

Brain Shape Homologous Modeling Using Sulcal-Distribution Index in MR Images

Kosuke Yamaguchi^{*1}, Syoji Kobashi^{*1,*2}, Ikuko Mohri^{*3}, Seturo Imawaki^{*4}, Masako Taniike^{*3}, Yutaka Hata^{*1,*2}

^{*1} Graduate School of Engineering,
University of Hyogo,
Hyogo, Japan

^{*2} WPI Immunology
Frontier Research Center,
Osaka University, Osaka, Japan

^{*3} Graduate School of Medicine,
Osaka University,
Osaka, Japan

^{*4} Ishikawa Hospital,
Hyogo, Japan

Abstract—The brain shape is deformed regionally by kinds of cerebral diseases and the degree of progress. Therefore quantitative evaluation of the deformation using MR images is effective for diagnosis of cerebral diseases. To evaluate the cerebral deformation, almost conventional methods are based on normalization of the brain shape which deforms the evaluating brain into the standardized brain. Because the normalization process does not take into account anatomical features such as the cerebral sulci and gyri, in some cases the normalization process produces that one sulcus of the evaluating brain miss-corresponds to the other sulcus of the standardized brain. This paper proposes a homologous brain shape modeling method for quantitative evaluation of the brain shape in MR images. We define a new image feature called sulcal-distribution index (SDI) to represent the 3-D distribution of sulci, and the proposed method deforms a template brain model so that SDI of the deformed brain model calculated from the evaluating brain MR images is similar to SDI of the template brain model. By using SDI, the proposed method can take into account anatomical features of the cerebral sulci. The experimental results showed that the proposed method homologically modeled the brain shape with a mean displacement of 1.3 mm.

Keywords—brain deformation, brain shape, cerebral sulcus, brain shape homologous modeling, magnetic resonance image

I. INTRODUCTION

To diagnose cerebral diseases, magnetic resonance (MR) images have been widely used [1][2][3]. However, image interpretation of MR images requires a large amount of labor and consumes a time of radiologists. In addition, there is inter- and intra reader variation of image interpretation performance. Therefore, a computer-aided diagnosis (CAD) system is eagerly desired to support a quantitative evaluation.

To evaluate the cerebral deformation caused by cerebral diseases, there are two kinds of CAD systems; voxel-based morphometry (VBM) [4][5] and deformation-based morphometry (DBM) [6][7]. VBM is a method which detects voxel group whose gray matter density is significantly different from the density distribution of the gray matter of normal subjects. DBM is a method which evaluates voxels' movement as amount of shape deformation. In addition, these conventional methods are based on a normalization process which uses the standardized brain previously prepared [8]. However, it is difficult to normalize subjects whose brain shape is differ from the standardized brain shape greatly. In addition, the conventional normalization

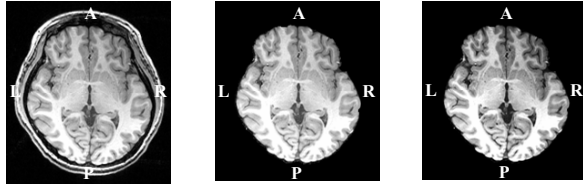
technique does not consider anatomical features such as the cerebral sulci and gyri.

Homologous modeling has been attracting considerable attentions because it can evaluate the shape using statistical approach [9][10]. Homologous modeling is a method which assigns the same number of points to the same characteristic position of the evaluating object. The homologous modeling has been performed with free form deformation (FFD) [9][11]. FFD is a method which puts control points around the evaluating object, and deforms internal shape smoothly by moving the control points. The homologous modeling has been applied to generate the average shape model of foot or body and to evaluate the shape feature of individuals [9][10][12]. However, homologous modeling is rarely applied to the brain shape. Only Ref. [13] applied FFD to the brain shape, although, it does not consider anatomical features of the cerebral sulci and gyri because the method uses the 3-D space curvature of the cerebral surface.

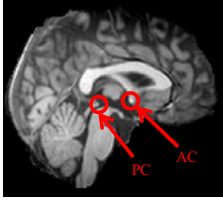
This paper proposes a novel method for brain shape homologous modeling in MR images. We introduce a new index called sulcal-distribution index (SDI), which represents the 3-D distribution of sulci on the cerebral surface. And, the proposed method deforms a template brain model so that the SDI of the deformed brain model calculated from the evaluating brain MR images is similar to SDI of the template brain model.

II. SUBJECTS AND MATERIALS

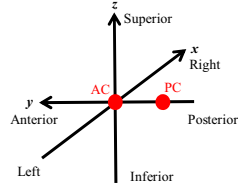
This study recruited four healthy adult subjects (22.0 ± 0.5 years, two males and two females). For each subject, MR images were taken using T1-weighted axial protocol using a 3.0 Tesla MRI scanner (Trio, Siemens, Germany). The image acquisition parameters were a repetition time (TR) of 2000 msec, an echo time (TE) of 4.38 msec, a voxel size of $1.0 \times 1.0 \times 1.0$ mm³, and a spatial resolution of $192 \times 256 \times 208$ mm³. A raw T1-weighted MR image of Subject 1 is shown in Fig. 1(a). At preprocessing, the cerebral region was segmented by using brain extract tool (BET) [14]. The segmented cerebral region is shown in Fig. 1(b). And, MR signals of the cerebral region are normalized into 256 gray levels where 0 means the minimum MR signals of the cerebrum, while 255 means the maximum signal. Also, the cerebral region is transformed into Talairach coordinate system [15] where the anterior commissure (AC) is the origin, a line connecting AC and posterior commissure (PC) is the y-axis (AC-PC line), and the longitudinal fissure is yz-plane as shown in Fig. 2.



(a) Raw T1-weighted MR image. (b) Segmented cerebral region using BET. (c) Intensity normalization.
Figure 1 Subject A (104/208). A; anterior, P; posterior, L; left, R; right.



(a) Anterior commissure (AC) and posterior commissure (PC).



(b) Talairach coordinate system.

Figure 2 Talairach coordinate system.

III. PROPOSED METHOD

A. Overview

The proposed method homogeneously models the evaluating brain by deforming a template brain model. The template brain model consists of points and its characteristic value. The characteristic value used in the proposed method is SDI which is extracted from MR images of the template brain. By deforming the brain model so that SDI of the deformed brain model calculated from the evaluating brain MR images is similar to SDI of the template brain model. Because SDI represents the 3-D distribution of sulci on the cerebral surface, the proposed method can achieve a homologous modeling with respect to the anatomical features of the cerebral gyri. The followings describe definition of SDI, construction method of the template model, and deforming method with considering SDI.

B. Definition of Sulcal-Distribution Index

SDI is a new index which represents the degree of existence of sulci at a point of interest on the cerebral surface. SDI at the voxel of interest (VOI) with a coordinate value of (x, y, z) is defined by:

$$SDI(x, y, z) = \frac{\sum_{\mathbf{p} \in \mathbf{V}(x, y, z)} I(x_p, y_p, z_p)}{d}, \quad (1)$$

where \mathbf{V} is a set of voxels on a half line drawn from the VOI to AC and the distance from VOI is shorter than or equal to d (Fig. 3), $\mathbf{p} = (x_p, y_p, z_p)^T$ is a voxel belonging to voxel set \mathbf{V} , and $I(x_p, y_p, z_p)$ is MR signal of a voxel with a coordinate value of (x_p, y_p, z_p) . d is an analysis parameter and is given manually. SDI is defined as the average MR signal of voxel set \mathbf{V} . SDI takes the higher value when voxel set \mathbf{V} is filled by the larger number of cerebral voxels,

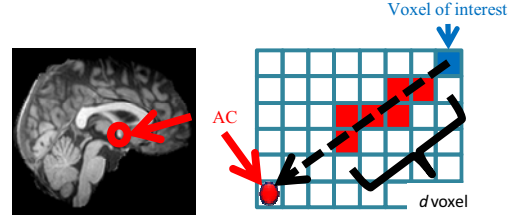


Figure 3 Half line drawn from voxel of interest to AC.

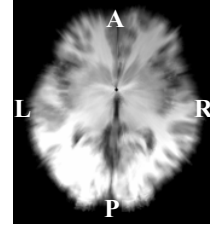


Figure 4 Example of SDIs.

while SDI takes the lower value when voxel set \mathbf{V} is filled by the larger number of cerebrospinal fluid (CSF). Because the gyri are concave regions on the cerebral surface and the gyri are fulfilled by CSF, SDI takes the lower value when VOI is on the gyri. And, because the sulci are convex regions on the cerebral surface and the sulci are composed of cerebral voxels, SDI takes the higher value when VOI is on the sulci. Thus, SDI represents the degree of existence of sulci on the cerebral surface. Fig. 4 shows an example of SDIs of a sagittal section located around the superior position of the cerebrum. As shown in this figure, the appropriate SDIs are given corresponding to the distribution of sulci.

C. Construction of Template Brain Model

The template brain model is composed of numerous points that form the cerebral surface, and each point has characteristic value, SDI. The template brain model is generated by using MR images of a subject. By applying marching cubes method [16] to the segmented cerebral region from the MR images, the cerebral surface is formed by a triangle polygon. Thus, the template brain model is described as a set of vertices of the triangle polygons:

$$TBM = \left\{ t(i) = (x_t(i), y_t(i), z_t(i))^T \mid 1 \leq i \leq N_{TBM} \right\}, \quad (2)$$

where N_{TBM} is the number of vertices, and for each vertex, SDI is calculated from the template brain MR images and is denoted by $SDI_{TBM}(i)$ as the characteristic value of the vertex.

D. Homologous Brain Shape Modeling

For the evaluating brain, homologous brain shape modeling is to assign vertices to points whose SDIs in the evaluating brain are same as those in the template brain. The assignment is done by deforming the template brain model described by an elastic model shown in Fig. 5 [17][18]. In this figure, nodes are set to vertices, and springs connect the nodes. The natural length of spring is set to the distance

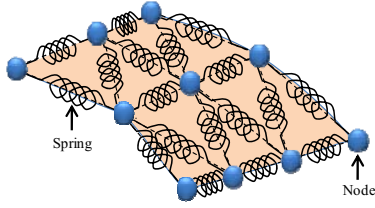


Figure 5 Elastic model.

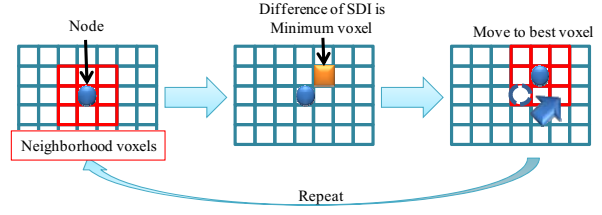


Figure 6 A node moves for where SDI is the most similar to template brain model.

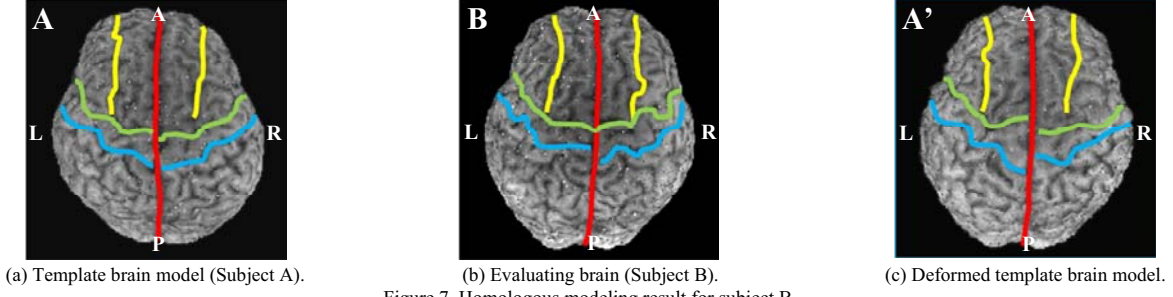


Figure 7 Homologous modeling result for subject B.

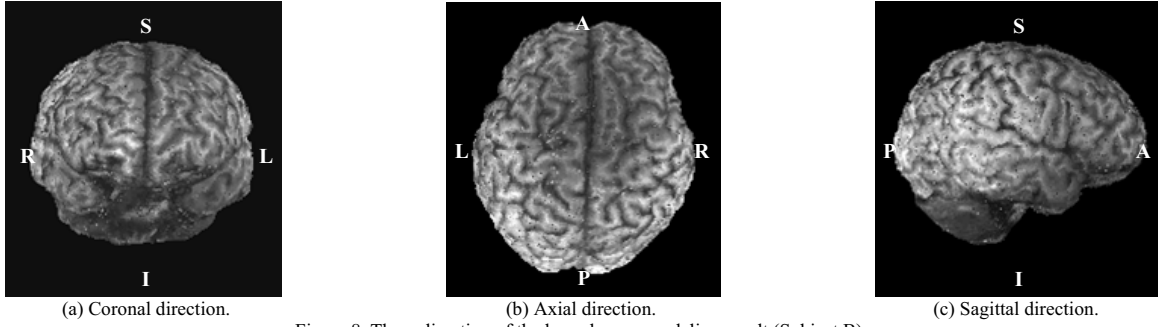


Figure 8 Three direction of the homologous modeling result (Subject B).

between the connecting vertices. The evaluating brain model (EBM) is described by:

$$EBM = \{e(i) = (x_e(i), y_e(i), z_e(i))^T \mid 1 \leq i \leq N_{TBM}\}. \quad (3)$$

The proposed homologous brain shape modeling method consists of the following steps.

- [Step 1] Initialize EBM using TBM. For each vertex i , $e(i) = t(i)$.
- [Step 2] For each vertex i , among the neighboring voxels of vertex i , find an update candidate position $e'(i)$ whose $SDI_{EBM}(e'(i))$ is the most similar to $SDI_{TBM}(t(i))$ (Fig. 6). $SDI_{EBM}(e'(i))$ is calculated from the evaluating brain MR images at $e'(i)$.
- [Step 3] For each vertex i , calculate moving vector according the fundamental law of dynamics, which is defined by;

$$\mathbf{F}(i) = m\mathbf{a}(i), \quad (4)$$

where $\mathbf{F}(i)$ is the force vector, and m is the mass of vertex i . $\mathbf{a}(i)$ is the acceleration vector, which is defined by;

$$\mathbf{a}(i) = k\mathbf{r}\{SDI_{EBM}(e'(i)) - SDI_{TBM}(t(i))\}, \quad (5)$$

where k is the spring constant, and \mathbf{r} is a unit vector from $e'(i)$ to $e(i)$. The moving vector is calculated by the Euler method.

- [Step 4] Move the all vertices by the moving vectors. When the total magnitude of moving vectors is less than a terminate condition parameter, D_{min} , terminate this procedure, otherwise go to Step 2.

The above procedure produces the list of coordinate values of vertices for the evaluating brain. Although the position of i -th vertex in the evaluating brain model is differ from that in the template brain model, SDI of the vertex is similar to each other. Thus, by deforming the template brain

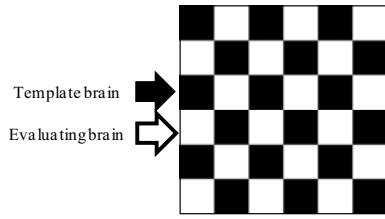
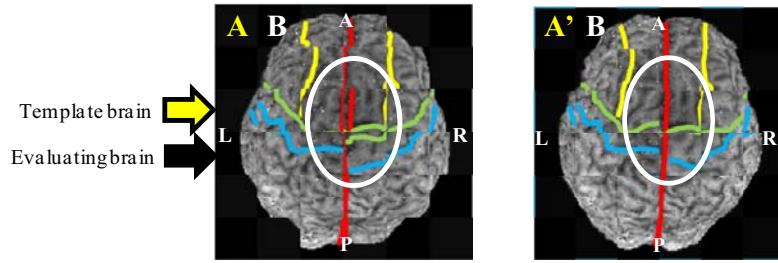
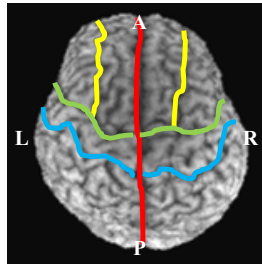


Figure 9 Example of the combined image.

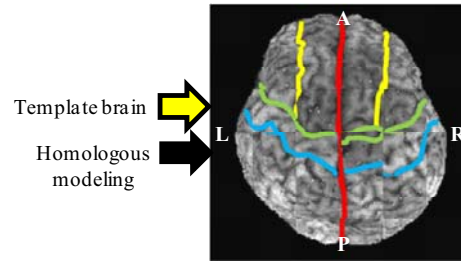


(a) Evaluating brain (Subject B) and template brain. (b) Evaluating brain (Subject B) and deformed template brain.

Figure 10 Combined image with the pre- and post-deformed brain.



(a) Homologous modeling of the deformed template brain.



(b) Combination of the template brain and the homologous modeling result of the deformed template brain.

Figure 11 Re-homologous modeling result of the evaluation brain 1 (subject B).

TABLE I. DISTANCE BETWEEN THE HOMOLOGOUS RESULT AND THE ORIGINAL POSITION [mm].

	Subject B	Subject C	Subject D
Maximum	7.4	7.9	7.3
Minimum	0.0	0.0	0.0
Average \pm Standard deviation	1.3 ± 0.7	1.3 ± 0.7	1.4 ± 0.7

model with evaluating SDI computed from the evaluating brain MR images, we can perform homologous modeling of the evaluating brain shape.

IV. EXPERIMENTAL RESULTS

The proposed method was applied to four subjects (Subject A, B, C and D). Analysis parameters used were $d = 10$ voxels, $m = 1.0$ kg, and $k = 1.0$ N/m for all subjects. In this paper, subject A was employed to construct the template brain model and the proposed method was applied to subjects B, C and D. Figure 7 shows the experimental results for Subject B. Figure 7(c) is generated by deforming the template brain MR images according to the displacement vectors of each vertex obtained by the homologous brain shape modeling. In these figures, to evaluate the brain shape change of the cerebral sulci, we draw lines on the longitudinal fissure, superior frontal sulcus, precentral sulcus, and central sulcus. Comparison of the evaluating brain with the deformed template brain showed that the proposed method assigned vertices to the appropriate positions. Figure 8 shows three directions of the homologous modeling result.

To evaluate the shape change with the proposed method, we combined the evaluating brain with the template brain (*i.e.*, before homologous deformation) or with the deformed

template brain (*i.e.*, after homologous deformation) as grid-like tile (Fig. 9). Figure 10 shows the experimental result for Subject B. Before homologous modeling, the brain shape and the cerebral sulci were discontinuous. By applying the proposed method, the brain shape of the deformed template brain was almost same as the evaluating brain, and the cerebral sulci continuously run over the boundaries of tiles. As shown in these figures, the proposed method appropriately finds the displacement so that the anatomical features correspond.

To evaluate the numerical accuracy of homologous modeling, the proposed method was applied to the deformed template brain. Thus, when the homologous modeling works perfectly, the obtained vertices from the deformed template brain return to the original positions of the template brain model. Figure 11(a) shows the homologous modeling result for the deformed template brain (Fig. 7(c)), which was obtained from subject B, and Fig. 10(b) shows the tiled image of the template brain and the homologous modeling result. As shown in these figures, by applying the proposed method to the deformed template brain, almost of the vertices returned to the original positions. Table I tabulates the maximum / minimum / average \pm standard deviation of distance between vertices' positions of the template brain model and those of the homologous modeling result for subject B, C and D. The mean displacement of homologous modeling for three subjects was 1.3 ± 0.7 mm.

To demonstrate the effectiveness of the proposed method, we investigated the similarity of the brain shape among four subjects by using the homologous modeling results. The similarity was quantified by using multidimensional scaling in which data were randomly chosen 100 vertices of the

homologous model and similarity between data was the distance between the corresponding vertices. The multidimensional scaling shows a relationship among objects in two dimensions. As shown in this example, the brain shape as the homologous model, we can apply various statistical analysis methods to investigate the brain shape.

V. CONCLUSION

This paper has proposed a novel homologous modeling method of the brain shape in MR images. The proposed method is based on deformation of the template brain model with respect to SDI. SDI describes the 3-D distribution of the sulci on the cerebral surface. Thus, the proposed method can correspond the sulci and gyri among the evaluating brains. The experimental results for four subjects showed that the proposed method achieved homologous modeling with a mean error of 1.3 mm. We also showed the multidimensional scaling result of the brain shape as an example of clinical research using the proposed homologous modeling method. The homologous modeling of the brain shape enables us to apply these statistical analysis methods to evaluate the brain shape quantitatively. In the future, we will improve the accuracy of the homologous modeling, and produce clinical application of the homologous brain shape modeling.

ACKNOWLEDGMENT

This work was supported in part by Berkeley Initiative in Soft Computing (BISC) program of UC Berkeley, USA.

REFERENCES

- [1] H. Braak and E. Braak, "Neuropathologic staging of Alzheimer-related changes," *Acta Neuropathol*, Vol. 82, No. 4, pp. 239-259, 1991.
- [2] H. Kitagaki, E. Mori, S. Yamaji, K. Ishii, N. Hirono, S. Kobashi, and Y. Hata, "Frontotemporal dementia and Alzheimer disease: evaluation of cortical atrophy with automated hemispheric surface display generated with MR images," *Radiology*, Vol. 208, No. 2, pp. 431-439, 1998.
- [3] A. Brun, B. Englund, and L. Gustafson, "Clinical and neuropathological criteria for frontotemporal dementia," *J. of Neurology, Neurosurgery, and Psychiatry*, Vol. 57, No. 4, pp. 416-418, 1994.
- [4] C. D. Good, I. S. Johnsrude, J. Ashburner, R. N. Henson, K. J. Friston, and R. S. Frackowiak, "A voxel-based morphometric study of ageing in 465 normal adult human brains," *NeuroImage*, Vol. 14, No. 1, Part 1, pp. 21-36, 2001.
- [5] J. Ashburner and K. J. Friston, "Why voxel-based morphometry should be used," *NeuroImage*, Vol. 14, No. 6, pp. 1238-1243, 2001.
- [6] P. Pieperhoff, M. Südmeyer, L. Hömke, K. Zilles, A. Schnitzler, and K. Amunts, "Detection of structural changes of the human brain in longitudinally acquired MR images by deformation field morphometry: Methodological analysis, validation and application," *NeuroImage*, Vol. 43, No. 2, pp. 269-287, 2008.
- [7] S. J. Teipel, C. Born, M. Ewers, A. L. Bokde, M. F. Reiser, H. J. Möller, and H. Hampel, "Multivariate deformation-based analysis of brain atrophy to predict Alzheimer's disease in mild cognitive impairment," *NeuroImage*, Vol. 38, No. 1, pp. 13-24, 2007.
- [8] K. J. Friston, J. Ashburner, C. Frith, J. Poline, J. Heather, and R. Frackowiak, "Spatial registration and normalization of images," *Human Brain Mapping*, Vol. 2, pp. 165-189, 1995.
- [9] M. Mochimaru, M. Dohi, and M. Kouchi, "Analysis of 3-D human foot forms using the free form deformation method and its application in grading shoe lasts," *Ergonomics*, Vol. 43, No. 9, pp. 1301-1313, 2000.
- [10] M. Mochimaru and M. Kouchi, "Statistics for 3D human body forms," *SAE Digital Human Modeling for Design and Engineering International Conference and Exposition*, 2000.
- [11] T. W. Sederberg and S. R. Parry, "Free-form deformation of solid geometric models," *ACM SIGGRAPH Computer Graphics*, Vol. 20, No. 4, pp. 151-160, 1986.
- [12] M. Kouchi and M. Mochimaru, "Development of a low cost foot-scanner for a custom shoe making system," *5th ISB Footwear Biomechanics*, pp. 58-59, 2001.
- [13] P. Aljabar, K. K. Bhatia, M. Murgasova, J. V. Hajnal, J. P. Boardman, L. Srinivasan, M. A. Rutherford, L. E. Dyet, A. D. Edwards, and D. Rueckert, "Assessment of brain growth in early childhood using deformation-based morphometry," *NeuroImage*, Vol. 39, No. 1, pp. 348-358, 2007.
- [14] S. M. Smith, "BET: Brain Extraction Tool," *FMRIB Technical Report*, pp. 1-25, 2000.
- [15] J. Talairach and P. Tournoux, *Co-Planar stereotaxic atlas of the human brain*, Georg Thieme Verlag, 1988.
- [16] W. E. Lorensen and H. E. Cline "Marching Cubes: A high resolution 3D surface construction algorithm," *ACM SIGGRAPH Computer Graphics*, Proc. of SIGGRAPH, Vol. 21, No. 4, pp. 163-169, 1987.
- [17] X. Provot, "Deformation constraints in a mass-spring model to describe rigid cloth behavior," *Proc. of Graphics Interface*, pp. 147-154, 1995.
- [18] L. P. Nedel and D. Thalmann, "Real time muscle deformations using mass-spring systems," *Proc. of Computer Graphics International 1998*, pp. 156-165, 1998.