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## Computer simulation of a neurosurgical operation: craniotomy for hypothalamic hamartoma

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**Abstract** Although magnetic resonance imaging has revolutionised the management of intracranial lesions with improved visualisation of anatomical structures, it only produces two-dimensional images, from which the clinician has to extrapolate a three-dimensional interpretation. Several approaches can be used to create 3D images; the discipline of image segmentation has encompassed a number of these techniques. Such techniques allow the clinician to delineate areas of interest. The resulting computer-generated outlines can be reconstructed in a three-dimensional arrangement. Although a plethora of “generic” segmentation techniques exist, we have developed a refined form, dependent on general and particular properties of the anatomical structures under investigation. High-contrast structures such as the ventricles and external surface of the head are found by using a localised adaptive thresholding technique. Less definable structures, with poor or nonexistent signal change across neighbouring structures, such as brain stem or pituitary, are found by applying an “energy minimisation”-based technique. To demonstrate the techniques we used the example of

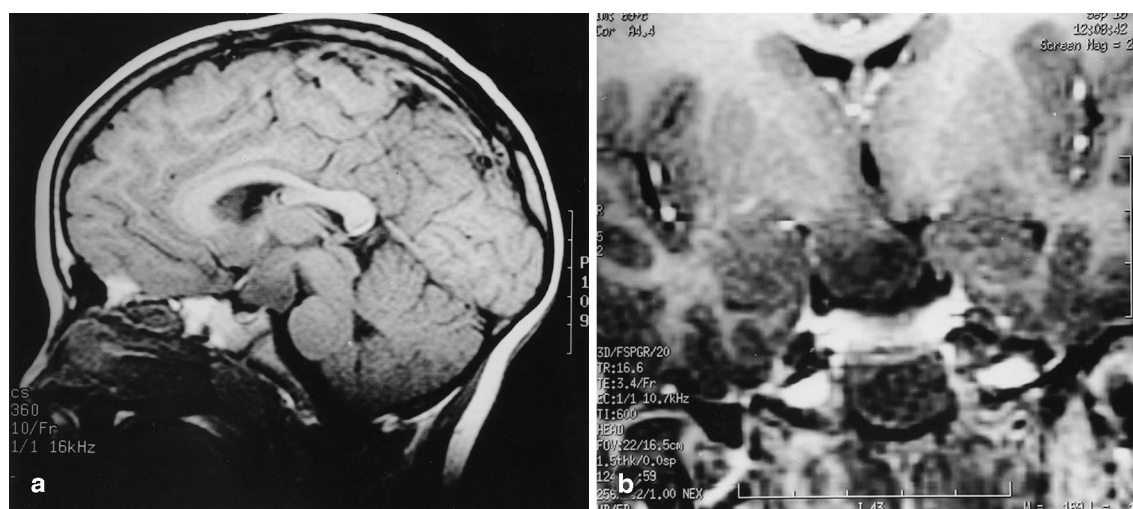
an 8-year-old boy with uncontrolled gelastic seizures due to a hypothalamic hamartoma, who is being considered for surgery. We were able to demonstrate the anatomical relationships between the hypothalamic hamartoma and adjacent structures such as optic chiasm, brain stem and ventricular system. We were subsequently able to create a video, reproducing the stages of craniotomy for excision of this tumour. By creating true 3D objects, we were able at any stage of the simulation to visualise structures situated contralaterally to the approaching surgical dissector. These 3D representations of the structures can be either invisible or opaque, in order to afford 3D localisation as the “virtual” surgical dissection proceeds. The clinical application of such techniques will enable surgeons to improve their understanding of anatomical relations of intracranial lesions and has obvious implications in image-guided surgery.

**Key words** Magnetic resonance imaging · Medical computing · Image-guided surgery · Image segmentation · Computer graphics

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**Fig. 1** T1-weighted contrast-enhanced MRI scan (**a** sagittal, **b** coronal view) of an 8-year-old boy with intractable gelastic seizures. A hypothalamic hamartoma is seen arising from the inferior aspect of the right hypothalamus, anteriorly to the brain stem. The tumour is well defined in all its aspects apart from the area of origin, where the division from normal hypothalamus becomes indistinct. The lesion is not enhancing with contrast. The optic chiasm has been shifted by the tumour superiorly and anteriorly

## Introduction

The advent of magnetic resonance imaging (MRI) has undoubtedly revolutionised the management of intracranial pathology. While MRI scanning offers improved detail on soft tissues, in its current form it produces only two-dimensional views of the pathology under scrutiny. Neurosurgeons have to mentally re-create a 3D reconstruction by extrapolating from 2D images while planning an operation. Any means of providing 3-dimensional graphical representations would help surgeons enhance their understanding of anatomical relationships of deep-seated structures and advance intracranial surgery even further.

Owing to differences in the digital signal and the ranges that MR imaging parameters (TR, TE) can take, the simple thresholding-based techniques used to create 3D bone and ventricular CSF reconstructions in CT scanning cannot be directly applied to MRI [4]. The variation of the grey range of the MRI signal is such that simple thresholding would eradicate a significant number of intracranial structures from the reconstruction, resulting in inaccuracies.

During the last decade, different segmentation techniques have been developed to overcome these difficulties [4, 5, 11, 19, 20]. Image segmentation is the technique of fragmenting a composite picture into several user-defined outlines/regions, thus accurately defining real-world objects. Several algorithms can be used to achieve this, ranging from manual to fully automatic methods [1, 2, 4, 17–20,

22]. The level of operator-independence achieved is related to the accuracy and the level of structural complexity that can be handled. The resulting outlines can be reconstructed in 3D. Various image modalities can be used with these techniques, including CT, MRI, MRA, SPECT and PET scan.

Although the technique has been available for a while, clinical application has been rather slow, owing partly to the unfamiliarity of clinicians with computer technology and to the time involved in achieving accurate and meaningful reconstructions. We demonstrate in this communication the clinical use of our segmentation approaches simulating the stages of craniotomy for intracerebral tumour. The rare and surgically difficult-to-treat hypothalamic hamartoma served as a good example of the clinical value of segmentation in creating 3D MRI images.

## Materials and methods

An 8-year-old boy had been suffering from gelastic seizures for several years, lately with increasing frequency and refractory to medical treatment. He was referred for assessment of suitability for surgical treatment.

On MRI scanning he was found to have a mostly well-defined, non-contrast-enhancing lesion arising from the right hypothalamus, which was thought to be a hypothalamic hamartoma (Fig. 1). At the area of origin from the hypothalamus, the definition between normal tissue and hamartoma was indistinct. The MRI examination used for the reconstruction was performed on an IGE 1.5 T scanner (IGE, Milwaukee, USA) and consisted of 124 contiguous images, T1-weighted (TE:20/TR:200), of 1.5 mm thickness, obtained following intravenous injection of paramagnetic contrast.

The availability of 3D MRI images would be particularly beneficial in the surgical planning in the case of such a deep-seated lesion. The surgical approach has several associated technical difficulties, mainly related to the anatomical relationship of the lesion to important structures such as the brain stem, the optic chiasm, and the pituitary stalk. 3D reconstruction would improve spatial perception of the lesion and assist surgical planning of a direct approach.

To perform the segmentation task we used an in-house X-Windows-based C program running on a UNIX operating system workstation. The workstation, a Sun SparcStation 20 (Sun Computers, California), is connected via a local area network to the MRI and CT scanner systems. The software environment has been developed with the ability to handle numerous image modalities and formats. Additionally, images obtained in other scanners can be imported via external media such as DAT, optical disc and floppy disk.

The software incorporates segmentation algorithms and 3D visualisation routines. Automatic, semiautomatic or manual algorithms can be used to outline structures, depending on the complexity of their shape and the difference in grey value from adjacent structures [5, 6, 15, 16].

In the case presented here, automatic segmentation was used for the skin and the cortical surface. The skin was easily outlined automatically, as the air-skin interface is clearly identifiable as a high-contrast area. For segmentation of the cortical surface CSF boundaries were determined from a seed derived from the centre of gravity of the current scan. This seed point was subsequently used for the other slices. This information was recorded in a database of cortical outlines for later use. When this technique failed a more "user-involved" semiautomatic algorithm was employed. Constraints on grey level, first- and second-order derivatives were used as primary factors [6]. The constraints were augmented by energy minimisation technique, adjusting the contrast between neighbouring structures, to isolate the region of interest. Where the boundary was weak or nonexistent, a constraining boundary of arbitrary shape was applied around the area of interest, to improve the possibility of semiautomatic delineation. The arbitrary shape was passed on to adjacent slices, to follow anatomical continuity of the structure of interest. This technique worked well for the ventricular system, the brain stem and the chiasm. The segmentation program allows a range of slices to be user-defined, with their anterior and posterior extent determined on the mid-sagittal plane. This enhances the possibility of correct results with semiautomatic methods. Whenever the boundaries were of the correct shape but incorrect size, too big or too small, the techniques of mathematical morphology erosion and dilatation were employed to improve the result. Finally, if errors still persisted, the contour was edited manually. A typical example was the hypothalamic tumour. The ill-defined plane of origin from the inferior aspect of hypothalamus had to be manually outlined. For selected objects, volumes were measured automatically from cross-sectional area and slice thickness.

The segmentation is performed on 2D images. The anatomical outlines produced are reconstructed in 3D. For the high-resolution dataset the volume is constructed by summing the cross-sectional area. For those cases where the 3D resolution is poor, volumes are generated by interpolation between cross sections. These object volumes are then superimposed on the actual 3D MRI data. Each structure outlined becomes a separate 3D object, coloured individually to be distinguishable. The surface geometry of the MRI data, for example the cortex, can then be viewed together with the coloured outline objects. Two modes of visualisation exist: depth shadows and perspective shading. These objects can be made transparent or removed completely, allowing demonstration of deeper situated structures. They can also be rotated and viewed from any desired angle. Simulated "surgical" cuts can be made in any desired trajectory, allowing customised visualisation. Subsequently a video can be produced, in predetermined sequences, simulating the entire virtual "operation". The whole procedure of 3-dimensional reconstruction is performed by the neurosurgeon and can take from 15 to 60 min, depending on the number of structures that are outlined, their complexity and their MR signal appearance.

The environment described above has been in daily clinical use for several years to measure hippocampal volumes in epileptic patients scheduled for hippocampectomy. In the last 2 years its use has been extended to surgical simulation of tumour resections and craniofacial research.

## Results

Using mostly automatic and semiautomatic outlining, after 40 min of computing work, a complete 3D reconstruction of the child's head had been achieved, including skin with marked skin flap, cerebral hemispheres, ventricular system, brain stem, tumour, and optic chiasm. Figure 2 demonstrates the process of segmentation. The areas of interest have been outlined. The resulting outlines were subsequently reconstructed in 3D together with the real MR digital data.

For this demonstration suitable viewpoint 3D co-ordinates were chosen to simulate the surgeon's view of the patient's head on the operating table. Figures 3-8 are stills from a video sequence simulating the steps of a craniotomy for resection of this tumour. In Fig. 3 the skin surface is seen, with the proposed skin flap marked in a different colour (purple). In Fig. 4 the skin flap is made transparent to demonstrate the relation of the flap to the underlying sylvian fissure. In Fig. 5 the superficial part of the brain has been made transparent to demonstrate the relationship of the tumour to the brain stem (green). This relationship is better demonstrated in Fig. 6, where the right frontal lobe has been removed, exposing the ventricular system (purple), the tumour (red), and the optic chiasm (yellow). In Fig. 7 an additional surgical approach via the subfrontal route is simulated, by "removing" the anterior part of the frontal lobe through a frontal "craniotomy". In Fig. 8 all the superficial structures have been removed to expose the tumour in relation to the ventricular system and the chiasm, which is seen to be severely deformed by the underlying tumour. The ability to rotate the 3D object allows better visualisation of the relationship of the tumour to the surrounding important structures. The tumour volume has been calculated as 3913 mm<sup>3</sup>.

## Discussion

Three-dimensional visualisation of intracranial structures offers realistic perception of the area of interest and, consequently, improved understanding of anatomical relationships. The high level of soft tissue detail that MRI offers combined with the stereoscopic visualisation of 3D reconstruction are opening a new perspective in surgical planning of deep intracranial lesions. The ability to interact with 3D structures and visualise their anatomical relationships from multiple viewpoints is helping surgeons rapidly increase their own personal experience.

Segmentation techniques have been present for some time now, and most of them have been used in various institutions predominantly for research [3, 12, 13]. The presence of in-house computer expertise allows the flexibility of continuing development according to the clinical need. Recently, simple forms of segmentation programs have ap-

**Fig. 2** Segmentation of a composite image. Using automatic, semi-automatic or manual algorithms, the composite MRI image is "split" into simple multiple outlines of the structures of interest. Ventricular system (*blue line*), optic chiasm (*yellow line*), tumour (*red line*) and pituitary stalk (*brown line*) have been outlined

**Fig. 3** 3D reconstruction of the patient's head. The skin flap (purple) is marked in the region of the right pterion

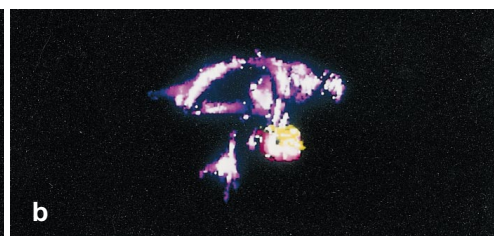
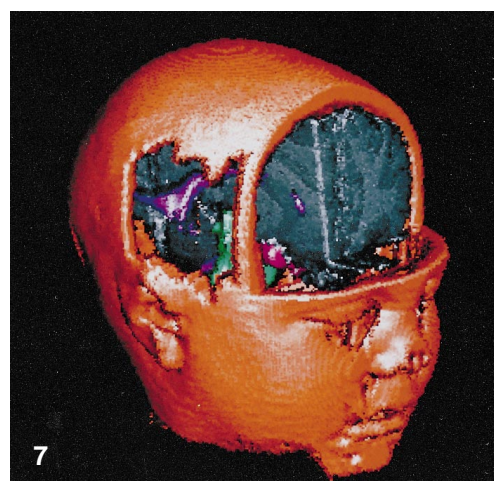
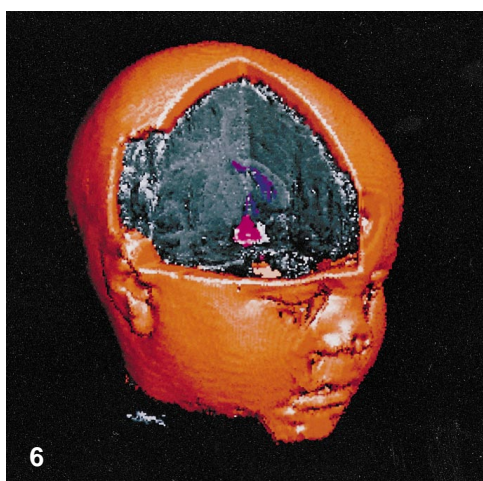
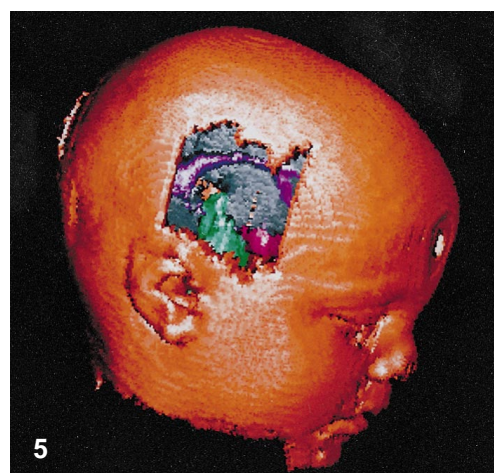
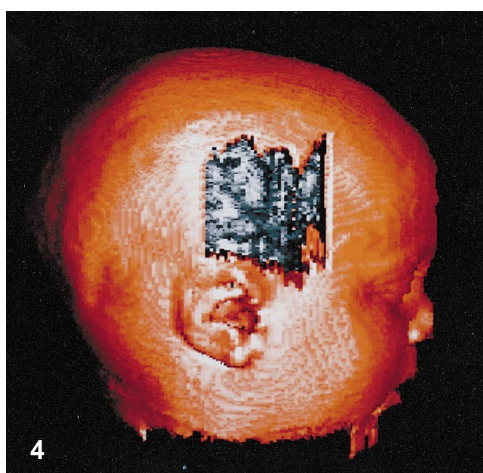
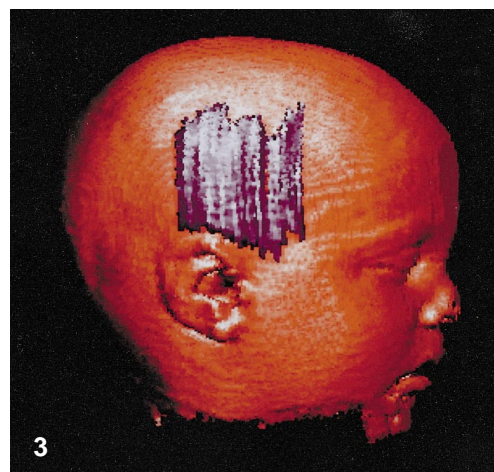
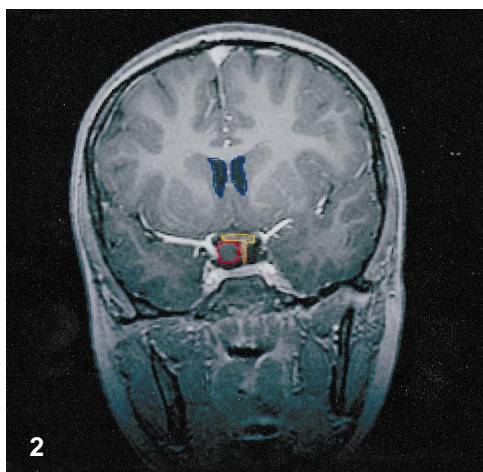
**Fig. 4** The skin flap is made transparent, allowing visualisation of the posterior aspect of the underlying sylvian fissure

**Fig. 5** The superficial part of the brain is made transparent. The surgical approach to the tumour (*red*) can be verified against deep-seated structures (lateral ventricle *purple*, brain stem *green*)

**Fig. 6** The right frontal lobe has been removed, to expose the ventricular system (*purple*), the optic chiasm (*yellow*), and the tumour (*red*). The displacement of the optic chiasm by the tumour is observed

**Fig. 7** In addition to the pterional approach, a subfrontal approach has been simulated by removing the anterior part of the frontal bone and the frontal lobe. The relationship of the tumour to surrounding deep-seated structures is demonstrated (ventricular system *purple*, brain stem *green*, tumour *red*)

**Fig. 8** **a** Lateral and **b** oblique views when all the superficial structures have been removed to visualise the tumour (*red*) in relation to the ventricular system (*purple*) and the optic chiasm (*yellow*). The optic chiasm displacement superiorly and anteriorly is clearly appreciated. Rotation of the three-dimensional object allows detailed assessment



peared as part of image manipulation software in image-guided surgery systems.

Widespread clinical application of image segmentation has been limited so far. This is largely due to the unfamiliarity of most neurosurgeons with computing, and the time and the level of interaction involved to create 3D objects of satisfactory quality for clinical use. Both factors operate synergistically, creating a gap between surgeons and computers. The busy clinical schedule of most neurosurgeons does not allow the luxury of a few spare hours to experiment with 3D MRI.

With improving technology both these factors are likely to change. The computer is gradually infiltrating into neurosurgical practice, initially as part of frameless stereotaxy systems. Parallel improvements in MRI technology and advances in computers' memory capacity and speed of execution are rapidly reducing the time required for 3D and 4D (including time axis) reconstructions.

Several workers have attempted to make use of these valuable segmentation techniques in clinical practice. Fields such as skull base or craniofacial surgery lend themselves particularly well to this purpose. Although it has not taken off routinely as yet, the feasibility of surgical planning using 3D reconstruction has been demonstrated, several imaging modalities often being combined [1, 3, 8–10, 13, 14, 23, 25].

Several fields of neurosurgery are likely to benefit from this technology. Brain tumour surgery, assisted by image guidance and 3D MRI, would become safer and more radical. Follow-up of cerebral tumours has obvious benefits from volumetric serial studies [17]. Stereotactic radiosur-

gery and epilepsy surgery would benefit from any 3D volumetric imaging technology [2]. In addition to surgical planning, surgical teaching would be improved by the use of 3D MRI. The advent of 3D atlases of the head [21, 24] is promising to revolutionise neurosurgical teaching. The difference between idealised atlases and a true 3D MRI object is that the latter conforms accurately to reality, at least in its preoperative imaging. In a similar way, the presented simulation of a neurosurgical operation would allow the surgeon to visualise the true anatomical relationships of the various structures to one another and "perform" the operation on the computer, thus anticipating potential surgical difficulties.

As the rate-limiting step remains the operator dependence and the associated time factor, the obvious next steps for further development would be in the area of improved automation. The incorporation of physics, anatomical and continuity constraints, which are currently under development in our laboratory [15, 16], would make the technique more appealing and will help establish its routine clinical use. Several workers have contributed significantly on these lines in recent years [1, 2, 4, 13, 17, 18, 22, 23]. Further development on dynamic MRI acquisition [7] is likely to improve the chances of existing automatic segmentation by improving the definition between various brain structures, which share similar grey values in ordinary MR sequences.

With wider use of segmentation in image-guided systems and the development of tele-surgery, a new perspective in visualisation of neurosurgical pathology is likely to evolve, which with time will improve surgical techniques.

## References

- Ardekani BA, Braun M, Hutton BF, Kanno I, Iida H (1995) A fully automatic multimodality image registration algorithm. *J Comput Assist Tomogr* 19: 615–623
- Ashton EA, Berg MJ, Parker KJ, Weisberg J, Chen CW, Ketonen L (1995) Segmentation and feature extraction techniques, with applications to MRI head studies. *Magn Reson Med* 33: 670–677
- Chalif DJ, Dufresne CR, Ransohoff J, McCarthy JA (1988) Three-dimensional computed tomographic reconstructions of intracranial meningiomas. *Neurosurgery* 23: 570–575
- Clarke LP, Velthuizen RP, Camacho MA, Heine JJ, Vaidyanathan M, Hall LO, Thatcher RW, Silbiger ML (1995) MRI segmentation: methods and applications. *Magn Reson Imaging* 13: 343–368
- Davis DN, Natarajan K, Claridge E (1994) Advanced segmentation. (AIM project A2032) Commission for the European Committees, DG 13
- Davis DN, Natarajan K, Claridge E (1995) Multiple energy function active contours applied to CT and MR images. *IEE Proceedings: Vision, Image and Signal Processing* 1995. IEE Conference, Publication 410: 114–116
- Duyn JH, Mattay VS, Sexton RH, Sobering GS, Barrios FA, Liu G, Frank JA, Weinberger DR, Moonen CT (1994) 3-Dimensional functional imaging of human brain using echo-shifted FLASH MRI. *Magn Reson Med* 32: 150–155, 545 (erratum)
- Ehrlicke H, Daiber G, Sonntag R, Strasser W, Lochner M, Siemens AG, Rudi LS, Lorenz WJ (1992) Interactive 3D graphics workstations in stereotaxy – clinical requirements, algorithms and solutions. *Visualisation Biomed Comput SPIE* 1808: 548–552
- Gandhe AJ, Hill DL, Studholme C, Hawkes DJ, Ruff CF, Cox TC, Gleeson MJ, Strong AJ (1994) Combined and three-dimensional rendered multimodal data for planning cranial base surgery: a prospective evaluation. *Neurosurgery* 35: 463–470
- Hayashi N, Endo S, Kurimoto M, Nishijo H, Ono T, Takaku A (1995) Functional image-guided neurosurgical simulation system using computerized three-dimensional graphics and dipole tracing. *Neurosurgery* 37: 694–703
- Holden M, Steen E, Lundervold A (1995) Segmentation and visualization of brain lesions in multispectral magnetic resonance images. *Comput Med Imaging Graph* 19: 171–183

12. Kikinis R, Cline HE, Altobelli D, Halle MW, Lorensen WE, Jolesz FA (1992) Interactive visualisation and manipulation of 3D reconstructions for planning of surgical procedures. *Visualisation Biomed Comput SPIE* 1808:553–559
13. Kikinis R, Gleason PL, Moriarty TM, Moore MR, Alexander E III, Stieg PE, Matsumae M, Lorensen WE, Cline HE, Black PMcL, Jolesz FA (1996) Computer-assisted interactive three-dimensional planning for neurosurgical procedures. *Neurosurgery* 38:640–651
14. Matsumae M, Kikinis R, Mórocz I, Lorenzo AV, Albert MS, Black PMcL, Jolesz FA (1996) Intracranial compartment volumes in patients with enlarged ventricles assessed by magnetic resonance-based image processing. *J Neurosurg* 84:972–981
15. Natarajan K (1993) A knowledge based system for radiological image recognition. PhD thesis, University of Birmingham
16. Natarajan K, Claridge E, Davis DN (1996) The symbolic atlas of the brain: handling non-visual information associated with neuroanatomy. *Med Inf (Lond)* 21:1–21
17. Phillips WE II, Velthuisen RP, Phuphanich S, Hall LO, Clarke LP, Silbiger ML (1995) Application of fuzzy c-means segmentation technique for tissue differentiation in MR images of a hemorrhagic glioblastoma multiforme. *Magn Reson Imaging* 13:277–290
18. Porrill J, Ivins J (1994) A semiautomatic tool for 3D medical image analysis using active contour models. *Med Inf (Lond)* 19:81–90
19. Robb RA, Barillot C (1989) Interactive display and analysis of 3D medical images. *IEEE Trans Biomed Eng* 8:217–226
20. Robb RA, Hanson DP (1991) A software system for interactive and quantitative visualization of multidimensional biomedical images. *Australas Phys Eng Sci Med* 14:9–29
21. Schubert R, Hohne KH, Pommert A, Riemer M, Schiemann T, Tiede U, Lierse W (1994) A new method for practicing exploration, dissection, and simulation with a complete computerized three-dimensional model of the brain and skull. *Acta Anat (Basel)* 150:69–74
22. Sivewright GJ, Elliott PJ (1994) Interactive region and volume growing for segmenting volumes in MR and CT images. *Med Inf (Lond)* 19:71–80
23. Sundaramoorthy G, Hoford JD, Hoffman EA, Higgins WE (1995) IMPROMPTU: a system for automatic 3D medical image-analysis. *Comput Med Imaging Graph* 19:131–143
24. Tiede U, Bomans M, Höhne KH, Pommert A, Riemer M, Schiemann T, Schubert R, Lierse W (1993) A computerized three-dimensional atlas of the human skull and brain. *AJNR Am J Neuroradiol* 14:551–559
25. Valentino DJ, Mazziota JC, Huang HK (1991) Volume rendering of multimodal images: application to MRI and PET imaging of the human brain. *IEEE Trans Biomed Eng* 10:554–562