Three-Dimensional Visualization in Medicine: A New Approach to Assessing Changes in Facial Relief to Improve Treatment Outcomes for Patients with Deformities and Asymmetries

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ABSTRACT:

The appearance of digital three-dimensional models of patients obtained by photogrammetric methods in the clinicians' arsenal has led to the fact that doctors can objectively make comparisons of structural (morphological) changes that occur in the course of treatment. The experience of using such technologies in neurology and evidence-based medicine is very small, while the number of diseases leading to facial changes is quite impressive. The simplest method of comparison is made by subtracting digital facial topography models. However, this method does not take into account the facial topography to the fullest extent. This paper proposes a method for estimating facial topography changes from three-dimensional polygonal models of the face. This method can detect and visualise the difference of changes closest to physiological plausibility. Finally, we provide several examples of analyses of facial topography changes, including statistical evaluation and comparison of the results of the two evaluation methods.

1. INTRODUCTION

The 21st century was a technological breakthrough in the means of three-dimensional reconstruction and visualisation of real objects. One of the most promising and important directions is three-dimensional modelling in medicine.

Modern digital photography equipment and programmes for automatic processing of digital images allow to obtain and measure with predictable accuracy, within the range from 0.2 mm to 2.0 mm (Verhulst at al., 2018; Savoldelli at al., 2019; Mao at al., 2022; Staller at al., 2022; Skrypitsyna at al., 2023) three-dimensional models of objects, including the human body, which allows obtaining objective estimated parameters of both the whole human body and its various parts (Khambay at al., 2008; Kozhevnikova at al., 2012; Nord at al., 2015; Pesce at al., 2016; Skrypitsyna, Spiridonova, 2018). Such technologies are in demand for the creation of artificial internal organs, prostheses or corsets. The appearance of digital three-dimensional models of patients in the arsenal of clinicians has led to the fact that doctors can objectively make a comparison of structural (morphological) changes that occur in the course of treatment (Kozhevnikova at al., 2012). The principle behind comparison methods is to compare the position of landmarks, distances (along a straight line or along a surface between landmarks), surfaces or volumes on a three-dimensional digital model of a patient's body (body part) before and after treatment (Sforza at al., 2010, 2012; Skrypitsyna, Kozhevnikova 2016, Sitaropoulou at al., 2020; Othman at al., 2020; Skrypitsyna at al., 2023).

Creation of three-dimensional facial models for therapeutic purposes is one of the most demanded tasks in medicine. Modelling is most often used in the treatment of craniofacial diseases and in orthodontics (Khambay at al., 2008; Sforza at al., 2012; Choi at al., 2018; Jung at al., 2018; Favero at al., 2019; Pojda at al, 2021; Mao at al., 2022), for planning the results of plastic surgeries, and in forensics and face identification systems (Zhou, Xiao 2018; Kukharev, Kazieva, 2019; Abbas at al., 2019). The experience of applying such technologies in neuroscience and evidence-based medicine is very small while the number of diseases leading to facial changes is quite impressive (stroke, Lyme disease, paresis of facial muscles caused by surgical interventions, etc.). And the change in appearance caused by such diseases leads to a deterioration in the life quality of a person. Methods of the therapy of neurological diseases represent a long sequence of various procedures that restore the usual appearance. Each stage is accompanied by an evaluation of the results of the treatment. Three-dimensional digital models are best suited for objective assessment of the dynamics of facial changes in the course of treatment, which will help clinicians to more accurately select therapy for a particular patient based on his or her individual characteristics.

This study is devoted to the development of methods and algorithms for creating and comparing multi-temporal digital models of the human face.

We proceed from the fact that changes in the surface of the face are expressed in changes in its facial topography. This is a consequence of the work of a complex system of facial muscles under the influence of nerve impulses of various origins.

On the one hand, the study of such displacements is similar to monitoring changes in the Earth's surface, under the influence of landslide processes or carst processes. Analyses of such dynamic processes have been successfully carried out using photogrammetric methods (Westoby at al., 2012; James at al., 2017). Therefore, it is quite obvious that we are entitled to use the tools of photogrammetry and GIS analysis to assess the change of the face surface.

On the other hand, for exogenous processes that occur on the Earth's surface we understand the forces that act on the moving surface. For example, a landslide begins to move down a slope due to gravity, and we can predict the direction of its movement. On the face, however, these displacements can come from many different directions. And to determine the cause and effect of changes in facial topography, it is very important that

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local changes are correctly represented in three dimensions on the surface of the overall facial model.
In addition, moving objects on the Earth's surface are in a stationary environment, which makes it possible to use stable reference points (markers) for relative orientation of multi-temporal models.

When studying the facial muscle movement, patients perform a series of facial tests and may shift relative to the surveying equipment, so it is difficult to speak about constant common reference points for all models. Therefore, a separate task is to overcome systematic errors that inevitably arise when there is a lack of stable anatomical landmarks.

It should also be noted that often the problem of integration of modern digital methods in medicine, as a sphere far from topography, is the complexity of perception of the proposed solutions. Thus, in a number of cases, it is necessary to train medical specialists and provide constant methodological and technical support. At the same time, it is important to introduce a work algorithm that is understandable for an untrained specialist and that produces a maximally unambiguous and visual result (not only numerical estimation, but also visual display).

2. METHODS FOR DETERMINING ASYMMETRY

In order to assess right-to-left asymmetry and facial muscle mobility, patients are asked to perform a series of facial mimicry tests. This process may be repeated several times over a time interval during the course of treatment. Thus, it is necessary to analyse the facial models in a series of surveys and compare the different temporal models with each other.

The topographic method of facial topography visualisation in the form of isolines highlights all morphological features of the face well (Skrypitsyna at al., 2023), but, as practice has shown, is difficult to perceive for medical workers and requires additional skills to interpret the results. It is also inconvenient to perform statistical analyses of areas of change.

The simplest way of comparison is made by subtraction of digital models of facial topography (DEM) of a quiet state of the face from DEM of any facial mimicry test (Fig. 1). The subtraction uses the bilinear interpolation method. In order to visualise the result, a scale is set to assess the change in facial topography (Skrypitsyna and Spiridonova, 2018; Mao at al., 2022; Skrypitsyna at al., 2023).

Figure 1 shows three digital patient models, each consisting of two layers: a hill-shadow DEM and a difference matrix. Obviously, this method allows changes, to see volume increases and decreases and to determine the areas of changes.

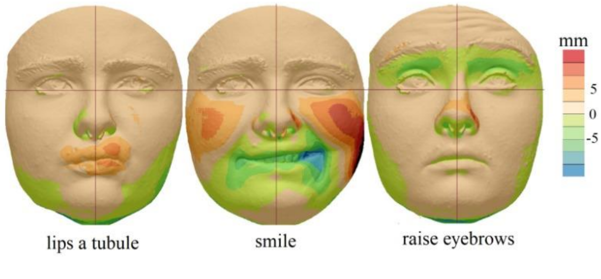

Figure 1. Difference matrices used for diagnostic visualisation of facial topography changes.

However, it should be noted that, while simple to calculate, the cartograms of changes have a number of significant disadvantages associated with the fact that projection takes place on a plane rather than on the surface of the skull (Fig. 2).

Firstly, the reliability of DEM comparison depends on the location of the working plane on which the DEMs are built. Usually, this plane is set manually and is oriented perpendicular to the sagittal plane of the skull, having some deviation from the vertical plane. It is built on the two most protruding points located at the tip of the chin and at the eyebrow line (Fig. 2).

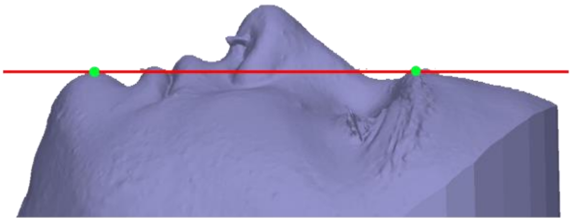

Figure 2. Working plane location for face DEM generation.

To exclude negative values, the plane is lowered by a fixed value. For women this value is 10 cm, for men 14 cm. In this case, the sagittal plane is built relative to the position of the eyes, passing through the middle of the supraperiosteum, dividing the head into two symmetrical halves - right and left. It is impossible to determine the sagittal plane accurately due to the lack of clear landmarks on the face. This problem is exacerbated when analysing patients with severe facial asymmetry. This means that there is uncertainty in the position of the working plane from survey to survey.

Secondly, in principle, it is incorrect to consider the face surface (from ear to ear) as a plane, because the curvature of the object can be ignored only if the size of the area does not exceed 0.1 of the mapped object radius. In fact, changes in facial face topography occur perpendicularly along the normal to the head surface (Fig. 3).

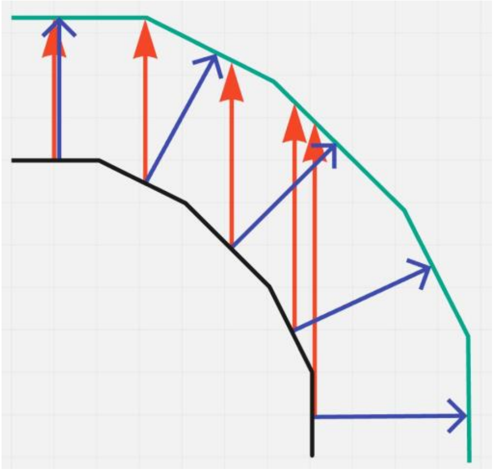

Figure 3. Methods of change measurement: along the specified direction (red), along the normal (blue).

In Figure 3, the shape of the measured object is drawn in black, the shape of the reference object is drawn in green, the deviation of models perpendicular to the working plane is drawn in red,

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and the deviation determined along the normal to the surface of the measured object is drawn in blue.

Thirdly, it is impossible to obtain muscle mass volumes by raster analysis from DEM plotted on a plane.

This study proposes an alternative method of change estimation that identifies and visualises the change difference closest to physiological plausibility.

The comparison of geometric deviations between two models relative to each other is performed by measuring distances projected from measured points of one model onto the initial model in a given direction. Each measured vertex is defined by coordinates on the new (measured) model and on the initial model, while the position on the initial model is defined by the projection direction along the normal.

The resulting values of the changes are displayed on the 3D model as a colour range map, which allows the change in facial topography to be assessed. The comparison results can be intuitively analysed globally or locally by annotating at specific positions. Deviation results ‘+ (Plus)’ or ‘- (Minus)’ show whether the measured data area or feature is larger or smaller than the original data.

3. DISCUSSION OF RESULTS

To analyze the proposed solution, three images of a patient diagnosed with a cut (numbness) on the right side of the face (in the illustrations in mirror image - this is on the left) were used. In each session, the patient performed 3 facial expression tests. During the treatment, models were built every 14 days.

To obtain digital models of the face, photographs obtained by a multi-camera photogrammetric system were used (Skrypitsyna et al., 2023). The setup, consisting of 11 Canon 2000D digital cameras with a sensor size of 6000x4000, a physical pixel size of 0.0037 mm and a focal length of 55 mm, was theoretically calculated to obtain a nominal spatial pixel size of 0.05 mm. In practice, the setup allows you to get a pixel size of about 0.06 mm.

Photogrammetric processing was performed using standard technology in the Agisoft Metashape Pro program and is described in sufficient detail in the previous study (Skrypitsyna et al., 2023). Then, polygonal models were built based on the depth maps. To compare the methods for assessing the dynamics of treatment, a DEM was built based on the model.

For all constructions, the Average quality was used, which corresponds to working with the second level of coarsening of the original images. In this case, the density of the model is on average about 0.08 mm^2 per polygon or about 110 points per 1 mm2, and the height matrix has a resolution of about 0.27 mm. When working with source images at high accuracy, it is necessary to use significantly more computing resources, which affects the processing time, but as a result, the noise in the final products increases without improving the quality of the surface.

To determine the topography changes in 3D models, we used the Geomagic Control X software platform for geometry and quality control when working with 3D models. To compare the methods, the difference matrices of the DEM were built in QGIS. The color scale and ranges were set the same as for the difference matrices. Figure 4 shows the color maps of the changes in facial topography, made by two methods.

To illustrate the determination of changes in facial topography by the DEM and the 3D model, we used three facial expression tests: pursing the lips, smiling and raising the eyebrows. Each test was performed three times, after 14 days. The sessions are designated by numbers 1, 2, 3. To monitor the treatment, sequential subtraction was performed: the model of the first session (2-1) was subtracted from the model of the second session, and then the model of the second session (3-2) was subtracted from the model of the third session.

It is visually obvious that the changes in the flattest part of the face - on the forehead, were determined in the same way in both methods. A completely different result is obtained in the cheek-temporal zone, on the wings of the nose and cheekbones - in a word, where there are strong bends in the topography. These differences are especially visible when raising the eyebrows.

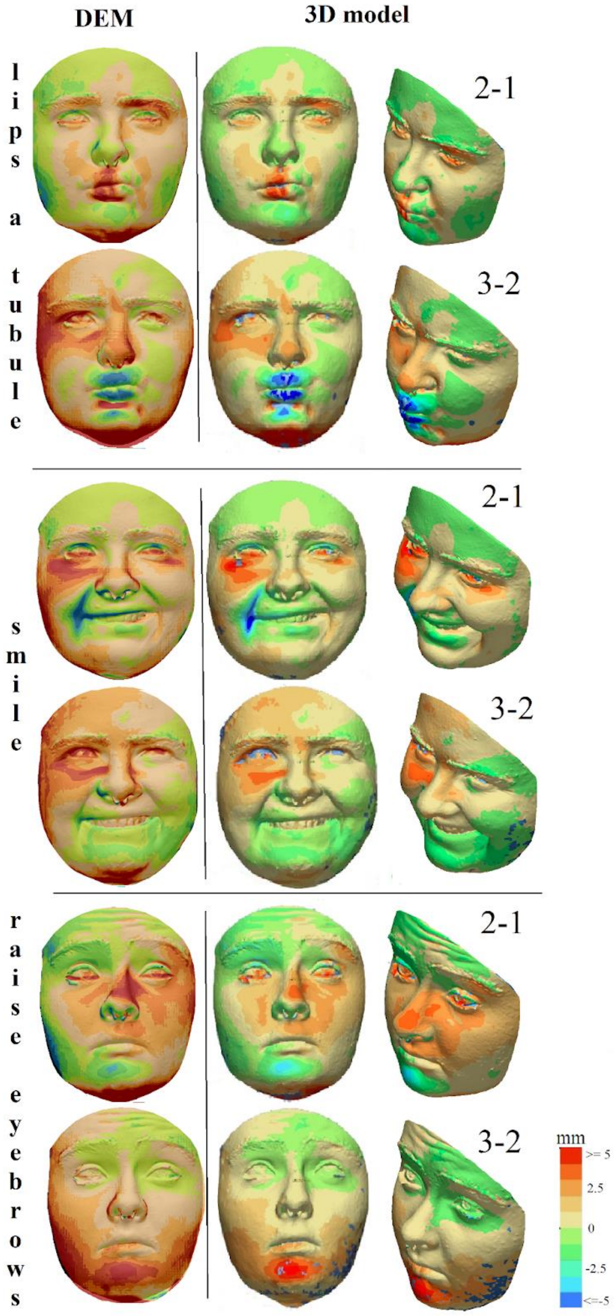

Figure 4. Comparison of two topography assessment methods

Also, to compare the two methods of assessing changes (D) in facial topography, an array of 54 points was specified (Fig. 5). Due to the lack of marking, 45 points were collected on a regular grid and 8 points were measured on key, reliably identifiable areas of the face. For all these points, values were obtained from both the difference matrix and the model. The models themselves can be seen in Figure 4, first row.

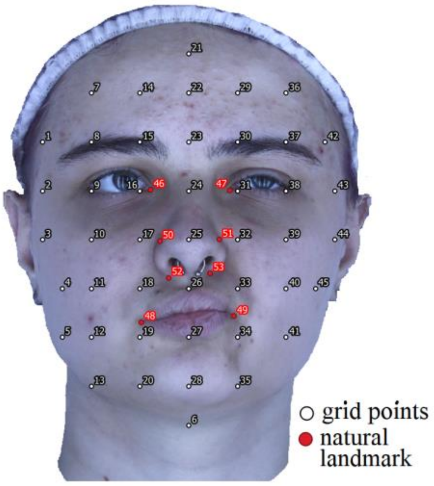

Figure 5. Point locations for comparing the two methods for assessing changes (D) in facial topography.

The standard deviation (δ) at the points is within 2 mm. Values less than δ are the points located in the frontal area of the face with the smallest inflections. These values can characterize the systematic error that occurs as a result of interpolation when constructing the DEM and 3-D model. Errors in the range of δ-2δ refer to the points located along the edge of the face or on the nose. Their distribution over the area of the face depends on the facial expression test performed. The array also contains rough measurements with values greater than 2δ. In all graphs, these errors are located in the same places. The peak on the left is point #6, which is on the neck. The peaks on the right refer to the points (58-53), which were measured in the area of the nasolabial folds and the wings of the nose.

Around these points, local areas of convex or concave areas on the face are created, which are not actually there.
Therefore, our hypothesis that the DEM does not correctly represent facial topography is reasonable.

mimicry test name	Lips shaped like a tube		Smile		Raise eyebrows	
	2-1	3-2	2-1	3-2	2-1	3-2
Max(-) (DDEM-DMod), mm	-6.04	-1.34	-3.97	-2.05	-5.20	-1.56
Max(+) (DDEM-DMod), mm	3.45	9.35	7.22	8.78	7.20	9.43
St.dev (DDEM-DMod), mm	1.34	1.70	1.40	1.43	1.64	1.88

Table 1. Main evaluation parameters

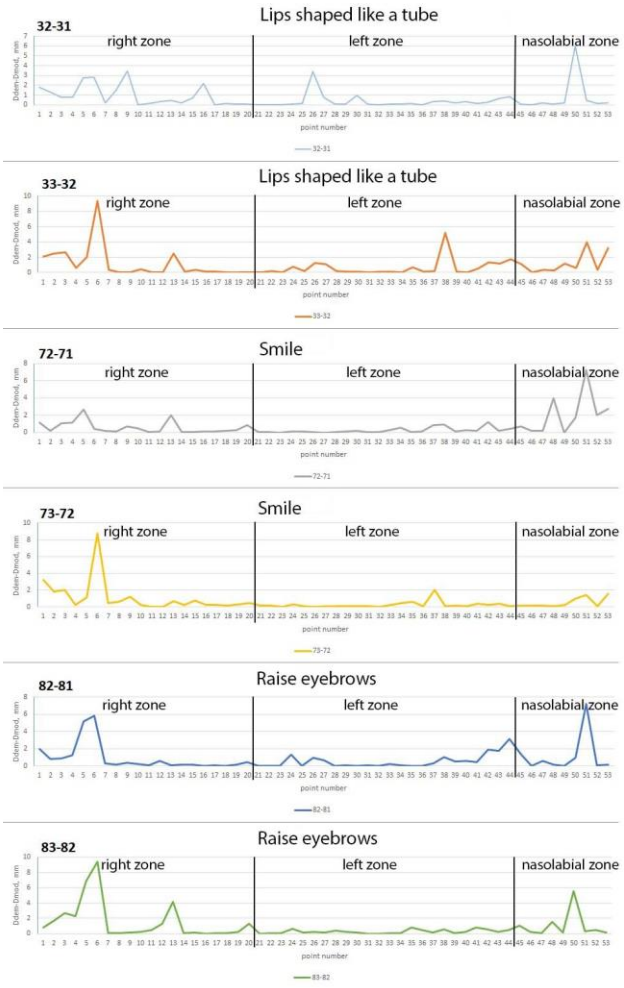

Figure 6. Graph of errors in determining heights using the difference matrix.

4. EVALUATION OF CHANGES IN FACIAL RELIEF CALCULATED FROM 3-D MODELS

At this stage, there are no universally accepted indicators in neurology and aesthetic medicine that would evaluate the results of treatment using digital models. With the advent of a new comparison method for evaluation, the following parameters can be proposed that can serve as a numerical measure for evaluating disease treatment:
Min: The greatest negative change. Describes the maximum decrease in volume.
Max: The greatest positive change. Describes the maximum increase in volume.
Median is the "middle" value. In this case, this parameter helps to evaluate which values are more - positive or negative.
Average is the average value by module. Shows, on average, the magnitude of changes occurring in the facial relief, regardless of the sign.
Std. Dev. can be proposed as a standard deviation of all values as a general measure of changes that occurred during treatment. A decrease in the standard deviation will indicate a decrease in the effect of relief changes.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(D_i - A)^2} \qquad A = \frac{1}{n}\sum_{i=1}^{n} D_i ,$$

Where D - the magnitude of the change;
n - number of measurements;
A - the arithmetic mean of all changes.

The assessment of changes in facial relief was carried out for all vertices of the D models.

Session numbers	**Sample name**	Min, **mm**	Max**., mm**	**Mediana, mm**	**Average, mm**	**Std. Dev., mm**
1-2	Lips shaped like a tube	-2,5	6,4	0,14	0,73	0,97
2-3		-7,5	10,6	0,72	1,03	1,40
1-2	Smile	-7,3	5,6	0,20	0,79	1,12
2-3		-3,1	6,5	0,50	0,86	1,05
1-2	Raise your eyebrows	-3,6	6,5	0,28	1.14	1,37
2-3		-1,7	5,6	0,44	0.65	0,88

Table 2. Main evaluation parameters

This table shows that in the interval between the first and second sessions, the largest area change in facial topography could be seen when performing the “raise eyebrows” test. In the interval between the second and third sessions, the effectiveness of the treatment is most noticeable when performing the “Tubular lips” test. The median parameter for all tests increases between the second and third sessions, which means that there is a general increase in volumes.

Of course, the presented sample is small enough to conclude certain statistical regularities. Nevertheless, this method of assessment with visual control by models will allow further numerical evaluation of the results of treatment of patients, which is an important factor in the selection of therapy and for the purposes of evidence-based medicine

5. CONCLUSIONS

The conducted comparative analysis of the proposed approach with the traditional method of visualizing changes in facial topography showed positive prospects for the proposed approach.

The proposed method takes into account the following positions as its main advantages:
1. Increased processing efficiency (since it contains fewer operations in the algorithm from the initial data to the obtained result);
2. Increased information content due to visual three-dimensional display. Models, unlike DEM, are dynamic, so changes can be analyzed from different angles. This is especially valuable when studying the lateral parts of the face (cheek and temporal areas) and the chin.
3. Minimization of errors caused by recalculating the face model into a digital relief matrix.

In conclusion, taking into account the above factors, the proposed approach to visualizing changes in facial topography is as visual as possible and can be effectively used in the practice of treating patients with facial deformations and asymmetry in compliance with accuracy requirements. This approach allows for a more accurate and visual assessment of changes in facial relief and visualization of them in three-dimensional space.

Future plans include developing a method for assessing right-left asymmetry.

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