Analysis of Intracerebral Hematoma Shapes by Numerical Computer Simulation Using the Finite Element Method

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Abstract

The distortion and stress distribution in the brain caused by putaminal hemorrhage were estimated by computer simulation using the finite element method (FEM). The two-dimensional model of a single cerebral hemisphere contained cortex, white matter, caudate nucleus, lenticular nucleus, thalamus, falk, and lateral ventricle. Five types of intracerebral hemorrhage were modeled at different locations in the lenticular nucleus. The models generated putaminal hematomas of various shapes influenced by the location of the bleeding points. Hematomas caused deformation of the brain, collapse of the lateral ventricle, and destruction of the internal capsule. The stress distributions revealed various patterns influenced by the site of bleeding. The stress in the area of the internal capsule corresponded to the extent of destruction of the internal capsule. This study suggests that FEM modeling of putaminal hemorrhage can provide a useful simulation.

Key words: computer simulation, putaminal hemorrhage, computed tomography, finite element method, brain model

Introduction

Hypertensive intracerebral hemorrhages are frequently encountered in clinical practice, although the choice of surgical or non-surgical treatment is still controversial. The shapes of hematoma vary greatly from case to case, as demonstrated by computed tomography (CT). This variation is thought to result from the location of bleeding and different blood pressure, as well as the mechanical properties of the surrounding structures. Although the influence of these factors on the shape of hematoma is easily accepted, verification is very difficult.

The mechanical aspects of intracranial pathology such as the brain distortion and stress distribution caused by intracerebral hemorrhage are very important factors affecting the shape of hematoma. However, methodological difficulties have prevented detailed studies even in animal models. One of the most serious problems with the experimental study of mechanical phenomena due to focal brain lesion is the requirement for many sensors inserted into the brain to determine the mechanical parameters of the structure. Such procedures will destroy the structural continuity of the brain architecture under study.

Mathematical methods are another way to investigate such problems. Simple analytical techniques are inadequate because of the heterogeneous properties of the brain. The finite element method (FEM) uses computer simulation to determine the distortion and stress distribution in complicated structures such as spaceship or aircraft and has been widely used in recent years. This method is also suitable for the analysis of mechanical phenomena in the brain because it allows complex geometry and several different internal structures.

This study analyzed how the location of the bleeding point affected the hematoma shape under constant blood pressure and mechanical properties of the brain using a FEM computer simulation.

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Materials and Methods

The two-dimensional FEM model was a single cerebral hemisphere including cortex, white matter, caudate nucleus, lenticular nucleus, thalamus, falx, and lateral ventricle. The model was divided into 326 triangular elements (Fig. 1). The model assumed that the surface of the cerebral cortex was attached to the inner table of the skull and was therefore fixed. The Young's modulus of gray matter, white matter, and falx was taken as 0.08, 0.04, and 1.0 kgf/cm², respectively. The Poisson's ratio was 0.47 for all regions of the model brain.

Lateral ventricle was assumed to be empty because the cerebrospinal fluid can flow freely in actual putaminal hemorrhage, so having no effect on brain deformation.

Bleeding at a pressure head of 100 mmHg was represented by six vectors of force radiating from a small area, representing the bleeding point (Fig. 2). Details of the FEM are presented in the appendix.

Five different locations for the bleeding point were examined: the anterior (Model 1), middle (Model 2), and posterior portions of the putamen (Model 3), the globus pallidus (Model 4), and the junction of the putamen and the external capsule (Model 5). Figure 3 (bottom left) shows the site of bleeding in the lenticular nucleus for each model.

FEM calculations were carried out using a 16-bit personal computer and the results were shown as deformation of the brain and distribution of stress.

Results

The FEM model generated putaminal hematomas with various shapes due to the small differences in the locations of the bleeding points (Fig. 3). Each hematoma caused a mass effect manifesting as a

Appendix: Finite Element Method

The finite element method (FEM) is a numerical analysis for obtaining approximate solutions to problems of continuum mechanics such as the deformation of structure and distribution of stress and strain.

The first step of FEM is the modeling of the actual structure with finite degrees of freedom. This model is called the finite element model and should retain appropriate mechanical properties for the structure to be analyzed. The finite element model consists of triangular elements with given Young's modulus and Poisson's ratio as shown in Fig. 1.

The equation of the stress-strain matrix for each element is

\[
\{\sigma\} = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = E/(1-v^2) \begin{bmatrix} 1 & v & 0 \\ v & 1 & 0 \\ 0 & 0 & (1-v)/2 \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}
\]

where \(\sigma_x\) and \(\sigma_y\) are stress in the x and y coordinates, respectively, \(\tau_{xy}\) is a shearing stress, \(E\) is Young's modulus, \(v\) is Poisson's ratio, \(\varepsilon_x\) and \(\varepsilon_y\) are strains in the x and y coordinates, and \(\gamma_{xy}\) is shearing strain.

Strain is given by

\[
\{\varepsilon\} = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \partial u/\partial x \\ \partial v/\partial y \\ \partial v/\partial x + \partial u/\partial y \end{bmatrix}
\]

where \(u\) and \(v\) are displacements in the x and y coordinates, respectively.

These matrix equations for each element, the element matrix, are assembled into a system matrix equation and solved by the computer to determine the deformation, stress, and strain values throughout the structure.
deformation of the lateral ventricle and internal capsule. The lateral ventricle was most collapsed by the hematoma of Model 4. The hematoma shape was elongated from the anterior to posterior direction except that in Model 5, which was elongated from the medial to lateral direction.

The hematoma affected the internal capsule to some extent in all models. Hematoma of Model 1 destroyed the anterior limb of the internal capsule, but spared the posterior limb. Hematoma of Model 3 extended into the posterior limb. Both the anterior and posterior limbs of the internal capsule were destroyed by hematoma of Model 4. The internal capsule was affected slightly by the hematomas of Models 2 and 5.

The distribution of principal stress calculated in each model is shown in Fig. 4. Deformation of the lateral ventricle in Models 1 and 4 was associated with greater stress adjacent to the lateral ventricle. The greatest stresses at the wall of the lateral ventricle were 60% in Model 4 and 41% in Model 1. The stress in the area of the internal capsule also corresponded to the extent of destruction of the internal capsule.

Discussion

This study demonstrated the utility of FEM for analyzing the mechanical aspects of intracranial pathology. Only a few applications of FEM have been reported in neurosurgery, including analysis of brain edema, subdural hematoma, and blow-out fracture of the orbit, probably because the method is unfamiliar.

Our previous study of subdural hematoma found that stress distribution in the contralateral cerebral hemisphere was very small, so we used a single hemisphere model in this study. This simplification enabled an increase in the number of elements to permit more accurate analysis.

This study revealed that the hematoma shape was affected by a small shift in bleeding point location in the lenticular nucleus when other factors, blood pressure and properties of the brain, are constant.

Kanaya et al. proposed a classification system for hematoma localization based on CT scans in patients with putaminal hemorrhage. The five models of putaminal hematoma in this study could be clearly correlated with this scheme: Models 1, 2, 3, 4, and 5 are equivalent to Kanaya type II, I, IIIa, IVa, and I, respectively (Table 1).

These results show that the location of the bleeding point is an important factor affecting the shape of hematoma because four out of the six Kanaya types were reproduced by the computer simulation. More variations of hematoma can be expected when the blood pressure and properties of the

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brain are also changed. These problems would need more detailed investigation.

Another point revealed by this study is the mode of stress distribution. The deformation of the lateral ventricle and destruction of the internal capsule were proportional to the stress transmitted to them. The distribution of stress, especially in the internal capsule, was affected by the point of bleeding and changed more between Models 1 and 3. These findings suggested that the location of the bleeding point has implications for the functional outcome of putaminal hemorrhage.

The model brain used in this study has certain shortcomings. Two points to be considered are: 1) a three-dimensional model, and 2) viscoelastic properties. Obviously a three-dimensional model would be far more realistic and more useful in clinical applications to support the selection of surgical procedure and approach. Incorporation of viscoelastic properties into the model brain would enable brain deformation to become a function of time elapsed. A more powerful computer and software could incor-

Fig. 4 Distribution of principal stress in the five models. The center of the concentric lines is the area of maximum stress, shown as 100%. The other values are percentages of maximum stress. The stress lines revealed various patterns influenced by the site of bleeding.
Table 1 CT classification of putaminal hemorrhage after Kanaya et al.,5) and results of computer simulation

<table>
<thead>
<tr>
<th>Type</th>
<th>Location of hematoma</th>
<th>Kanaya's classification</th>
<th>Our computer simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>localized in the outside of internal capsule</td>
<td>Models 2 and 5</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>extended to the anterior limb</td>
<td>Model 1</td>
<td></td>
</tr>
<tr>
<td>IIIa</td>
<td>extended to the posterior limb without V*</td>
<td>Model 3</td>
<td></td>
</tr>
<tr>
<td>IIIb</td>
<td>extended to the posterior limb with V*</td>
<td>Model 4</td>
<td></td>
</tr>
<tr>
<td>IVa</td>
<td>extended to the anterior and posterior limbs without V*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IVb</td>
<td>extended to the anterior and posterior limbs with V*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>extended to the thalamus or subthalamus</td>
<td></td>
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V*: massive ventricular hemorrhage.

porate these features into a better model of the brain and provide a more accurate simulation.

References


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