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Computer-generated surgical simulation of morphological changes in microstructures: concepts of "virtual retractor"

Technical note

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The author's goal was to develop a computer graphics model to simulate the displacement and morphological changes that are caused by the retraction of fine intracranial structures.

The authors developed an application program to interpolate the contour of models of an artery and a retractor. The center of the displacement was determined by spatial coordinates, and the shape of the displacement of the arterial model was calculated by using a cosine-based formula with representation of a brain retractor. This computer graphics model was applied to the simulation of the displacement and morphological changes that occur when retraction is performed in the optic nerve. An illustrative case is presented, in which the optic nerve was displaced by a retractor to simulate the surgery performed in a carotid cave aneurysm of the internal carotid artery.

The authors have named this methodological tool "virtual retractor." This new navigational system for open microneurosurgery would be useful in teaching surgical microanatomy and in presurgical operative planning.

Key Words * microsurgical anatomy * three-dimensional imaging * spine function * brain shift * open neurosurgery * virtual reality

There are several recent reports that discuss intraoperative brain shift, and several trials have been undertaken to determine the correlation between brain shift and imaging characteristics of the displaced brain structures.[3,4,9,23,24] However, simulation of microstructures that are displaced by brain retractors in open microneurosurgical procedures is hardly possible. Although recent advances in techniques such as computerized tomography (CT) or magnetic resonance (MR) imaging have markedly improved in quality, they can hardly simulate the geometric relationships among microstructures in a deep area that are exposed after retraction of superficial structures.[5,8,12,20,21,28] In addition, brain atlas database or figures obtained from dissection performed in cadavers do not represent dynamic morphology that is encountered in open microneurosurgery.[22] The combination of displacement and morphological changes caused by retraction is one of the most important factors in surgical simulation of

open microneurosurgery. To achieve practical surgical simulation of microstructures, simulation of both displaced microstructures and representation of a brain retractor are necessary.

In this article, we describe a computer graphics model that simulates the displacement and morphological changes of microstructures caused by a brain retractor, and we have named this system "virtual retractor." It may be useful for teaching surgical microanatomy in presurgical operative planning for open microneurosurgery. The concept and technical details are described, and future possibilities in the simulation of microsurgery are discussed.

CLINICAL MATERIAL AND METHODS

System Design

We created an application program by using a spline function using a commercially available operating system and personal computer. A high-resolution computer monitor was required to display images with 16.77 million colors.

Models of an Artery and a Retractor

We made axial- and lateral-view images of models of an artery and a brain retractor that showed the contour of each structure. The arterial model was cylindrical, and the shape of the retractor was determined from the actual brain spatula. To show contours of these structures, the x, y, and z coordinates of each reference point were configured (Figs. 1 and 2).

Fig. 1. Axial (left) and lateral (right) views depicting surface contours of an arterial model superimposed on graph paper. This model is cylindrical and composed of 5 X 4 manually input points. The points A, B, C, and D illustrate each corresponding point between the axial and lateral projections.

After we entered input points, interpolated points were calculated by the application program, and each point was connected with lines that passed through in a regular order.[14]

Fig. 2. Axial (left) and lateral (right) views showing the surface contours of a model of a brain retractor superimposed on graph paper. The shape of the retractor is decided from the actual brain retractor. The points, from one to eight, indicate each corresponding point between the axial and lateral projections.

Displacement and Morphological Changes of the Arterial Model

To simulate the displacement and morphological changes in the arterial model, the center of the displacement was fixed in the spatial coordinate. The distance between the point and each polygon was calculated, and two points that showed the minimal and maximal distances were determined. The direction of the displacement was determined as a vector, aiming the center of the displacement toward the point that showed the minimum distance (Fig. 3 upper).

Fig. 3. Surface contours of the arterial model after displacement and morphological changes. Upper: The center of the displacement is decided in the spatial coordinate (open circle). The distance between the point and each polygon is calculated, and two points showing the minimum and maximum distances are determined. The direction of the displacement is selected as a vector, and the center of the displacement (open circle) is aimed toward the point that shows the minimum distance (closed circle). When the constant, F , is larger, the displacement becomes stronger (center and lower). The constant, N , is 5, and F is 0 (upper), 20 (center), and 40 (lower), respectively. d_{min} = minimum distance; d_{max} = maximum distance.

The intensity of the displacement was calculated using the cosine-based formula as follows:

$$g(\theta) = f \times \cos^N \theta$$

where F is a constant that determines the intensity of the displacement, N is a constant, (approximately five), that determines the shape of the displacement, and θ is a variable, that ranges from 0 to 90°. We

decided that the point that demonstrated the minimum distance corresponded to 0° , and the point that showed the maximum distance corresponded to 90° . The distance between the center of the displacement and each polygon was calculated, and the theta was selected according to the distance. When the F was larger, then displacement became greater (Fig. 3), and when N was larger, then the shape of the displaced model became concave rather than arc shaped (Fig. 4). When F and N were appropriately manipulated, we could obtain a model that simulated the displacement and morphological changes of the artery.

Fig. 4. Surface contours of the arterial model after displacement and morphological changes. When the exponent of cosine N is larger, then the shape of the displaced model becomes concave (lower) rather than arc shaped (upper). The constant F is 40 and N is 1 (upper), 3 (center), and 5 (lower), respectively. The open circle is the center of the displacement, and the closed circle is the point showing the minimum distance.

Representation of the Retractor

At first, the retractor was represented in a downward direction, and the position of the tip was at the center of the monitor. When the retractor was adequately rotated and the tip of the brain retractor moved to the point that indicated the minimum distance, we could use the model to illustrate the displaced artery and retractor under full color shading by using a Z-buffer algorithm (Fig. 5).[16]

Fig. 5. A computer-generated representation of the displaced artery and a retractor under full-color shading using a Z-buffer algorithm, perspective projection. The original direction of the retractor is downward. The tip of the retractor is moved to the point that shows minimum distance (closed circle), and the model of the artery and retractor is rotated. The open circle is the center of the displacement. Rotation angle around the y axis is -20 degrees. The constant F is 40 and N is 5.

Data, including rotation angles of the arterial model and coordinates of the graphic center, were preserved when the center of the displacement was determined. This model could be rotated, magnified, and moved freely without changing the geometric relationship between the artery and retractor. With this system, it took approximately 20 seconds to obtain a computer graphics model of the artery and brain retractor, and it took more time when the represented microstructures were more complicated. This computer graphics model could be applied to the simulation of displacement and morphological changes that occur when retraction of the optic nerve is performed.

ILLUSTRATIVE CASE

A 50-year-old man presented with an unruptured right carotid cave aneurysm of the internal carotid artery (ICA), and clipping was performed using such procedures as resection of the anterior clinoid process and cutting of the distal dural ring (Fig. 6 A).[13] Postoperatively, we made a computergenerated model of the carotid cave aneurysm using a previously designed model of the paraclinoid area and the supraclinoid portion of the ICA under full-color shading.[14-16] The source of the input data was a variety of publications that showed the detailed anatomical area.[6,7,11,19,26] Aneurysm shape was input according to angiographic findings. We used our computer graphics model to simulate the retraction of the optic nerve and the exposure of the aneurysm. When the F was larger, the optic nerve was displaced further, and the aneurysm was exposed as the surgical view (Fig. 6 B-D).

Fig. 6. A: Schematic drawing of the operative view of a right carotid cave aneurysm of the ICA. B-D: Computer-generated representations of the carotid cave aneurysm, simulating the operative view. When the constant F is larger, then the displacement of the optic nerve becomes greater, and the carotid cave aneurysm is exposed by retraction (C and D). The constant N is 5, and F is 0 (B), 20 (C), and 40 (D), respectively. A large asterisk shows the carotid cave aneurysm, and small asterisks indicate the superior hypophyseal arteries. ON = optic nerve; I = ICA; O = ophthalmic artery; AC = anterior clinoid process; DR = distal ring; PR = proximal ring; III = oculomotor nerve; R = retractor. Arrowheads show the contour of the displaced optic nerve.

DISCUSSION

Registration and Navigation for Open Microneurosurgery

In modern neurosurgery, the introduction of frameless stereotaxy caused a major trend in minimally invasive surgery; however, the results of initial registration failed because the intracranial structures change their original shapes during surgery. Direct factors that cause intraoperative brain shift include the decompressive effect of craniotomy, dural opening, suction of cerebrospinal fluid, and surgical procedures such as brain retraction and dissection.[23] The authors of several recent reports describe intraoperative brain shift, and several trials have been undertaken to accurately monitor the correlation

between brain shift and imaging characteristics of the displaced brain structures.[3,4,9,23,24] Although there have been several attempts to improve the accuracy of frameless stereotaxy in open microneurosurgery, intraoperative brain shift and the displacement and morphological changes caused by retraction have remained major causes of errors in surgical simulation.

Computer Graphics Models of Microstructures

Although calculation and representation of the intraoperative brain shift or morphological changes caused during brain retraction are difficult, designing computer graphics models that can represent previous surgical experience is possible. We have reported conceptual aspects of a computer-assisted geometric design of cerebral aneurysms for surgical simulation and represented contours of perforators.[17] To represent multiple microstructures, such as perforators, dura, and cranial nerves, and to allow understanding of the three-dimensional relationship of the paraclinoid area and supraclinoid portion of the ICA, we devised a computer graphics model from a variety of publications that showed the detailed anatomy of the area.[14,16] To simulate the geometric relationship between a basilar bifurcation aneurysm and the posterior clinoid process, we adjusted rotation angles and shifting distances between these structures.[18] Although stress distribution in the brain was already estimated by using a finite element method,[27] we had to introduce another function to simulate the displacement and morphological changes of microstructures that occur during retraction.

Simulation of Morphological Changes Caused by Retraction

In this article, we have introduced a cosine-based formula to simulate the displacement and morphological changes of an arterial model. This function was originally used for full-color shading in computer graphics rendering to represent adequate speculum.[16] When the number of the exponent is larger, then the change of the function becomes greater around 0° (Fig. 7). During the microneurosurgical procedure, the displacement and morphological changes of microstructures are maximum at the tip of a brain retractor, and we applied this function to simulate the microstructural morphological changes caused by retraction.

Fig. 7. Schematic representation depicting the formula to determine the intensity of the displacement. When the exponent of the cosine is larger (M and N, respectively), then the change in the intensity of the displacement becomes greater around 0° . $g(\varnothing)$ = the intensity of the displacement; $\varnothing$ = degrees, ranging from 0 to 90.

Each microstructure, such as artery or nerve, possesses different elasticity. For example, an artery is cylindrical and easy to deform by retraction; on the other hand, a nerve is parenchymatous and difficult to deform. To simulate such differences, adjustment of constants in the function that we have introduced would be necessary.

Future Possibilities in Surgical Navigation for Open Microneurosurgery

Virtual reality is a method used to visualize, manipulate, and interact with a computer system that places one in a three-dimensional world.[2] For instance, virtual endoscopy offers several advantages over conventional endoscopy, and virtual reality technology is applied to osteotomies of the facial skeleton.[10,25,29,30] For neurosurgical purposes, simulation of surgical manipulation, including retraction or dissection is necessary for preoperative simulation and planning. Our concept, "virtual retractor," is designed to simulate surgical manipulation, in which both brain retraction and retraction of microstructures, including perforators and cranial nerves, are not actually necessary. This technique can be utilized to detect morphological changes obtained by three-dimensional CT and MR images.

We are moving into an era in which the practical use of virtual reality in the operating room or in surgical planning and training will be possible, and our method would be a valuable contribution as an example of computer manipulation of anatomical data and its morphological changes.[1,2] A CD-ROM manual, available to students, residents, and practicing surgeons, would be ideal and cost effective.[2,16] After multiple computer-generated models that represent various anatomical variations and surgical experience are prepared, multiple image-based data of the brain can be utilized in surgical simulations and in anatomical education and preoperative discussions.

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