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How to cite

JIMÉNEZ DEL TORO, Oscar Alfonso et al. Epileptogenic lesion quantification in MRI using contralateral 3D texture comparisons. In: Lecture Notes in Computer Science, 2013, vol. 8150, p. 353–360. doi: 10.1007/978-3-642-40763-5_44

This publication URL: https://archive-ouverte.unige.ch/unige:97706

Publication DOI: 10.1007/978-3-642-40763-5_44

Published in Lecture Notes in Computer Science Volume 8150, 2013, p. 353-360
which should be used for any reference to this work.
The final publication is available at link.springer.com

3D epileptogenic lesion texture analysis and quantification in MRI using contralateral 3D Riesz wavelet transform

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Abstract. Epilepsy is a disorder of the brain that can lead to acute crisis and if possible an intervention can help patients. The exact localization of epileptogenic lesions influences the outcome of epilepsy surgery. Magnetic resonance (MR) imaging is clinically used for lesion detection and treatment planning, mainly through simple visual analysis. However, visual inspection in MR imaging can be highly subjective and subtle 3D structural abnormalities can be missclassified or not resected completely during the surgery. In this paper, a measurement of the differences in texture of the cerebral cortex between brain hemispheres is proposed. The 3D Riesz wavelet transform and the Hausdorff distance are used in MR T1 weighted images of the brain. A classification accuracy of 85% is obtained with 10 healthy control subjects and 8 patients with various types of epileptogenic lesions. The proposed quantitative measure of the texture alterations of these lesions allows an objective pre–surgical evaluation of patients undergoing epilepsy surgery.

Keywords: 3D texture analysis, Riesz transform, epilepsy, magnetic resonance imaging, computer–aided decision support.

1 Introduction

Brain alterations on the cortical mantle are often associated with neurological disorder such as epilepsy [18]. A precise localization of the epileptogenic lesions in the brain cortex is an important step in selecting the appropriate treatment or intervention for these patients [16]. The most common way of visualizing these lesions is by performing a standard control using high–resolution 3D magnetic resonance imaging (MRI) [13]. When the lesions can be clearly visualized in MRI, the epilepsy surgery has been associated with a more favourable outcome [19]. However, the alterations of the brain tissue are often subtle and differentiating them from the normal cortex is a difficult task [20, 11]. Studies regarding lesion detection by visual examination of MR images in patients undergoing epilepsy surgery have reported an accuracy of $50 - 60\%$ at 1.5 T [17, 16].

Texture analysis in MRIs of the brain has been proposed as a way of enhancing visualization of certain types of epileptogenic lesions such as focal cortical

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dysplasia (FCD) [13, 11, 1, 2, 4]. In some cases, these methods have shown to outperform visual assessment in discerning subtle anatomical changes, particularly in formerly cryptogenic epilepsy where the lesions produce seizures and were not detected by visual assesment of MRI [13, 4]. In [11, 1], voxel–based morphometry was used to create feature maps based on the characteristics of FCD that are visible on MRI. To characterize the texture of the regions, features are extracted from co–occurrence matrices . Other approaches have also shown high accuracy for lesion detection using gray matter quantification or anatomical feature analysis like the depth of the brain sulci [5, 4].

However, the problem of objectively measuring and segmenting these lesion remains since most of these methods results still have to be visually interpreted by the examiner [9]. In addition, methods using voxel–based morphometry require the use of templates or atlases to align the patient brains among them and to compare voxel–based characteristics to the average gray matter and white matter densities of a population [23, 11, 9, 7]. When visual features based on gray–level co–occurrence matrices are used, the number of gray–levels are often reduced to be able to compute a reliable and simple representation of the texture properties [21]. This method is neither scale nor rotation invariant and an exhaustive exploration of these parameters is required for an accurate characterization of the texture properties. This is not appropriate in three–dimensions, for example, since the number of possible orientations grows exponentially when compared to 2D. 3D Riesz wavelet transforms can perform a multiscale analysis of the space and frequency information that is contained in biomedical tissue [6]. 3D directional Riesz wavelets are used allowing a continuous characterization of scales and orientations.

The question posed by the paper is: Does texture analysis using Riesz wavelet transforms on previously obtained regions of interest (ROI) allows an objective measurement of candidate epileptogenic lesions when compared to healthy brain tissue? A method for comparing the cortical brain tissue texture between a region of interest (ROI) in patients with epileptogenic lesions and the corresponding contralateral anatomical region is used. Performing such an analysis in patients with subtle epileptogenic lesions could help clinicians in quantitatively assessing the texture visual properties of candidate lesions. This information would be included in the pre–surgical planning of patients with epilepsy for a better classification of the lesion.

2 Materials and Methods

2.1 Dataset

The database used for this article consists of: Eight cases (3 females, 5 males, mean age 21.8 years old) with seizures caused by a lesion located in the cerebral cortex as well as 10 control cases were selected for the study. The 8 patients with epilepsy underwent surgery and had confirmed diagnosis of the proposed epileptogenic lesion. These lesions include 5 cases with dysplasia, 1 ganglioglioma, 1 cavernoma and 1 case with tuberous sclerosis. Table. 1 shows the details from the

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different cases included in the study. All cases have complete MR image series including T1 weighted, 3DFLAIR images and diffusion tensor imaging (DTI) as part of an epilepsy presurgical standard control. They were acquired on a 3T MR imaging scanner (Magnetom Trio a Tim System, Siemens, Germany) using a head coil.The high resolution isotropic T1–weighted 3D dataset was obtained consisting of sagittal and coronal planes(TR= 1.6–1.9ms, TE=2.32ms, flip angle=9) but were resliced as axial slices for a better visualization of the lesions. The images had a matrix of $= 192 \times 255 \times 512$, with a voxel size= $0.9mm \times 0.9mm \times 0.449mm$ in the axial view. The ROI's were manually annotated by a neuroradiologist for each case where the epileptogenic lesion was visible in the cerebral cortex. Annotations were made on the MR image where the lesion was most visible (i.e., either T1, 3DFLAIR or DTI). Both 3DFLAIR and DTI were used for the annotations. If the manual annotation was made on the 3DFLAIR or DTI image of the patient, the coordinate transformation was estimated using image registration for the T1 weighted image of the patient. The T1 weighted images are then transformed to NIFTI format and bias corrected using statistical parametric mapping (SPM) to reduce the effect of the spatially varying artifact that modulates the intensity of MR images [1].

Table 1. Details of the epilepsy cases show the heterogeneous set of diseases included in the study. The age of the patient, brain lobe location of the lesion, MR image selected for the manual annotation because of the better visualization of the lesion and the volume of the manually annotated ROI are presented for each patient.

	age	epileptogenic lesion	lobe	MRI annotation	Volume (cm^3)
Patient 1	19	Dysplasia	Parietal	DTI axial	5.53
Patient 2	18	Dysplasia	Frontal	3D FLAIR axial	0.51
Patient 3	49	Cavernoma	Temporal	3D FLAIR axial	0.18
Patient 4	22	Tuberous Sclerosis	Occipital	3D FLAIR axial	0.17
Patient 5	17	Ganglioglioma	Temporal	3D FLAIR sagittal	0.27
Patient 6	21	Dysplasia	Parietal	3D FLAIR axial	23.1
Patient 7	20	Dysplasia	Frontal	3D FLAIR axial	12.35
Patient 8	13	Dysplasia	Parietal	3D FLAIR coronal	11.51

2.2 Texture analysis based 3D directional Riesz wavelets

3D multiscale Riesz filterbanks are used to characterize the texture properties of the brain cortex in MRI. Because of their texture discrimination properties in multiple scales and orientations, Riesz 3D wavelets are ideal for the detection of local characterizations in texture with high reproducibility and productivity compared to other texture based methods. The arbitrarly selection of scales and orientations only allows a limited number of feature selection from local texture

[1] `http://www.fil.ion.ucl.ac.uk/spm/`, as of 19 December 2012.

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analysis which is not desired particularly in small epileptogenic lesions [9]. The N–th order Riesz transform $\boldsymbol{\mathcal{R}}^{(N)}$ of a three–dimensional signal $f(\boldsymbol{x})$ is defined in the Fourier domain as:

$$\widehat{\mathcal{R}^{(n_1,n_2,n_3)}f}(\boldsymbol{\omega}) = \sqrt{\frac{n_1+n_2+n_3}{n_1!n_2!n_3!}}\frac{(-j\omega_1)^{n_1}(-j\omega_2)^{n_2}(-j\omega_3)^{n_3}}{||\boldsymbol{\omega}||^{n_1+n_2+n_3}}\hat{f}(\boldsymbol{\omega}), \qquad (1)$$

for all combinations of (n_1, n_2, n_3) with $n_1 + n_2 + n_3 = N$ and $n_{1,2,3} \in \mathbb{N}$. Eq. (1) yields $\binom{N+2}{2}$ templates $\mathcal{R}^{(n_1,n_2,n_3)}$ and forms multiscale steerable filterbanks when coupled with a multi–resolution framework based on isotropic band–limited wavelets (e.g., Simoncelli) [6]. It therefore allows continuous descriptions of three–dimensional scales and orientations.

2.3 Experimental Setup

The manual annotations were used as initial ROIs to perform 3D Riesz wavelet texture analysis since its common practice to already estimate the pathological origin of the seizures during pre–surgical planning [16]. Alternatively, the output of another lesion detection method with high accuracy like the one from Huppertz et. al. [11] can be used as an initial ROI for our method. A contralateral comparison of the brain cortical texture in the ROI to the opposite brain's hemisphere same anatomical area of the patient is performed. This is a clinical approach commonly used in the visual evaluation of the lesions when physicians want to compare the same anatomical region of interest to the lesion–free contralateral brain hemisphere. A similar approach for analyzing brain texture was used in [3].

To obtain the ROIs in the contralateral anatomical region, the hemispheres are registered with the method reviewed in Klein et. al. [15] implemented with Elastix software[2]. The quality of the registration is evaluated in every iterative optimization by a cost function of the transformation from the moving image to the fix target image. An affine registration that globally aligns both hemispheres using an iterative stochastic gradient descent optimizer with a multi–resolution approach [14]. was used. The obtained ROIs were all visually inspected to ensure that they label the same anatomical region in the opposite brain hemisphere of the patient.

For each patient both the candidate lesion ROI and the contralateral ROI are registered with the same registration method to the complete control set for testing 3D Riesz wavelet analysis on the cortial tissue. No images are used for training in our experiments. The T1 weighted images from the patients with epilepsy are set as moving images and registered independently to the T1 fixed images of the control set using affine registration. In the end, one ROI is found for each hemisphere for each patient with epilepsy in each of the 10 control patients. This leads to 80 inter-hemisphere texture analysis comparisons with 160 brain ROIs based on the manual annotations made by the neuroradiologist.

[2] `http://elastix.isi.uu.nl`, as of 19 December 2012.

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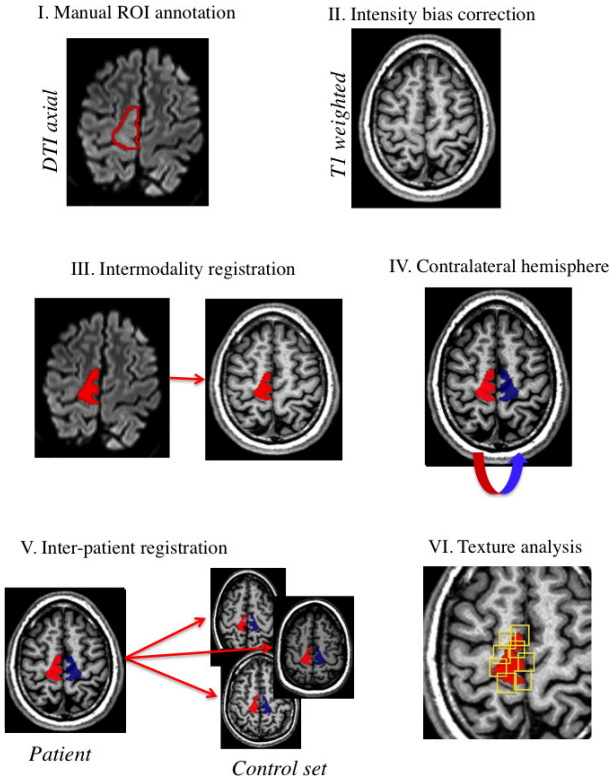

Fig. 1. Pipeline of the method. I. Manual delineation of the regions of interest with the epileptogenic lesions in the MR images with best visualization of the lesion. II. Bias correction of the T1 weighted images. III. Registration of the images with the manual delineations to the T1 weighted images of the patients. IV. Mirror of the images by the sagittal mid–brain plane to obtain ROIs in contralateral side. V. Registration of the patients images to the control set with the resulting coordinate transformation applied to the label images of the ROIs. VI. Texture analysis of the ROIs using 3D directional Riesz wavelets

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The images are resliced into isotropic voxels for a linear interpretation of the Riesz wavelet transform coefficients. ROIs are divided into 32^3 or 16^3 blocks centered in a defined number of ROI samples. Varying numbers of 100, 200 and 500 blocks were randomly selected for the validation. Whenever the number of samples was larger than the total number of voxels in the ROI, the instances were repeated to make sure that all patients had the same number of blocks tested for texture analysis. The Riesz transform was used with an order $N = 2$ and 4 different scales, which yields 24 subbands. The Riesz energy coefficients of the 24 subbands were used for each of the ROIs for both sides in the patients with epileptogenic lesions and the control set.

The Hausdorff distance computed in the 24–dimensional feature space was used as a measure of the distance between the subsets of blocks for each ROI and for their contralateral anatomical region in an Euclidean metric space [12]. Given two finite point sets $A = \{a_1, ..., a_p\}$ and $B = \{b_1, ..., b_q\}$, the Hausdorff distance is defined as:

$$H(A, B) = \max(h(A, B), h(B, A)) \tag{2}$$

where

$$h(A, B) = \underset{\mathbf{a}\in\mathbf{A}}{max}\ \underset{\mathbf{b}\in\mathbf{B}}{min} \parallel a - b \parallel$$

and $\| \cdot \|$ is an underlying norm on the points of A and B . A high Hausdorff distance reflects a high difference in the texture from the two subsets of coefficients that are compared.

3 Results

For each patient the Hausdorff distance is computed in the comparison of the brain texture from the lesion ROI and its contralateral equivalent anatomical ROI in MR T1w images of the patients. The experiments are performed using 50, 100, 200 and 500 ROI samples as center voxels for 32^3 and 16^3 blocks. The blocks are randomly selected inside each ROI and can overlap with each other producing texture descriptive multiscale Riesz energy coefficients for every block. Blocks were randomly selected since the size of the ROIs can vary significantly among patients (i.e., from 0.17 to 12.35 cm^3). The Hausdorff distance is computed with the resulting energy coefficients of all of the blocks from both sides of the brain. The mean Hausdorff distance from the control subsets is compared to the mean Hausdorff distance of each of the 8 patients patients with epileptogenic lesions comparisons varying the parameters for the no. of samples used and the size of the block created for each sample. An accuracy of 85%, specificity of 90%, positive predictive value (PPV) of 89.47% and negative predictive value (NPV) 85.71% is obtained for the 80 comparisons (8 patients×10 control cases) of contralateral ROIs.

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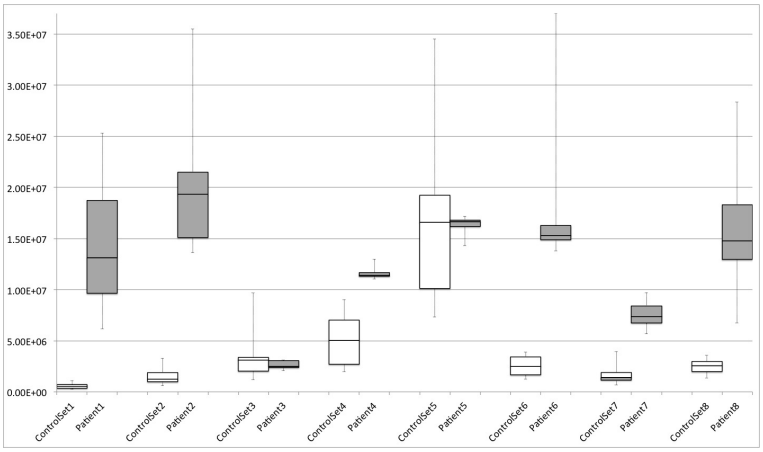

Fig. 2. Mean average Hausdorff distance between the subsets of energy coefficients from the control set (white boxes) for every ROI compared to its contralateral region in the opposite brain hemisphere and mean Hausdorff distance from the patients (gray boxes) after 10 experiments. The boxes represent the cases whose hausdorff distance was in the range of the medianstandard deviation.

4 Discussions and Conclusions

We propose a method for 3D texture analysis of brain cortical tissue with candidate epileptogenic lesions to be used in patients undergoing surgery for drug–resistant epilepsy. The method provides a quantitative measure of the difference between the texture from a region of interest to the contralateral healthy anatomical region in the brain. This measure could be used in clinical routine to objectively quantify abnormal tissue in the brain and consequently assist in the decision making on the treatment of patients with subtle epileptogenic lesions.

The results show that the Hausdorff distance between subsets of the energies of Riesz wavelet coefficients can discriminate between ROIs in healthy cases and patients with a suspicious abnormality in the brain tissue. The challenge in performing the method without inter-patient normalization is to overcome the influence of anatomical variability and inter-hemisphere differences when measuring the candidate lesions. The continuous characterization of scales and orientations allowed by Riesz wavelets provides a multiscale analysis validation of the features in the local texture that can be caused by these lesions in the brain. To the best of our knowledge, this is the first attempt at lesion classification of different types of epileptogenic lesions based on the texture features in suspicious ROIs.

The main objective of future work will be to provide a lesion segmentation based on the inter-hemisphere comparison of the abnormality score in inter-patient ROIs. It could provide a voxel–by–voxel difference using the output of the 3D Riesz wavelet texture features of various samples inside the ROI. These

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patients can benefit from better interpretation of the available images in order to improve the outcome of the surgical curative procedure. 3D texture analysis on 3DFLAIR and DTI can also be included to fuse the information from all of the presurgical standard control MRI series and improve the robustness and specificity of our method. An enlargement of our database is also planned.

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