PERFORMANCE EVALUATION OF ADVANCED IMAGE FUSION ALGORITHMS FOR GAMMA KNIFE TREATMENT PLANING

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Abstract: Image fusion is a process of combining information from multiple sensors. It is a useful tool implemented in the treatment planning programme of Gamma Knife Radiosurgery. In this paper we evaluated advanced image fusion algorithms for Matlab® platform and head images. We developed nine level grayscale image fusion methods: average, principal component analysis (PCA), discrete wavelet transform (DWT) and Laplacian, filter – subtract – decimate (FSD), contrast, gradient, morphological pyramid and a shift invariant discrete wavelet transform (SIDWT) method in Matlab® platform. We tested these methods qualitatively and quantitatively. The quantitative criteria we used are the Root Mean Square Error (RMSE), the Mutual Information (MI), the Standard Deviation (STD), the Entropy (H), the Difference Entropy (DH) and the Cross Entropy (CEN). The qualitative criteria are: natural appearance, brilliance contrast, presence of complementary features and enhancement of common features. Finally we made clinically useful suggestions.

Introduction

In the 1950s, Swedish professors B. Larsson and L. Leksell began to investigate combining proton beams with stereotactic (guiding) devices capable of pinpointing targets within the brain. In 1967, the researchers arranged for construction of the first “Gamma Knife” device using cobalt –60 as the energy source. Leksell termed this new surgical technique “stereotactic radiosurgery” [1].

Precise and powerful, the 20-ton Gamma Knife can destroy deep-seated vascular malformations and brain tumors once considered inoperable. It can treat brain tumors, arteriovenous malformations (AVMs), collections of abnormal brain arteries and veins that can cause disastrous or even fatal bleeding into the brain; and pain or movement disorders. The treatment is unique because no surgical incision is performed to “expose” the tumor [1].

The Gamma Knife contains 201 cobalt-60 sources of approximately 30 Ci (Curie) each, placed in circular array in a heavily shielded unit. The unit directs gamma radiation to a target point. Such target points selected in the brain can be placed at the center of the radiation focus, allowing a tumoricidal radiation dosage to be delivered in one treatment session. Helmets of removable 4,8,14 or 18 mm tungsten collimators with circular apertures are used to create different diameter fields at the focus point [1].

Stereotactic computed tomography (CT) and magnetic resonance imaging (MRI) is used for target determination, depending on the indication. After the placement of the stereotactic frame, the patient is taken to the imaging area of CT and MRI successively. Imaging studies help the Gamma Knife team (neurosurgeon and physicist) pinpoint exactly where to target the radiation. The stereotactic frame stays in place throughout all the imaging studies, and the markers of a localizer box attached to the stereotactic frame appear on the image. These markers are used for different imaging modalities to be registered in order to transform image coordinates into stereotactic coordinates. Thus, the clinicians can easily and effectively plan the individual treatment (figure 1).

In this work we developed and evaluated algorithms for the appropriate CT and MRI image fusion needed in the Gamma Knife treatment planning.

Materials and Methods

For fusion tests, we registered-aligned the CT and the MR images with the affine transformation method using the least squares. The specialist used at least three of the six stereotactic frame pinpoints shown on each scan. These points are the artificial landmarks used for the registration. This is the reason why the patient wears a stereotactic frame tightly fixed on his/her head before imaging. Each time two images of highly clinical interest are registered. The scans that have clinical interest are defined and chosen each time by the physician. For the MRI images we used the T1 scans, the T1 scans with contrast agent and the T2 scans. The couples of the reference and the registered image used are depicted in table 1.For the fusion algorithms and the evaluation criteria we developed Matlab® scripts using the Matlab® platform. The scans are fused using the platform as shown in figure 2. Our methods were inspired by Rockinger and Fechner [2], who implemented several classical grayscale fusion methods:

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Table 1: Reference and Registered Scans Forming Couples for Fusion

Scan couples for fusion
CT-T1 MRI
CT-T1 MRI with contrast agent
CT-T2 MRI
T1 MRI-T1 MRI with contrast agent
T1 MRI-T2 MRI

average, principal component analysis (PCA), discrete wavelet transform (DWT) and Laplacian, filter–subtract–decimate (FSD), contrast, gradient, morphological pyramid and a shift invariant discrete wavelet transform (SIDWT) method in Matlab® platform. We developed all these nine methods with the Matlab® platform and evaluated them as for their clinical usefulness in the Gamma Knife treatment operation.

In the literature, almost all image fusion evaluations are done qualitatively. However, there are some quantitative criteria that can be used. Some need an ideal fused image (root mean square error, mutual information, difference entropy) while others do not (standard deviation, entropy, cross entropy). From these, the standard deviation and the entropy measure respectively the contrast and the information content in an image. The cross entropy measures the similarity in information content between the source and the fused images. For the qualitative evaluation, we considered the following criteria: natural appearance, brilliance contrast, presence of complementary features and enhancement of common features [3].

In general terms the requirements of an image fusion process are as follows: it must preserve all valid and useful pattern information from the source images, and at the same time it must not introduce any new pattern elements, or artifacts, that could interfere with subsequent analysis [4]. However, it is almost impossible to combine images without introducing some form of distortion. The quantitative criteria-parameters we use for the evaluation of the CT and MR scans fusion are [3]:

A. RMSE

The root mean square error (RMSE) is used as the evaluation criterion between the reference image R and the fused image F.

$$\text{RMSE}=\sqrt{\frac{\sum_{m=1}^{M}\sum_{n=1}^{N}[R(m,n)-F(m,n)]^2}{MxN}} \quad (1)$$

B. MI

The mutual information (MI) between the reference image R and the fused image F is given by the following formula.

$$\text{MI}=\sum_{i=1}^{L}\sum_{J=1}^{L} h_{R,F}(I,J)\log_2\frac{h_{R,F}(i,j)}{h_R(i)h_F(j)} \quad (2)$$

Where $h_{R,F}$ indicates the normalized joint gray level histogram of images R and F, h_R and h_F the normalized marginal histograms of the two images, and L is the number of gray levels.

C. Standard deviation

The standard deviation (STD), which is the square root of the variance, reflects the spread in the data. Thus, a high contrast image will have a high variance, and a low contrast image will have a low variance.

D. Entropy

The entropy (H) of an image is a measure of information content. H is the average information supplied by a set of g symbols whose probabilities are given by p(g).

$$\text{H}=-\sum_{g=0}^{L-1} p(g)\log_2 p(g) \quad (3)$$

While the range of g is [0,…,L-1].

E. Difference entropy

The difference entropy (ΔH) between two images reflects the difference between the average amount of information they contained.

$$\Delta\text{H} = |\text{H}_R - \text{H}_F| \quad (4)$$

Where H_F and H_R are the entropy of the fused image and the reference image.

F. Cross entropy

Let P and Q denote the grey distributions of two images, cross entropy (CEN) evaluate the information difference between them.

$$\text{CEN(P,Q)}=\sum_{g=0}^{L-1} p(g)\log_2\frac{p(g)}{q(g)} \quad (5)$$

Results

Fusion algorithms have been tested on real patient images for Gamma Knife treatment.

Laliberte et al [5] in their work for retinal images observed that select maximum is the best method according to the standard deviation, but the fused image does not have a natural appearance and important dark features are missing. For the two other criteria, the first two positions are disputed by the discrete wavelet transform and its shift invariant extension. The images

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have good contrast and exhibit much detail. They also observed that for the standard deviation criterion, the best fused result is worse than the source image. Thus, in fusing image they lost a little contrast but gain a lot in information content.

In our work the results for the radiological scans of a head were quite different. We conducted the following statistical test. We measured all the proposed quantitative parameters for all the fused image couples. The reference image was always the CT scan and whenever there was not the CT, it was the T1-MRI scan that played the reference image. We expected that for the RMSE parameter, the best fusion method had the lowest value, while for the rest parameters the best method had the highest value. The PCA method [6] offered the best results measuring the RMSE and the MI parameters. The morphological pyramid method offered the best results measuring the standard deviation, the entropy and the difference entropy parameter. The FSD method [7] offered the best results measuring the CEN parameter. Table 2 shows the best fusion methods for each evaluation criterion that we concluded in.

Table 2: Best Fusion Method for Each Evaluation Criterion

Standard Deviation (STD)	Entropy (H)	Cross Entropy (CEN)
morphological	morphological	fsd
RMSE	Mutual Information (MI)	Difference Entropy (DH)
pca	pca	morphological

According to all results of all parameters comparably, the best method for fusing CT and MR stereotactic images for Gamma Knife operations is the morphological pyramid. This fact is statistically supported in figures 3-8. Thus, we understand that among all fusion methods, the morphological pyramid works better than all the others for all scan couples.
Then we defined the best couple of scans used in order to produce the fused image. Among morphological pyramid, the PCA, the FSD and the gradient pyramid method that generally offered the best quantitative and qualitative results, we concluded that the best couple, offering the most useful clinical information for the needs of the Gamma Knife treatment is the one formed by the CT scan and the T1 MRI scan with contrast agent. This couple offers the best values among all measured quantitative parameters for the morphological pyramid, the PCA, the FSD and the gradient pyramid method.

The next step we followed in our test was to show the fused images to the Gamma Knife treatment planning team, formed by clinicians, medical physicists and computer scientists. Their report was in agreement with our quantitative results. Moreover, the natural appearance, the brilliance contrast, the presence of complementary features and the enhancement of common features were graded best in the fused images of the CT scan with the T1 MRI scan with contrast agent and the morphological pyramid fusion method.

Discussion

In our work we tried to develop advanced techniques fro fusing CT and MRI images, important for the Gamma Knife Treatment Planning. The problem is that the images have to be registered before they are fused. The fusion techniques are only suitable for greyscale level. Our future work is to establish our platform in a daily clinical routine.

Conclusions

We introduced a set of fusion algorithms for the CT and MRI images used in the treatment planning of Gamma Knife operation. We tested nine grayscale methods for fusing CT and MRI head scans. We evaluated them qualitatively and quantitatively. The statistical results we produced are accepted by the clinicians. We concluded that the best fusing method is the morphological pyramid offering the most clinically useful information. Moreover, the best couple of scans in order to produce the fused image are the CT scan and the T1 MRI scan with contrast agent.

Figure 1: Removable stereotactic frame with visible markers for CT and MRI imaging

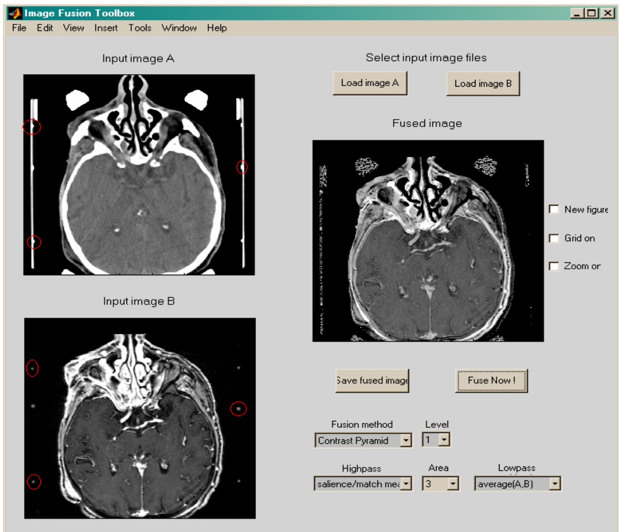

Figure 2: The Matlab® platform for fusing CT and MRI scans before Gamma Knife operation. The red circles show the pinpoints used for the image registration

ISSN: 1727-1983

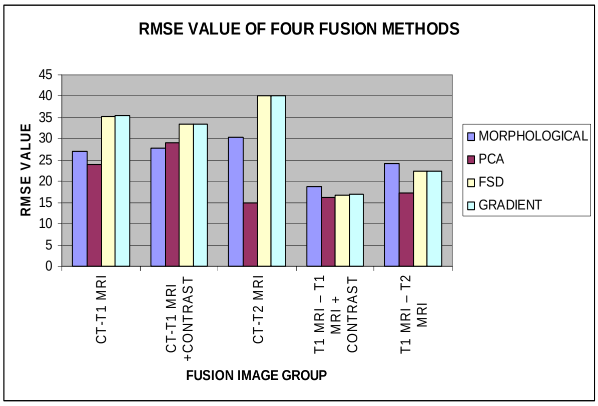

Figure 3: RMSE value of four fusion methods

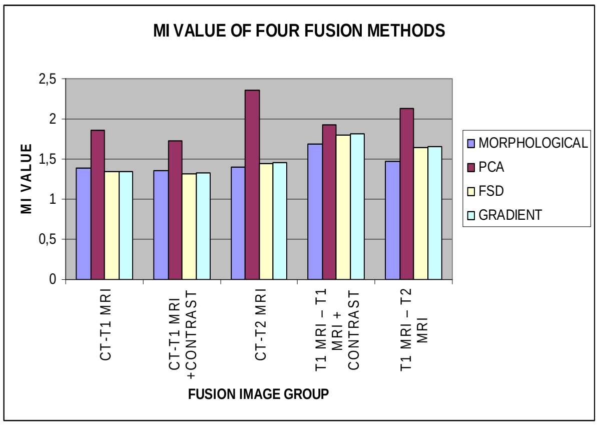

Figure 4: MI value of four fusion methods

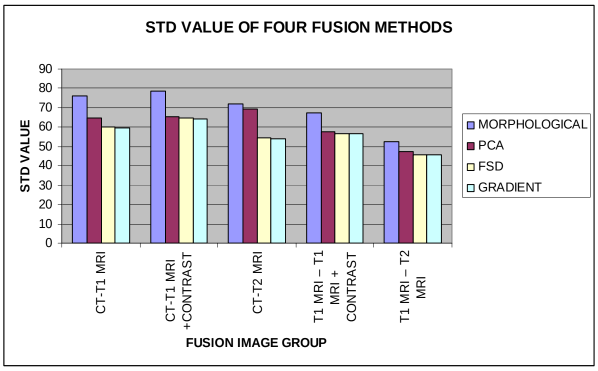

Figure 5: STD value of four fusion methods

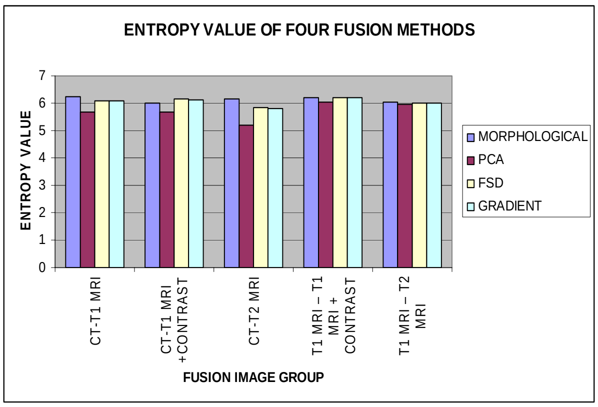

Figure 6: H Entropy value of four fusion methods

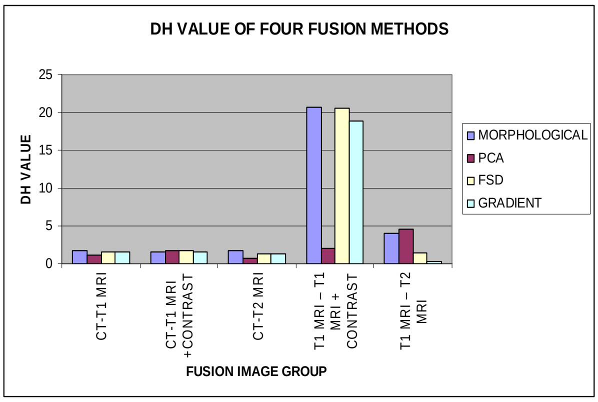

Figure 7: DH value of four fusion methods

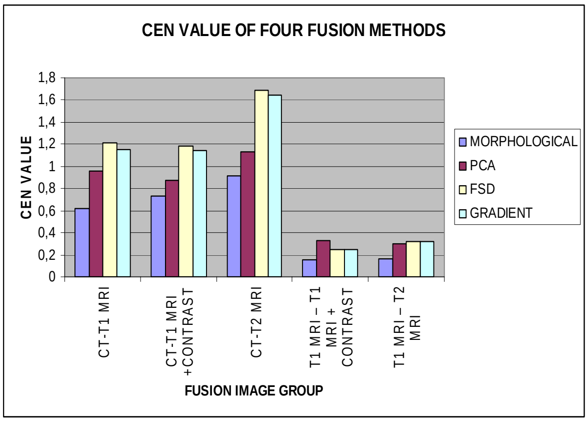

Figure 8: CEN value of four fusion methods

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