons with the aim to enlarge the intracranial volume and reshape the forehead. CT-images are used for confirmation of the diagnosis, evaluation of preoperative deformity, as a planning tool for the surgery and for evaluation of the surgical outcome. The children undergo a preoperative and postoperative CT-scan and a follow up CT-scan at the age of three.

Two different surgical techniques are used. Both includes remodeling and separation of the frontal bones using a saw. Remodeling is made with the purpose to flatten and widen the forehead. The first technique involves a midline bone graft. A bone graft is a transplanted piece of bone used to separate the two frontal bones when they are put back in place (fig.3). This technique is generally used for patients older than 6 months. The second method, generally used for patients younger than 6 months, is a spring-assisted cranioplasty. The spring is placed between the frontal bones (fig. 4) and has the same purpose as the bone graft namely to separate the bones to prevent hypotelorism.

The most often seen postoperative abnormality is a temporal contour deformity called temporal hollowing (6). The abnormality is also known as indented or narrow temples which gives the side of the head a sunken or concave contour and the head gets an unnatural hourglass shape. Today the evaluation of the correction of temporal hollowing is based on subjective methods such as visual...
observation of the skull and CT-images. The subjective evaluation is observer dependent making the assessment hard to use when comparing techniques. To be able to evaluate the degree of temporal hollowing, the surgical outcome and to compare surgical techniques an objective method is desired.

The aim of the project is to define a quantitative measure of the surgical success rate of metopic synostosis with regard to temporal hollowing. For this aim a MATLAB tool is constructed, able to calculate how successful the surgery is. The program is tested on a group of patients and used to compare the two surgical techniques used at Sahlgrenska University hospital.

The quantitative measure is based on each patient being paired with an age and gender matched control. The MATLAB program segments the outer bone contour in CT-scans for the patient and the matched control. Combining the two segmentations makes it possible to calculate the difference in the outer bone structure in the temporal area. The area being compared starts at the orbital superior wall. The posterior limit is at the skulls widest point.
2. Theory

2.1 Digital Image

A digital image is made up of a series of pixels aligned in a matrix specified by rows and columns (Fig. 4). A pixel is the smallest component of an image and each pixel has a numeric value that represents the gray intensity in that certain pixel. The values are integers between 0 and 255 where 0 is black and 255 is white.

A binary image is an image where the pixel value only has two possible values (Fig. 5). Typical binary images are black (pixel value=0) and white (pixel value=1). Binary images can be obtained by thresholding gray scale images, see 2.3.1.

A 3D-image is made up by several 2D images stored in a 3D matrix, i.e. rows, columns and the number of images defines the 3D matrix. It’s possible to view different sections of the 3D image by selecting slices from different directions, see section 2.3.

![Figure 4. Digital gray scale image.](image1)

![Figure 5. Binary image.](image2)

2.1.1 DICOM

DICOM stands for Digital Imaging and Communications in Medicine. It is a standard system for storing and handling medical imaging. Mainly it specifies a file format and a communication protocol.

A DICOM file stores the patient’s personal data as name, gender and personal number. It also stores the type of scan, manufacturer and the image data. The information is stored in DICOM tags.

2.2 MATLAB

MATLAB stands for MAtrix LABoratory and is developed by MathWorks. It’s a high-performance language used worldwide by engineers, scientists and at universities for education and research. The software is based on matrices and vectors and integrates programming, numerical computing and visualization. As described, images are built as two-dimensional matrices which makes MATLAB a preferable computing language for image processing, analysis, segmentation and visualization.
2.3 SEGMENTATION

Image segmentation is a process in image analysis in which regions are separated from each other, for example structures of interest can be isolated and segmented from the background. This means that pixels are organized in different groups based on certain criteria. For example, pixels with similar grayscale values belongs to the same category, pixels with different grayscale values belongs to different categories. In medical imaging it may be used to identify different tissues, locate tumors and to plan surgery.

2.3.1 THRESHOLDING

The simplest method of segmentation is thresholding. It’s a simple but effective way to extract objects from the background. According to the range of values in which a pixels lies, pixels are allocated to categories. Given a single threshold \( T \), pixel at position \((x,y)\) with grayscale value \( f_{x,y} \) is allocated to category 1 if
\[
f_{x,y} \leq T.
\]
Otherwise the pixel is allocated to category 2. With a single threshold the output will be a binary image.
\[
g_{x,y} = \begin{cases} 
1 & \text{if } f_{x,y} \geq T \\
0 & \text{if } f_{x,y} < T
\end{cases}
\]

The threshold can be both manually and automatically chosen to get the most optimal value for identifying the structure of interest. It’s also possible to have multiple thresholds.

2.3.2 REGION GROWING

Region growing is a region-based image segmentation method producing coherent regions. The first step is to choose one or several seed points as starting points for the algorithm and a range for how much a pixel value is allowed to differ to be included in the region. The range is often chosen to be grayscale intensity values.

The region growing algorithm starts from a seed point and works its way out. The region grows iteratively as it compares neighboring pixels intensity values including them in the region if the difference is small enough to be within the range (Fig.6).

A similarity measure \( S(i,j) \) is defined such that if pixel \( i \) and \( j \) are similar, it produces a high result. Otherwise it produces a low result. A neighboring pixel \( q \) to the chosen seed point \( p \) is compared with the similarity measure \( S(p,q) \) and threshold \( T \). If \( S(p,q) > T \), \( q \) is added to the region. Similarly the other neighboring pixels of \( p \) are considered and the algorithm continues with neighbors of \( q \) and so on. This continues until no neighboring pixels fulfills the criteria.
2.3.3 Dilation and Erosion

Dilation and erosion are two morphological image processing tools based on set theory. Morphology are image processing operations that process images based on shapes (7). They are usually applied to binary images but can also be used on grayscale images. A structuring element is applied to an input image which creates an output image of the same size. The structuring element is just a sub-image, a smaller set used to find structures (Fig.7).

Erosion removes pixels from the boundaries of the objects. The erosion of set A (Fig.8) by a structuring element B is described by equation 2.

\[ A \ominus B = \{ z | (B_z) \subseteq A \} \]

Equation 2.

Point z is included in the erosion if the translated B offset by z is entirely within the set of A (Fig. 8). So the translated B is shifted by z one step at the time. If the translated, shifted B is entirely within A the output is one at that location, otherwise it’s set to zero.

Figure 7. Set A in an image I and structure B.
Figure 8. Element B is shifted one step at the time. If B is completely inside A the output is 1. A) Structure B is not overlapping set A at all. The output is zero. B) Structure B is completely overlapping set A. The output is one. C) Structure B is partly overlapping set A. The output is zero.

Dilation does the opposite and adds pixels to the boundaries of the objects in an image when applying the structure element. Set A is an object in image I. The dilation of set A by a structuring element B is described by equation 3.

\[ A \oplus S = \{ z \mid (\hat{B})_z \cap A \neq \emptyset \} \]

Equation 3.

Point z is included in the dilation if the reflection of the structuring element S offset by z intersects at all with the set A (Fig.9). So the reflected B is shifted one step at a time which means it is offset by z. In every new pixel position calculations is made to see if the reflected B is at all overlapping set A. If it is the pixel value is set to one otherwise its set to zero.
Figure 9. A) If structure B doesn’t overlap A at all the output is zero. B) The center of structure B overlaps with. The output is one.

2.4 ANATOMICAL PLANE

There are three anatomical planes which dissect the body with imaginary horizontal and vertical planes (Fig.10). They are used to describe locations of structures and directions of movements. The sagittal plane divides the body into right and left. The coronal plane divides the body into back and front (posterior and anterior). The transverse plane divides the body in upper and lower (cranial and caudal).

Figure 10. A descriptive image of the transverse, sagittal and coronal planes.

(https://creativecommons.org/licenses/by-sa/4.0/)

2.5 COMPUTED TOMOGRAPHY

X-ray computed tomography is an imaging technique generating cross-sectional images used for diagnostic and therapeutic purposes.

An X-ray tube paired with an opposite detector rotate around the patient while measuring the amount of radiation that passes through the body. Usually several slices are scanned at the same time as the detector has several detecting elements. Most used is the spiral-CT where the scanning...
has a helium pattern over the volume (8). Cross-sectional slices are reconstructed using computerized algorithms.

Each image is a projection of a thin slice of the body showing the distribution of the linear attenuation coefficient \( \mu(x, y) \). Materials attenuate the radiation differently and it is the difference in absorption that makes it possible to distinguish one organ from another.

The images produced are digital images. Hence the CT-images are produced using a numerous amount of angles around the body creating two-dimensional images. To retrieve three-dimensional images the individual images are stacked in a three-dimensional dataset. Different axial resolutions is gained changing the distance between the slices and the slice thickness. With a three-dimensional matrix of voxels it’s possible to view transversal, sagittal and coronal slices using computer techniques.

The pixels values displays the computed attenuation coefficient as a CT-value (gray-scale value) specified in Hounsfield units (HU). The CT-value is calculated relative to the attenuation of water using the Hounsfield scale. The Hounsfield scale is a linear transformation of the linear attenuation coefficient measurement according to equation 1.

\[
I = \frac{\mu_x - \mu_{\text{water}}}{\mu_{\text{water}}} \times 1000 \ [HU]
\]

Eq. 1.

The gray-scale value \( I \) assigned to a pixel corresponds to the attenuation \( \mu_x \) within the associated voxel. The CT-value for water is defined as zero.
3. Method

An objective method and quantitative measure of the surgical success rate has been designed to be able to compare different surgical techniques with respect to temporal hollowing.

MATLAB R2014b has been used to calculate the differing area in the temporal area between a patient and a control (Fig.7). The program starts by reading one stack of CT images of a patient and one of the control. After rotation of the images in the transverse, sagittal and coronal planes in order to align the patient and control the same way, the program segments the outer bone contour as described in section 3.3. Starting from the first slice above the end of the orbital roof, the slices are paired, the first slice of the patient with the first of the control, the second slice of the patient with the second of the control and so on upwards. The paired slices are joined at the foremost points of the skull.

The quantitative measure was given as the ratio between the differing area in the measured slices and the whole frontal area (Fig.15) in the same slices. The ratio was used to compare preoperative and postoperative patients to evaluate the correction of temporal hollowing for individual patients. It was also used to evaluate which out of two surgical techniques had the most successful correction of temporal hollowing.

![Temporal Hollowing](image)

*Figure 11. The image shows the definition of temporal hollowing.*

3.1 Patients and controls

Every patient was paired with two controls. The controls were both gender and age matched. Preoperatively, the patients were between 3 and 12 months old and matched with controls whose ages were ±1 month of the patient’s age. Postoperatively, the patients were 3 years old and were matched with controls whose ages were ±3 months of the patient’s age. The age match was based on the skulls growth during the first years (Fig.12). The skull grows more rapidly during the first months compared to when they are three years old. All patients and controls had a slice thickness of 5 mm.
3.2 IMAGE ROTATION

The patient and control had to be aligned the same way in order to make the comparison in the right area. Therefore, the images were rotated in the sagittal, coronal and transversal plane using the built in Matlab function imrotate.

Images of different patients have different pixel spacing. Pixel spacing is stored as a two dimensional vector and describes the dimensions of a pixel in reality. The row spacing is the first value of the vector and is the spacing between the centers of two vertical neighboring pixels in mm. The second value is the column spacing which is the spacing between the centers of two horizontal neighboring pixels in mm.

To be able to compare patients and controls, the images of one of them had to be rescaled to achieve same pixel spacing. This was done with the built in MATLAB function imtransform. The translation was made maintaining the original image size.

Before rotation new slices needed to be interpolated from the original images to get cubic voxels which made it possible to view sagittal and coronal slices. This due to the large difference between the slice thickness and pixel spacing. After linear interpolation the voxels are cubic and the slice thickness equal to the pixel spacing. For rotation of all images in the transversal plane the rotation angle was calculated using the foremost point of the head and the position of sella turcica (Fig. 13.a). The angle used for rotation in the coronal plane was calculated using the bottom of the temporal fossa. The bottom of the left and right temporal fossa was defined by examination of transversal planes. If the left and right temporal fossa starts in the same slice the rotation angle is zero otherwise the angle was calculated so that both temporal fossa starts in the same slice. For rotation in the sagittal plane the nasal sella line was used (Fig.14). The nasal sella line is a line starting in the middle of the cavity of sella turcica and nasion. The angle was calculated by using the coordinates for sella turcica and nasion. All points were chosen manually.
Figure 13. Shows how the angles used for rotation are defined. A) Shows a transversal slice where the foremost point and the middle of Sella turcica are chosen. The angle $\nu$ is the angle used for rotation. B) shows a transversal slice where it is noticeable that the left temporal fossa starts a few slices before the right temporal fossa. After rotation they start in the same slice. C) Shows, I a sagittal slice, the nasal sella line and the angle for rotation of the sagittal slices.

Figure 14. Image of the nasal sella line. The nasal sella line is a line starting in the middle of the cavity of sella turcica and nasion. (Fjeld et al. Pediatric Rheumatology 2010 8:13 doi:10.1186/1546-0096-8-13)

3.3 SEGMENTATION

3.3.1 REGION GROWING

The first step of the bone segmentation was a region growing algorithm that starts from a single seed point. The region grows iteratively as it compares neighboring pixels intensity values including them in the region if the difference is smaller than 100 HU. Starting in the middle of the brain, the region grows until it reaches the inner bone structure as the difference is greater than 100 HU between the brain substance and the bone. To include the complete bone structure the built in MATLAB function `imdilate` was used for dilation to expand the area obtained by region growing.

The similarity measure used was the region’s mean intensity value. When a pixel was added to the region a new mean intensity value of the region was calculated. The algorithm stops when the difference in intensity value became larger than the threshold (100 HU).

The dilated region growing image was multiplied with the original image to remove all objects outside the skull.
3.3.2 Thresholding
Every pixel whose intensity value was above 100 was set to one and every pixel whose intensity value was below 100 HU was set to zero (9). The segmented image was a binary black and white image containing only bone. Using the built in function edge, the outer bone structure, one pixel wide, was found.

3.3.3 Dilation and Erosion
Sutures lead to gaps in the bone contour. For closure of the sutures dilation and erosion was used. Dilation was done until the bone parts were connected. Erosion was used to get back to the true shape as dilation adds pixel around the complete structure.

3.4 Defining Measured Volume
The patient and control were joined together slice by slice connected at the foremost points of the skull in every slice. A manual adjustment was made after a first automatic match by the program.

The region of interest was the temporal areas. The area needed to be defined in order only to measure the differences in the temporal area. The area was limited by the outer bone contour and chosen to be defined as follows. The caudal limit was the first slice after the orbital roof as it was easily defined and it is the caudal limit of the frontal volume which was the area of interest. The cranial limit was the top of the head. The anterior limit was the foremost point of the head. The posterior limit was the widest point of the head which was calculated by the computer in every slice. The posterior limit was used to exclude the back of the head thereby only the shape of the temporal area was measured. Within this volume only one slice was chosen to be measured. The decision of which slice to measure was based where the slice containing the largest differing area was positioned, see 3.5.4.

The differing area in the measured slice was related to the whole frontal area in the same slice (Fig.15). The quantitative measure was given as the ratio between the differing area in the measured slices and the whole frontal area.
Figure 15. The area being studied is defined by the top of the orbital roof and the widest point of the skull. The starting slice above the orbital roof is chosen manually and the widest point will be calculated by the computer in every slice.

3.5 Defining possible outcomes of matched patients and controls

There were four possible ways for the matched patient and control to be aligned. They are always connected at the foremost point of the skull. Fig. 16 shows type 1-4 where the green line represents the control and the red line represents the patient. The hypothesis was that type 1 and 3 were the most common types. The differing area defined as temporal hollowing will be negative in type 2 and 4 since the patient has less degree of temporal hollowing as the bone structure is outside the one of the control.
3.5 EVALUATION OF THE SOFTWARE
In order to evaluate the accuracy of the software different measurements and tests has been made. All measurements has been made with 5 mm slices.

3.5.1 STABILITY
The stability of the program was verified by 10 repetitive measurements of the same patient and its control. The exact same slices and positions for the structures (see step 1,2,3 and 4 in the user manual) were used as well as the manual movement to match the patient with the control (step 6 in the user manual).

3.5.2 INTRA-USER VARIABILITY
The intra-user variability was estimated by repetitive measures of two patients and their controls. Every time new slices as well as new positions of the anatomical structures were chosen.

Repetitive measurements of the same two patients, measured three times each instead of ten, were also made by 10 different users for further estimation of the intra-user variability. Results from these measurements were only used to confirm the above intra-user variability.

Figure 16. Definition of the 4 possible types of outcomes between a patient and a control.
3.5.3 INTER USER VARIABILITY
Two different patients were measured by ten different users to evaluate how much the results depend on the user. Every user measured both patients three times. All users were familiar with the anatomical structures used for rotation.

3.6 SELECTING MEASURED SLICE
The purpose was to choose only one slice to measure for every patient. Ten 6 month old patients and ten 3 year old patients were measured. Everyone was measured from the chosen starting slice and 35 mm in the upwards. The reason for not measuring more than 35 mm is to include as many patients as possible in the study. Because of the fontanel, several patients would have been excluded if measurements were wanted above 35 mm. 10 preoperative patients and 10 postoperative patients were measured and it was calculated in which slice the largest differing area was located. The mean value of the calculations were used to choose which slice for the program to use. The calculations are made for preoperative and postoperative patients separately. The program will use different slices for preoperative and postoperative patients.
4. RESULTS

4.1 EVALUATION OF THE SOFTWARE

4.1.1 STABILITY

The same patient with a matched control was measured 10 times with the same selected slices and positions for the anatomical structures as well as the manual movement to fit the patients CT slice with the control. Given the exact same input parameters the program returns the exact same output which shows a good stability.

4.1.2 INTRA USER VARIABILITY

Four matched patients and controls, two preoperative and two postoperative, has been measured ten times each. The results are shown in table 1. The intra-user variability was 0.08 %.

When studying the inter-user variability every user measured every patient 3 times. The results (Table 2) was used to confirm the results of the intra-user variability.

| Table 1. Results from measuring two preoperative and two postoperative patients. |
|---------------------------------|-----------------|-----------------|
| Preoperative                    | Mean Ratio [%]  | CV [%]          |
| 1                               | 3,9             | 3,4             |
| 2                               | 3,1             | 4,3             |
| Postoperative                   |                 |                 |
| 1                               | 2,4             | 7,7             |
| 2                               | 1,8             | 5,7             |

4.1.3 INTER-USER VARIABILITY

10 different users measured 2 patients 3 times each to evaluate the inter user variability. For every user, the mean ratio for temporal hollowing as well the standard deviation for the 3 measurements are calculated (Table 2). The mean of the three measurements are used to compare the users (Table 3). The inter-user variability was 3.0 %.

| Table 2. The mean ratio for patient 1 was 3.34 % and 4.0 % for patient 2. The standard deviation between the 10 users measurements was 0.22 % and 0.14 for patient 1 and patient 2 respectively. |
|---------------------------------|-----------------|-----------------|
| Mean Ratio [%]                  | 3,34            | 4               |
| Inter-user variability [%]      | 3,0             |                 |
Table 3. Results for intra-user variability. Every patient was measured 3 times by each user. The table is showing the mean ratio and variation coefficient for every user’s measurements.

<table>
<thead>
<tr>
<th>User</th>
<th>Patient 1 Mean Ratio [%]</th>
<th>CV [%]</th>
<th>Patient 2 Mean Ratio [%]</th>
<th>CV [%]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>3.2</td>
<td>3.6</td>
<td>3.9</td>
<td>4.8</td>
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<tr>
<td>2</td>
<td>3.7</td>
<td>3.4</td>
<td>3.8</td>
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<tr>
<td>3</td>
<td>3.3</td>
<td>2.7</td>
<td>4.2</td>
<td>8.2</td>
</tr>
<tr>
<td>4</td>
<td>3.7</td>
<td>0.5</td>
<td>4.0</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>2.5</td>
<td>3.9</td>
<td>4.6</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>2.8</td>
<td>4.0</td>
<td>4.8</td>
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<td>3.1</td>
<td>3.4</td>
<td>3.8</td>
<td>0.2</td>
</tr>
</tbody>
</table>

4.2 Selecting measured slice

A study of the first 3.5 cm after the orbital roof for 10 preoperative patients and 10 postoperative patients shows that the mean largest differing area lies 3.6 mm after the start slice for the preoperative and 6.6 mm for the postoperative patients (Fig.17). The slice measured will therefore be the one at 3.6 mm and 6.6 mm respectively after the starting slice as it displays where temporal hollowing is largest.

![Selecting measured slice](image)

*Figure 17. Diagram showing how many millimeters from the start slice that the largest differing area was for 10 patients.*
4.3 COMPARING BONE GRAFT AND SPRING ASSISTED CRANIOPLASTY

14 patients with both preoperative and postoperative CT examination were measured. The slice thickness used is 5 mm. The mean decrease of temporal hollowing is 36% for bone graft and 61% for spring assisted cranioplasty. A T-test was made and the p-value was calculated to be >0.2 which shows no significant difference.

Table 3. Results showing the ratio of temporal hollowing from measuring seven patients using bone graft and seven patients using spring assisted cranioplasty.

<table>
<thead>
<tr>
<th>BONE GRAFT</th>
<th>PATIENT</th>
<th>Preop. [%]</th>
<th>Postop. [%]</th>
<th>Improvement [%]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1,6</td>
<td>0,9</td>
<td>44</td>
<td></td>
</tr>
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<td></td>
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<td>70</td>
<td></td>
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</tr>
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<td>4,9</td>
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<td></td>
</tr>
<tr>
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| MEAN BONE GRAFT | 63 % |

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</table>

| MEAN SPRING    | 91 % |
5. USER MANUAL

STEP 1.

The first step is to open MATLAB on your computer and open the m-file called “programtemporalhollowing” and press Run.

![Figure 10. Start page MATLAB.](image)

STEP 2.

The first window to pop up (Fig.1) is where the patient is chosen. An identical window will pop up afterwards to choose the control.

![Figure 11. Chose patient and control.](image)

STEP 3.

Step three is to choose different slices and anatomical structures for the rotation of the 3D-matrices. A window (Fig. 2) will pop up. The text above the image shows the chosen patient. Use the slider to scroll between the slices. Three slices are supposed to be chosen. Scroll to the slice which shows the middle of sella turcica and click on the pushbutton “Sella turcica”. The slice shown when you push “Sella turcica” is chosen. Scroll to the slice showing the first slice of the temporal fossa on the left side and click on “Select fossa temporalis left”. Scroll to the slice showing the first slice of fossa temporalis on the right side and click on “Select fossa temporalis right”. When all three slices are chosen, push “Done” and repeat step three for the control.
Figure 12. Select slice for the middle of Sella turcica and the bottom of right and left temporal fossa.

**Step 4.**

The first slice shown is the slice showing the middle of sella turcica. Click on the foremost point of the head as shown in figure. Thereafter click in the middle of sella turcica (Fig. 13 b). Fig. 13 c shows a sagittal slice. Click on the nasion. Repeat for the control.

Figure 13 a. Figure 13 b. Figure 13 c.

*Fig. 13 a shows how to choose the foremost point of the skull. Fig. 13 b shows how to choose the point in the middle of sella turcica. Fig. 13 c shows how to choose the point for nasion.*

**Step 5.**

Step five is to choose the start slice. The 3D-images are now rotatated to be aligned the same way. Use the slider as before and choose the slice above the orbital roof by pressing “chose start slice” and “Done” (Fig. 14). This window can also be used to control that the rotation was made correct by scrolling through the slices. Repeat for the control.
Figure 14. The starting slice is the first slice above the orbital roof.

**STEP 6.**

The last step is to manually match the patient with the control. The computer has made a first match and it’s only an adjustment to be made in this step. A window (figure 15) will pop up showing the outer bone structure as two white lines. The control is moveable. Use the slider and click on done when the suitable match has been made.

Figure 15. Match the patient and the control by using the slider.

The results will be displayed in the MATLAB command window but will also be saved in a dat-file called myPatientData.dat. This file will be overwritten when another patient is chosen so in order to save the data and continue with next patient the results needs to be copied to a new file.
6. DISCUSSION

In the development of the MATLAB tool the method was first to use all slices from the start slice above the orbital roof to the last slice of the stack. Since the program segments the outer bone contour this was not possible mainly because of the absence of bone in the fontanel. The alternative method was to use as many slices as possible without having to exclude any patients because of the fontanel. Similar to the fontanels large sutures also lack bone. For large sutures the program will not be able to fill them and calculate the outer bone structure. By using the first 3.5 cm after the start slice no patients had to be excluded from the study due to the fontanel or large sutures. During the first 3.5 cm the ratio of temporal hollowing was within a small range and it was noted that the largest ratio often was in the first slices. The mean for the position of the largest ratio was located 3.6 mm after the starting slice for the preoperative patients and 6.6 mm after the starting slice for the postoperative patients. Therefore only one slice, after 3.6 and 6.6 mm was measured for the preoperative and postoperative patients respectively.

Another problem leading to exclusion of controls was that the nasion was not included in the images which meant that a correct rotation could not be made. In contrast, this was never a problem with the patients since their CT scan includes the complete volume of head.

For bone segmentation the threshold was set to 100 HU. That is a low limit for bone but it gives the best results when using this software. Using a higher CT value, the sutures was to large for the program to fill. The bones of the skull of small children is very spongious which lowers the CT value. Another factor that lowers the CT value is the interpolation which creates new slices where bone is mixed with air. A lower CT value also makes it easier to handle the sutures which otherwise might create a great issue when finding the outer bone contour.

The used measurement area was defined to only include the temporal area. The orbital roof was used as a caudal limit as it is the caudal limit of the frontal intracranial volume and easily defined in the images for all patients. The posterior limit was chosen to be the widest point of the skull since it is a well-defined point and close to where the temporal area ends. The coronal suture and the auditory meatus are other option for the posterior limit. The coronal suture is easy to define for most preoperative patients but for the 3 year old postoperative patients the suture has fused and is much harder to detect which is why the widest point of the skull was chosen instead. The same reason applies for the auditory meatus. It defines the temporal area well but is hard to define in the CT-scans.

Only one slice is selected to be measured for all patients. The selection is based on the rotation, form of the skull and the location of the largest differing area. The structures used for image rotation are all situated below the orbital roof. The further away from the structures the slice is the less precise is the rotation of the chosen slice. The form of the head has more influence of the differing area in slices more cranial. This implements to choose a slice close to the starting slice.

Measurements to calculate the intra-user variability was made for both preoperative and postoperative patients in case there might be differences in how difficult it would be to define structures. There was no significant difference between preoperative and postoperative patients in this respect. Both intra and inter user variability were minor, indicating a well-functioning method.

Using a thinner slice thickness would be better given a better resolution in the sagittal plane not having to interpolate as many new cross-sections between the original slices. As 5 mm is the most frequently used slice thickness it’s hard to find controls with thinner slices than 5 mm.
7. CONCLUSIONS

A MATLAB-tool for calculation of the ratio between the differing area defined as temporal hollowing and the total frontal area in patients with metopic synostosis was constructed. Repeated measurements of the ratio has been made and the software has a good precision with a deviation of 0.14 %. It will be a useful tool for comparing different surgical techniques used to treat metopic synostosis.

8. FUTURE ASPECTS

The method developed in the present work will make it possible to determine the temporal hollowing in large groups of patients. Thereby, it will be possible to compare different surgical techniques with respect to their ability to correct skull shape in the temporal region.

9. ACKNOWLEDGEMENTS

I would like to thank my supervisors Lars Kölby, Emma Wikberg and Peter Bernhardt for all the support through this work. I would also like to thank Tobias Magnander and Jonas Högberg for all the pleasant coffee breaks.
10. REFERENCES

9. <quantitative evaluation of bone density using the hounsfield index.pdf>.