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Principles of computer planning in the functional nasal surgery

***Abstract**. The theoretical foundations and principles of computer planning for functional rhinosurgical interventions are proposed in this paper. The theoretical base, stages and possibilities of computer planning for functional nasal surgery are described. Computed surgical planning should be based on a complex anatomical and functional model, that combines data from X-ray computed tomography (X-ray CT) with the results of functional studies from rhinomanometry. Practical recommendations for evidence based surgical computer planning are discussed. Future of proposed method is to study the effect of various anatomical structures of the nasal cavity on the aerodynamic characteristics of the nasal airways and the creation of a database with containing information about the type changes of nasal resistance at typical rhinosurgical interventions*

***Streszczenie.** W artykule zostały zaproponowane podstawy teoretyczne i zasady komputerowego planowania zabiegów neurochirurgii czynnościowej. Zostały opisane podstawy teoretyczne, etapy i możliwości planowania komputerowego w czynnościowej chirurgii nosa. Planowanie komputerowe w chirurgii powinno bazować na kompleksowym anatomicznym i funkcjonalnym modelu, który zawiera wyniki rentgenowskiej tomografii komputerowej i badań funkcjonalnych rynomanometrii. Zostały omówione praktyczne zalecenia dotyczące komputerowego planowania opartego na dowodach w chirurgii. Przyszłością zaproponowanej metody jest zbadanie wpływu różnych struktur anatomicznych jamy nosowej na charakterystyki aerodynamiczną nosowych dróg oddechowych i stworzenie bazy danych zawierającej informacje o zmianach oporu nosowego przy typowych zabiegach neurochirurgicznych (**Zasady planowania komputerowego w czynnościowej chirurgii nosa**).*

Keywords: evidence based medicine, functional rhinosurgery, medical visualization, surgical computer planning, tomography, nasal airways
Słowa kluczowe: medycyna oparta na dowodach, neurochirurgia funkcjonalna, wizualizacja medyczna, komputerowe planowanie w chirurgii, tomografia, drogi oddechowe nosa

Introduction

One of the most actual social problems, at present, in all industrially developed countries around the world is the development and introduction of new medical technologies to improve quality of health care, which is confirmed, in particular, the priority areas of the 7th Framework Program of the European Union [1] and its continuation - the program «Horizon 2020» (Program EU "Horizon 2020/H2020") [2]. The use of modern information technologies in medicine can significantly improve the quality of diagnosis and treatment of various pathologies by providing the clinician with additional, advanced information about the disease process, the use of high-precision surgical instruments and means of functional control [3-5].

The direction associated with computer planning of surgical interventions, has become in the last two decades, a logical development of methods for diagnostic imaging [5-7]. Computer planning is a virtual simulation of surgical intervention in order to determine the optimum impact on the criterion of the maximal therapeutic effect and minimal invasiveness on the basis of the prognostic indicators.

The relevance of computer planning systems of surgical interventions is particularly acute in the poorest regions by means of functional diagnostics – rhinology. One of the main tasks is to develop methods of restoration of nasal breathing disorders on the basis of accurate diagnostic information about the aerodynamic characteristics of the air flow in the nasal cavity and the anatomical and functional status of the upper respiratory tract [7-9].

Initially, three-dimensional computer modeling technology in rhinosurgical planning began to be used in conducting the external aesthetic rhinoplasty for predicting outcome and evaluation cosmetic effect [10, 11]. Various authors have considered aspects of getting digital images of face to predict and evaluate the results of cosmetic rhinoplasty [12]. There was also a lot of works on forecasting the results of endonasal interventions on base of introscopy data during rhinoplasty and treatment of various forms of sinusitis [13], considered choices of surgical access to the maxillary [14] and the wedge-shaped sinuses.

However, during the diagnosis and planning based only on the anatomical features according to the introscopy mapping (for example, by applying pre- and post-operative 3D-models), the functional component is not included in the assessment of the upper respiratory tract. Therefore, in recent years the majority of studies aimed at observing the restoration of nasal breathing after treatment according to the objective function rhinomanometry survey methods [6-9]. It is carried out justification of the necessity of monitoring of nasal aerodynamics indicators in functional rhinoplasty, which are the basis for determining of level of the operational treatment [15], and the use of computer modeling to study the nasal cavity geometry.

However, most researches are purely theoretical and developed models have large computational complexity and it is difficult to apply them for the assessment of nasal breathing function of real patients in the planning of operations in the practical rhinosurgery. At the same time, as a rule, there is no analysis of the efficiency of the procedure of surgical planning, as well as there are no clear quantitative criteria and methods of prediction and assessment of achieved therapeutic effect.

Experimental

The purpose of computer planning of functional rhinosurgery based on the configuration principle [7] is the prediction and assessment of results of endonasal surgery on the basis of allocation of areas of the nasal cavity with the greatest air resistance which must be surgically corrected according to the results of aerodynamic simulation based on X-ray spiral computer tomography (SCT) and rhinomanometry. The main working hypothesis in this case is that difficulty in breathing caused by an increased aerodynamic resistance of the nasal passages.

Thus, the purpose of the work is to create the theoretical foundations of computer planning in the functional rhinosurgery and justification of indicators of the effectiveness of evidence-based medicine criteria.

Determination of the aerodynamic resistance of the nose. The input data for functional computer planning of surgical interventions in the functional rhinology are the following:
– the halftone voxel model based on endoscopic SCT-mapping which contains information about the anatomical and geometric proportions of the upper respiratory tract;
– rinomanometry diagnostic results (indicators of air resistance, pressure difference and air flow in the nasal cavity at different modes of breathing).

The flow of air in the nasal cavity is accompanied by losses of pressure, both in length and in the local resistances which cause vortex formation due to changes in basal areas (expansion or contraction) or changing the direction of air flow. A fundamental role in these calculations is to determine the mode of air flow. Taking into account that in most modes of breathing there is turbulent air flow in the nasal passages [9], the basic formulae for calculating air resistance are given for the turbulent flow regime.

If consider the nasal cavity as a parallel connection of three nasal passages we can make the following assumptions:
– the total volumetric flow Q_S through the nasal cavity according to the continuity equation is the amount of volume flows Q_A and Q_B through the left and right nasal passages, respectively:

(1) $$Q_S = Q_A + Q_B\,;$$

– pressure loss in each nasal passage (Δp_A, Δp_B) is determined from the constant pressure drop between the common input (in the nostrils) and access to the nasopharynx (in the area of choanae):

$$\Delta p_A = \Delta p_B = \Delta p = const\,;$$

– total aerodynamic nasal resistance $A_{//}$ of parallel (left and right) nasal passages in the turbulent regime is the ratio of the pressure difference Δp between the input and output holes of the nasal cavity to the square of the total volumetric flow rate and it is calculated as $A_{//} = \Delta p / Q_S^2$.

Taking into consideration sizable mutual influence of local resistance, associated with abrupt changes in the air channel configuration with a small total length of the nasal cavity, the calculation of pressure loss for local resistance can be neglected and calculations can be limited to calculation of losses along the length of the nasal passages, according to [15]:

(2) $$A_A = \sum_i \lambda\rho \frac{\Delta l_{A.i}}{d_{A,i} 2S_{A,i}^2}\,;\; A_B = \sum_i \lambda\rho \frac{\Delta l_{B.i}}{d_{B,i} 2S_{B,i}^2}\,,$$

where ρ =1,205 kg / m^3 is the density of the air, Δp_A and Δp_B are the pressure loss over the length of the left and right nasal passages, respectively, $\Delta l_{A,i}$, $\Delta l_{B,i}$ are lengths of i-th calculated sections of the left and right nasal passages, respectively, $S_{A,i}$ $S_{B,i}$ are areas of calculated sections of the left and right nasal passages, respectively, $d_{A,i}$, $d_{B,i}$ are characteristic dimensions (hydraulic diameter) of i-th sections of the left and right nasal passages [9], respectively, λ is dimensionless coefficient of hydraulic friction, equal to $\lambda = 0{,}32 / R\mathrm{e}^{0{,}25}$ for turbulent regime of the air flow [15].

Total air flow through the nasal cavity can be defined by the formula (1) taking into account expressions (2):

$$Q_S = Q_A + Q_B = \sqrt{\frac{\Delta p}{A_A}} + \sqrt{\frac{\Delta p}{A_B}}\,.$$

Thus, during the computer configurational surgical planning aerodynamic resistances of the nasal passages in the original (pre-operative) state and after virtual changing of the configuration of the anatomical structures of the nasal cavity are calculated. Then we calculate coefficients that characterize the relationship of nasal resistance values before and after the virtual correction and determine intervention option corresponding to the largest values of these coefficients, taking into account the physical possibilities of the implementation of changes in anatomical structures during surgery. Similarly, it is possible to evaluate the effectiveness of treatment and the overall effectiveness of computer planning by finding the corresponding coefficients after the real surgical intervention.

Virtual modeling of the nasal cavity configuration is performed according to the base algorithm of 2D-warping in the plane of each living section of the nasal channels. To change the configuration of anatomical objects it is performed the definition of a regular grid of initial reference vertices $T_S(x,y)$, where each object should have no less than 2 peaks (at the Nyquist criterion), as well as set the displacement (strain) vectors $\vec{P}_l(P_x, P_y)$ for each of the *l*-th predetermined reference peaks:

(3) $$T_B(x_i, y_i) = T_S(x_i, y_i) + s_r(d_{i,l}) \cdot \vec{P}_l(p_x, p_y)\,,$$

where T_S and T_B are original and moved points, respectively, $s_r(d_{i,l})$ is deformation scale factor, determined on the basis of values of the degree of deformation elasticity coefficient b, distance $d_{i,l}$ from *i*-th point of raster to *l*-th defining reference peak and radius r of deformation action (usually equal to half of the grid spacing), by the formula

(4) $$s_r(d_{i,l}) = 1 - \left(\frac{d_{i,l}}{r + k_d}\right)^{b+1}.$$

To eliminate defects in the warped image which are in the "cuttings" of intensity on a raster, the averaging filter technique is used for converted image data. Thus, the method of the virtual deformation of the nasal structures consists of two phases: at first, the interactive movement of reference peaks, and then the deformation of the raster elements associated with each reference peak. The subsequent stage is the interactive adjustment of the simulated anatomical objects at which the geometric constraints are introduced, such as the thickness of the bone and cartilage structures, and mucous membranes.

Results and discussion

Let us consider practical realization of the proposed method by the example of computer planning and evaluation of functional endonasal septoplasty. In the preoperative stage it is performed study of nasal breathing function according to the rhinomanometry and SCT-study of the nasal cavity. The first stage is the construction of frontal multiplanar reconstruction of the upper respiratory tract, nasal segmentation and determining of the geometric characteristics of their sections, such as area, perimeter, and the hydraulic diameter [9] for the calculations according to the formulae (2) with the step (2 mm) between the sections of the nasal passages, and air flow 1.15 l/s at a differential pressure 6 kPa according to data of rhinomanometry. Then an expert performs the movement of primary reference peaks on the front multiplanar spiral CT reconstructions (clearly visible septum deviation to the right) (Fig. 1a) and warping program calculates the new coordinates changing anatomical objects (see Fig. 1b) according to the formulae (3) and (4). For comparison, at figure 1, it is shown frontal SCT-reconstruction of the same portion area of the nasal cavity, performed after 2 months of surgery.

Next step is calculation of aerodynamic resistance for left and right nasal passages determined according to the formulae (2) on the initial and simulated data (see Fig. 2) (number of sections n = 35, slice thickness 2 mm). The initial (pre-operative) data are shown in Fig. 2a and 2b. Virtual simulation results (see Figs. 2c and 2d) show a decrease of aerodynamic resistance of critical areas (in sections 11 to 29) of both nasal passages more than 2.5 times (in some sections). For comparison, Figs. 2e and 2f show postoperative data (SCT-study was carried out after 2 months of surgery).

Curves of integral nasal resistance (at summation over the length of the nasal cavity) are shown in Figs 3a and 3b, respectively.

As seen from Figs. 2 and 3, the maximum aerodynamic resistance (1) increases at the entrance to the nasal cavity (the resistance of the nasal valve, section 1 - 5), in the area between the 10th and 30th sections, due to the curvature of the nasal septum. Comparatively small asymmetry (20%) in the values of nasal resistance for the left and right nasal passages with the obvious curvature of the nasal septum to the right side (see Fig. 1a) is due to compensatory changes in configuration of the nasal turbinates. As it follows from Fig. 2, decrease of postoperative real total aerodynamic resistance (2) is more asymmetrically and larger (about 2 times) for the right nasal passage, in the direction of which there is a septum distortion, for the left nasal passage aerodynamic resistance decreased approximately 1.7 times. The predicted data (3) of computer planning differ from the actual progress after intervention on the value not exceeding 12%.

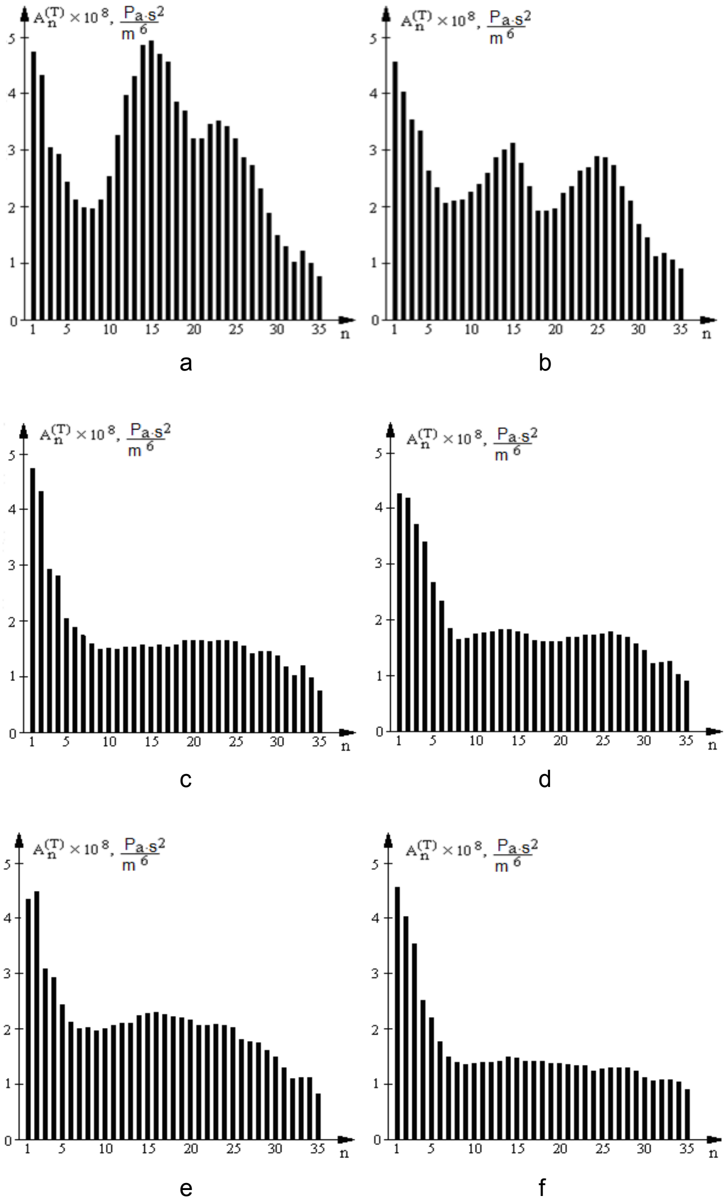
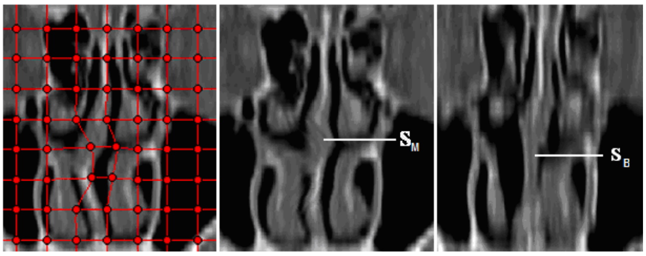
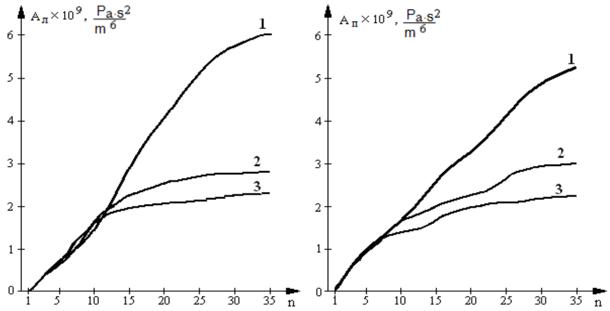


Fig. 1. Diagrams of change of aerodynamic resistance of portions areas of the nasal cavity by SCT-data during the turbulent regime for right (a, c, d) and left (b, d, e) nasal passages: a, b - by preoperative data; c, d - by virtual simulation; e, f - postoperative data after 2 months of surgery



a b c

Fig. 2. Two-dimensional warping on the initial reference points set as a grid: a - the original image; b - the result of warping; c - postoperative multiplanar SCT-reconstruction (S_M and S_B - modeled and postoperative position of the nasal septum)



a b

Fig. 3. Change of the total aerodynamic resistance during turbulent air flow mode along the length (by sections) of the nasal passages: a - for the right; b - for the left (1 preoperative, 2 - postoperative, 3 - projected data)

Conclusions

The basic principles of computer planning are:

– getting of initial diagnostic introscopy (CT) and functional (rhinomanometry) data;
– construction of complex deformable anatomical and functional model of the nasal cavity;
– prediction of functional result of surgical intervention for various respiratory conditions according to the correction of the nasal cavity structures virtual simulation;
– comparative analysis of the initial, simulated and post-operative data;
– verification of the results obtained by means of independent, for example, cytological and histological techniques.

Conducting of computer surgical planning should be based exclusively on the complex anatomical and functional model that combines introscopy data with the results of functional studies. Disadvantages of virtual modeling of rhinosurgery is lack of account of mobility, flexibility, and therefore the degree of change of various anatomical structures and tissue, as well as lack of strict compliance with the geometric deformation in the adjacent sections of the nasal cavity, it is leading to the appearance of stepped contours of anatomical structures during the formation of 3D-model and decreases adequacy of the virtual correction. When modeling, it is necessary to take into account that the basic requirement in modern functional rhinology is only a configuration change (correction) with the least possible resection of the anatomical objects. The total reduction of the aerodynamic nose resistance after the reduction of deformation of the nasal septum is on average no more than 1.5 times, according to the authors. Perspective of development of the proposed method is to study the effect of different anatomical structures of the nasal cavity on the aerodynamic characteristics of the upper respiratory tract and the creation of database containing information about the nature of changes of nasal resistance at typical rhinosurgery interventions.

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