Cerebral Ventricular Volumetry in Pediatric Neuroimaging

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Abstract. A prospective NIH funded study examines the effects of early brain damage on selective aspects of cognitive development in children. We describe an efficient method to segment and visualize the intracerebral fluid spaces in children and adults based on MRI and to quantify ventricular volumes which is (a) robust (for normal and pathological anatomy), (b) reproducible (less than 2 % relative variation), and (c) fast (less than 5 min for image analysis).

1 Introduction

Cerebral ventricular volume is an important factor in quantitative neurological diagnosis, for indirectly monitoring the progress of brain damage, e.g. after neonatal white matter damage or associated with neurodegenerative diseases, and for assessing post-operative outcome, e.g. on hydrocephalus patients.

A prospective, epidemiologic and neuropsychological NIH funded study examines the effects of early brain damage on selective aspects of cognitive development in children comprising the best documentation of localized neonatal brain damage to date. To investigate the long-term cognitive outcomes of white matter damage (WMD), a sample of 597 surviving children of very low birth weight (< 1501 g) was recruited for thorough neuropsychological evaluations at an age of six years. These children received extensive examinations at birth, including systematized ultrasonographic (US) brain scans at postnatal days 1–3, 7–10, and 21. A follow-up at age six offers an unprecedented opportunity to test hypotheses about the developing brain and its compensatory response to acquired insults. We hypothesize that cranial magnetic resonance images (MRI) that have been obtained for a sub-sample at age six will show reduced WM volume and ventricular enlargement associated with presence and location of neonatal WMD documented by US.

None of the tested volumetry methods are suitable to quantify the ventricular volumes in all given 34 datasets. Fully automated methods failed where anatomical or pathological variability was too large (as for example in Fig. 1 bottom). Manual or two-dimensional methods, such as described in [1] and [2], resulted in long interaction times or poor reproducibility. A volumetry method combining three-dimensional (3d) segmentation based on the watershed transformation [3] with a volumetric histogram analysis [4, 5] produced satisfactory results in cases with medium or strong ventricular

enlargement. Though, problems occurred with normal pediatric cerebral anatomy that often shows lateral ventricles of 5–10 cm length containing roughly 1 ml of fluid.

2 Methods

The presented method combines acquisition of standard MRI data, fast 3d marker based segmentation, and automatic histogram analysis. T1-weighted anatomic data is acquired on a GE Signa 1.5 T: GR 3D, 1.5 mm slice thickness, no interslice gap, TR 34 ms, TE 5 ms, matrix 256×256, 124 slices, 0.78 mm pixel spacing.

The segmentation algorithm is a modified version of the fast watershed transformation described in [3] and is applied to the original image data after resampling to an isotropic grid (0.7 mm cubic voxels using a Lanczos 3-lobed filter). Five different marker types are used for ventricle labeling (R, L, 3rd, and 4th) and region exclusion (Ø), thereby imposing watersheds at respective borders [4]. Mislabeled regions are interactively attributed to the correct structure by additional markers. The watershed transformation takes approx. 1 sec on a standard PC (Pentium III, 700 MHz, 256 MB) for a typical region of interest (1 million voxels). It automatically tracks the ventricular boundaries in 3d, taking the marker positions into account. In a standard case, less than 10 markers suffice to define the ventricular anatomy accurately. The segmentation procedure, including user interactions, takes 2 min for all slices on average.

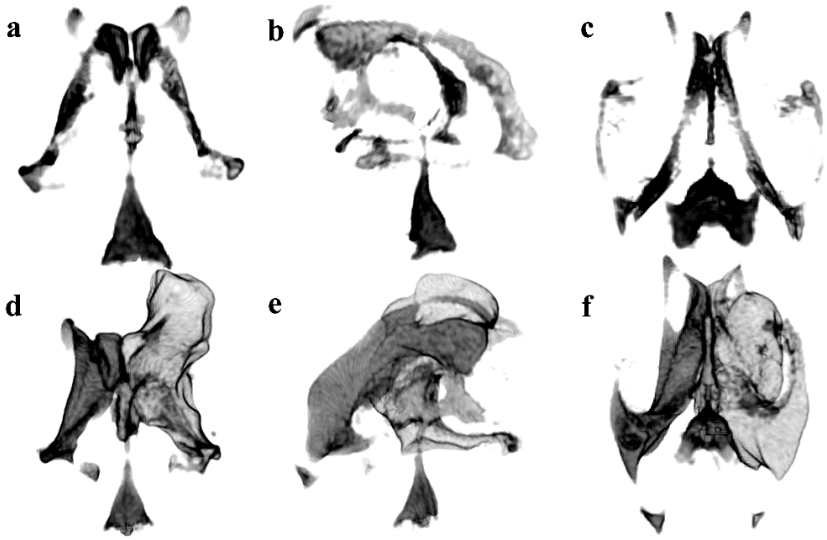

Fig. 1. Direct volume rendering of segmentation result for two 6yo subjects. **top (a–c)**: normal neonatal US; in this case, additional markers were required to specify the mean CSF gray value (ref. Fig. 2 left). **bottom (d–f)**: neonatal WMD, predominantly on the left hemisphere.
results: volumes (in ml) ± inter-observer variance:
a–c: 1.72 ± 0.03 (L), 1.74 ± 0.04 (R), 0.32 ± 0.07 (3rd), 1.58 ± 0.05 (4th);
d–f: 47.47 ± 0.12 (L), 9.52 ± 0.09 (R), 2.51 ± 0.07 (3rd), 1.23 ± 0.06 (4th).

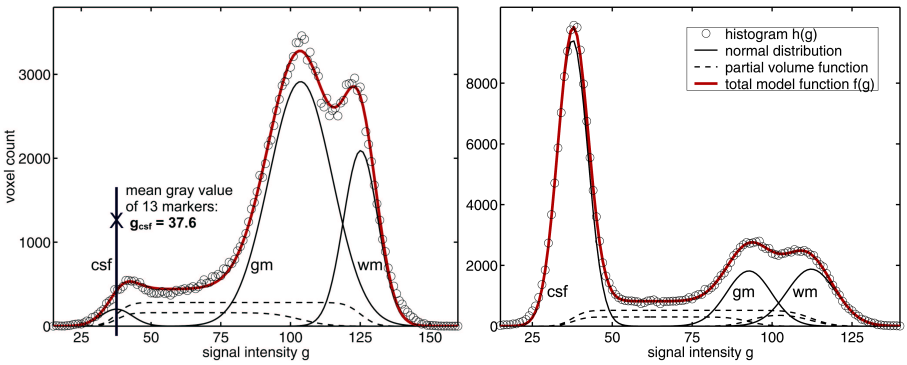

Fig. 2. model based histogram analysis for automatic quantification of tissue volumes; for the over-inclusive segmentation resulting from the watershed transformation, three tissue types are modeled; mixed Gaussians [5] are used as partial volume model (dotted lines). **left:** marker based specification of mean CSF gray value for histogram with sparse CSF representation (Fig. 1 top, all 4 ventricles). **right:** fully automatic histogram analysis (Fig. 1 bottom, left ventricle).

The volumes of each of the four segmented ventricles are computed automatically from corresponding over-inclusive regional image histograms. Assuming symmetric, equally distributed partial volume effects, we use a set of mixed Gaussians to extend the trimodal normal distribution model [5]. Least squared error minimization is used to fit the model (Fig. 2). The expected volumetric uncertainties are calculated individually, based on image noise, contrast, and resolution.

The histogram analysis was modified for very narrow ventricles (n = 15 cases, Fig. 1 top, Fig. 2 left) that typically occur in pediatric neuroimaging. In these images, partial volume effects play a more dominant role than we presumed when developing the methods for quantitative neuroimaging on adults [4]. The histogram analysis then automatically rejects the model fit and requests the user to specify at least 10 anatomical positions that are completely surrounded by cerebro spinal fluid (CSF); their mean gray value is given to the histogram model as center of the CSF Gaussian (g_{csf}).

3 Results

With the above modification, also the smallest ventricles were reliably quantified in all 34 datasets. We evaluated intra- and inter-observer variance. Mean values and standard deviations have been recorded. Inter-observer variance for lateral ventricular volumes was less than 2 % even for small volumes. Larger relative variations have been observed for 3rd and 4th ventricles due to small object sizes and the frequently imprecise delineations in MRI. Repeated acquisitions on a ventricle shaped paraffin phantom yielded a relative inter-examination variance of 0.4 % for the total volume (Mean ± SD: 60.89 ± 0.22 ml).

Resampling the original image data to an isotropic grid of 0.7 mm size was performed to provide sufficient information to the segmentation algorithm and histogram analysis on small ventricles. However, a finer grid did not change the results nor improve the stability of the method. Furthermore, we put emphasis on testing the above

modification of the histogram analysis against systematic errors (n = 19 cases). Placing the additional markers resulted in an increased mean interaction time (approx. 3 min), but did not produce biased results within the given variance. Nonetheless, a slightly larger inter-observer variance was recorded; i.e., an additional source of error has been created and requires special care of the operator.

Preliminary results indicate a strong correlation between ventricular volume at age six and neonatal WMD on the one hand and IQ at age six on the other hand.

4 Conclusion and Future Perspectives

We present a new semiautomatic approach which allows to quantify pediatric ventricular anatomy accurately while reducing image analysis and interaction times compared to manual or semiautomatic slice-based evaluation. User-induced errors are minimized by placing markers inside the objects instead of tracing object borders interactively. The 3d segmentation procedure is likewise applicable to normal and pathological anatomy since it does not require any anatomical model. Moreover, asymmetry of the lateral ventricles is directly quantified.

Accurate measurements are achieved from commonly available high-resolution T1-weighted MR images. Image fusion and higher dimensional image analysis are avoided. An automatic histogram analysis robustly accounts for image noise, non-uniformity, and partial volume effects. Combining short interaction times, broad applicability, and high reproducibility, the presented method meets the requirements posed by imaging and workflow conditions in a clinical setting.

Recently, the presented method has been successfully applied to MR data of a preterm baby two weeks after birth. Difficulties imposed by the small head size have been solved by using a finer resampling grid; the comparably poor image quality did not pose any problem. Employing a modified histogram model, also the brain volume of the baby has been quantified. Finally, an approach identical to the presented solved the problem of robustly quantifying the volume of small lung nodules (< 1 ml) based on multi-slice CT data with less than 2 min user interaction. Markers have been used to interactively separate the nodule from neighboring vessels.

5 References

1. Tsunoda A, Mitsuoka H, Sato K, et al.: A Quantitative Index of Intracranial Cerebrospinal Fluid Distribution in Normal Pressure Hydrocephalus. *Neuroradiology* 42: 424–429, 2000.
2. Schierlitz L, Hüppi PS, Jakab M, et al.: Three-dimensional Modeling and Volume Assessment of the Fetal and Neonatal Intracranial Ventricles. *ISMRM 2001, Proc. Intl. Soc. Mag. Reson. Med* 9: 402, 2001.
3. Hahn HK, Peitgen HO: The Skull Stripping Problem In MRI Solved By A Single 3D Watershed Transform. *MICCAI 2000, LNCS* 1935: 134–143, Springer, Berlin, 2000.
4. Hahn HK, Lentschig MG, Deimling M, et al.: MRI Based Volumetry of Intra- and Extracerebral CSF Spaces. *CARS 2001, ICS* 1230: 384–389, Elsevier, Amsterdam, 2001.
5. Hahn HK, Peitgen HO: Clinical MRI Based Neuroanatomic Volumetry. *3rd Caesarium – Computer Aided Medicine, Bonn*: Springer, Berlin, 2001, in press.