ORIGINAL CONTRIBUTION

Application of Eigen Value Expansion to Feature Extraction from MR Images

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The eigen value expansion technique was utilized for feature extraction of magnetic resonance (MR) images. The eigen value expansion is an orthonormal transformation method which decomposes a set of images into some statistically uncorrelated images. The technique was applied to MR images obtained with various imaging parameters at the same anatomical site. It generated one mean image and another set of images called bases for the images. Each basis corresponds to a feature in the images. A basis is, therefore, utilized for the feature extraction from MR images and a weighted sum of bases is also used for the feature enhancement. Furthermore, any MR images with specific features can be obtained from a linear combination of the mean image and all of the bases.

Images of hemorrhaged brain with a spin echo sequence and a series of cinematic cerebro spinal fluid flow images with a ECG gated gradient refocused echo sequence were employed to estimate the ability of the feature extraction and the contrast enhancement. Results showed us that proposed application of a eigen value expansion technique to the feature extraction of MR images is good enough to clinical use and superior to other feature extraction methods such as producing a calculated MR image with a given TR and TE or the matched-filter method in processing speed and reproducibility of results.

INTRODUCTION

It is the first step for diagnoses to find out the abnormal features in images. But in magnetic resonance (MR) images, the intensity of the signal depends upon several tissue-related factors such as the proton density, the spin-lattice relaxation time (T_1) and the spin-spin relaxation time (T_2), and operator-selectable parameters such as the pulse sequence, the repetition time (TR) and the echo time (TE). So it is difficult to detect the abnormal features precisely.

Computational contrast enhancement techniques help us to find out these features. There are two methods for find out the feature. One is that the feature are selected manually, the other is to calculate a reason-

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able image with any set of TR and TE parameters.

Windham *et al.* used the former technique as an eigenimage filtering for the contrast enhancement of MR images[1),2)] and this technique was one of applications of the "matched filter" method. On the application of a matched filter technique, the small region of interest must be chosen as a template first and then the region which has the same properties of the MR signal as a template are selected as the feature. But the signal intensity of a pixel in the template is similar to the one of another pixel in the same template. Therefore, the application of a matched filter to the contrast enhancement of MR images becomes a ill-posed problem and it is necessary for overcoming the problem to introduce a new conditional parameters[3),4)].

Kaufman et al continue to study calculated MR images[5)~7)]. This is based on that given a set of images obtained with two values of TR and two values of TE, and assuming a reasonable behavior for slice profile, it is possible to calculate a spin-echo or inversion-recovery image with any set of TR, inversion-time and TE parameters. But on calculating images, a set of images obtained with two values of TR and two values of TE are needed. Imaging parameters, therefore, are restricted on the assumption that images are processed to generate new images by a back-end computer.

In this article, the eigen value expansion method is utilized for a new feature extraction and contrast enhancement technique of MR images. This eigen value expansion method is a technique which is useful for detecting some features automatically in MR images and do not need any templates and any restrictions on imaging parameters[8)].

METHODS

A given number of MR images, which were obtained with various imaging parameters at the same anatomical site, were employed to find specific features. These images are represented by an array of pixels, which has N rows and N columns. But for purposes of analysis it is convenient to convert the image matrix $\mathbf{F}$ to vector form by row scanning $\mathbf{F}$ and then stringing the elements together in a long vector. It is possible easily to convert between vector and matrix representations of a two-dimensional array and the advantages of dealing with images in vector form are a more compact notation and the ability readily to apply some results for one-dimensional signal processing applications. So the image vector $\mathbf{f}$, which is the vector representation of the image matrix $\mathbf{F}$ and would consist of the N^2 brightness values of the pixels, is a one-dimensional horizontal arrangement of the element $f(i)$, where $i=1, 2, \ldots, N^2$. In this article, unless otherwise indicated, all boldface lower case letters denote vectors.

$$\mathbf{f}= [f(1)\ f(2) \ldots f(N^2)]$$

Because a set of images considered here assumed to be obtained at the same anatomical site but with different imaging parameters such as TR and TE, a set of these images would form the multispectral image vector $\mathbf{x}$ and each of images would corresponds to a specific spectrum,

$$\mathbf{x}= [\mathbf{f}_1\ \mathbf{f}_2 \ldots \mathbf{f}_n]^T$$

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where n is the number of MR images employed for this study and f_j $(j=1, 2, \dots, n)$ is the above-mentioned image vector. Furthermore, T means the transpose of a vector. So the multispectral image vector x is equivalent to a $(n \times N^2)$ matrix. In order to accentuate salient features to assist in subsequent diagnoses, enhancement procedures performed on the multispectral image are usuful. The eigen value expansion method, considered in this article, is suitable for the feature extraction and the enhancement. The eigen value expansion method is one of orthonormal transformation techniques, which decomposes the multispectral image vector x into some linearly independent component images. Each of these linearly independent images corresponds to the feature in the multispectral image vector x and is called a basis for x. Therefore, a basis is utilized for the feature extraction and a linear combination of these bases is also utilized for the feature enhancement.

The technique to be described here are very closely related to the topic in stochastic process theory. In order to calculate the bases from given multispectral images with using the eigen value expansion technique, suppose that each component image of the multispectral image vector x is a function of a stochastic process and fluctuates around the mean of the image vector, where the mean of the image vector x_m is

$$\mathsf{x}_m = E\ \{\mathsf{x}\}$$

and $E\ \{*\}$ means the statistic expectation. Similarly, the covariance matrix of the image vector is defined by

$$\mathsf{K} = E\ \{(\mathsf{x}-\mathsf{x}_m)(\mathsf{x}-\mathsf{x}_m)^T\}$$

Note that the covariance matrix is symmetric and positive semidefinite. If an orthonormal transformation U is a square matrix that satisfies the relation

$$\mathsf{U}\mathsf{U}^T = \mathsf{U}^T\mathsf{U} = \mathsf{I}$$

where I is the identity matrix and the matrix U performs a diagonalization of the covariance matrix K such that the covariance matrix of the transformed imagery is a diagonal matrix Λ whose elements are the eigenvalues of K arranged in descending.

$$\mathsf{U}\mathsf{K}\mathsf{U}^T = \Lambda$$

Consequently, it can be seen that the components of $\mathsf{U}(\mathsf{x}-\mathsf{x}_m)$ are linearly independent or statistically uncorrelated each other, that is, no member of these components can be written as a linear combination of the other components. Therefore, these components vectors are orthonomal and called as bases for the multispectral image vector x.

A new eigen image vector u, which would consist of these bases, is defined as follows,

$$\mathsf{u} = [\mathsf{u}_1\ \mathsf{u}_2\ \dots\ \mathsf{u}_n]^T$$

where u_j $(j=1, 2, \dots, n)$ is a basis for the multispectral image vector x. Then by using these bases, any image vector f_a can be represented by a linear combination

$$\mathsf{f}_a = a_1\mathsf{u}_1 + a_2\mathsf{u}_2 + \dots + a_n\mathsf{u}_n + \mathsf{x}_m$$

where the a_j $(j=1, 2, \dots, n)$ is a real number, and any vector f_j in x has such a representation. The $\{a_j\}$ are called the components of x with respect to the basis $\{\mathsf{u}_j\}$ and one obtains the relation

$$\mathsf{u}_j^T\mathsf{f}_a = a_j, \qquad j=1, 2, \dots, n$$

which provides a direct approach to determining the vector components $\{a_j\}$ with respect to the basis $\{\mathsf{u}_j\}$. Therefore, any MR images, such as the image with a specific feature enhanced, can be obtained by increasing the corresponding components.

MATERIALS AND RESULTS

Two cases were selected in order to examine the clinical usefulness of the abovementioned eigen value expansion technique. One was the application of it to the image enhancement of the hemorrhaged region in brain images to clarify the border of its region. The other was to detecting the abnormality in the flow of the cerebro spinal fluid (CSF) by extracting some features from a series of cinematic spinal CSF flow images. All MR imaging studies were performed on a 1.5-T whole body imager (Signa system, GE Medical Systems, Milwaukee, and Yokogawa Medical Systems). MR images were obtained at the same anatomical site, while the signal intensity of each image was different according to the imaging parameters such as TR and TE in the former case, or according to the CSF flow velocity in the latter case. All of images obtained were transfered to the workstation SUN 386i/150 via BLACK BOX, which was a RS422-RS232 converter, by the public domain file transfer protocol KERMIT and processed in this workstation.

APPLICATION TO IMAGE ENHANCEMENT IN HEMORRHAGED BRAIN IMAGE

The eigen value expansion technique was applied to images of a hemorrhaged brain, which were obtained with a spin echo (SE) sequence, to enhance the bleeded region as the first example.

Four SE images as shown in Fig.1, which were obtained with A(TR/TE=2300/90), B (2300/180), C(600/20) and D(600/40) respectively, were employed for the feature extraction and the image enhancement. The mean image of these four was shown in Fig.2. Furthermore, the bases for these four image vectors were calculated according to the eigen value expansion formula and were shown in Fig.3, where A was the first eigen value image, B the second one, C the third one and D the fourth one. The ratio of contribution for each eigen value image to the sum image of them was 60.7%, 38.2%, 1.02% and 0.02%, respectively.

An arbitrary image can be represented by a weighted sum of the mean image and all of the basis images. To evaluate the precision in representation of an image by a linear combination of the mean image and the four bases, two images were processed. The one was the image A in Fig.1 and the other was the image C in Fig.1. The components of an image with respect to the bases were $[a_1\ a_2\ a_3\ a_4] = [-0.41\ 0.75\ 0.16\ 0.50]$ in case of the former image and $[-0.49\ -0.47\ -0.55\ 0.49]$ in case of the later image. In Fig.4 and 5, the image A is the original image (same as the image A and C in Fig.1, respectively), the image B is the linearly combined image of the mean image and the four bases, the image C is the difference between the image A and B. The image C means the calculation error on representing an arbitray image by a linear combination of the mean image and the basis images. Judging from the results shown in Fig.4 and 5, there were little errors in both cases and this fact means that each basis image represents the characteristic in a set of original images, it is possible to find out some characteristics in common with them by using an eigen value expansion and there will be few loss of informations when an image is represented by a weighted sum of these characteristic images.

Fig.6 shows the result of an image enhance-

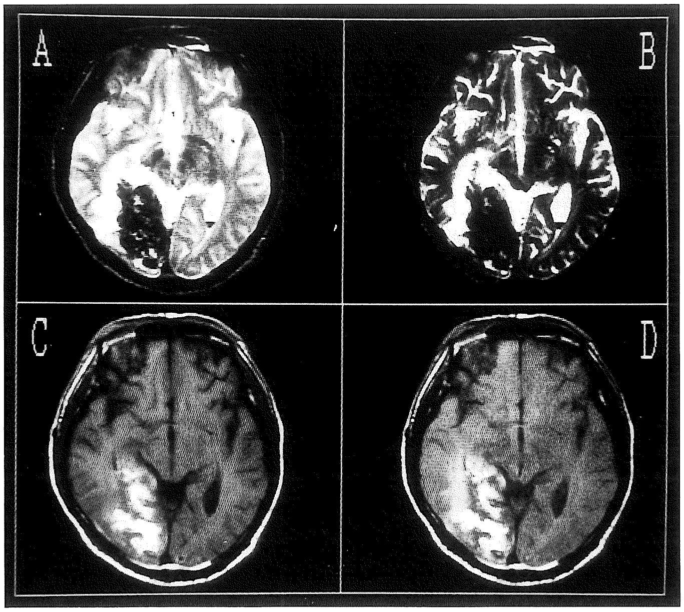

Fig. 1. Four images of a hemorrhaged brain with a spin echo sequence which were used for estimating the ability of the feature extraction. The TR/TE times in ms are (A) 2300/90, (B) 2300/180, (C) 600/20, and (D) 600/40.

Fig.2. The mean image calculated from the four images shown in Fig.1.

ment by a linear combination of the mean image and the basis images, where the hemorrhaged region is discriminated from other normal regions and easy to understand the size or the border of it compared with the corresponding image B in Fig.5. The components of the image in Fig.6 with respect to the bases were [a_1 a_2 a_3 a_4]= [-0.49 -0.94 -0.55 0.49], where the coefficient for the second basis was twice as much as one in case of the image B in Fig.5. This was because of the enhancement of the second property in the four bases, in which the hemorrhaged region was found that the relaxation time was different from one at other regions in the brain.

APPLICATION TO DETECTING ABNORMLITY IN CSF FLOW

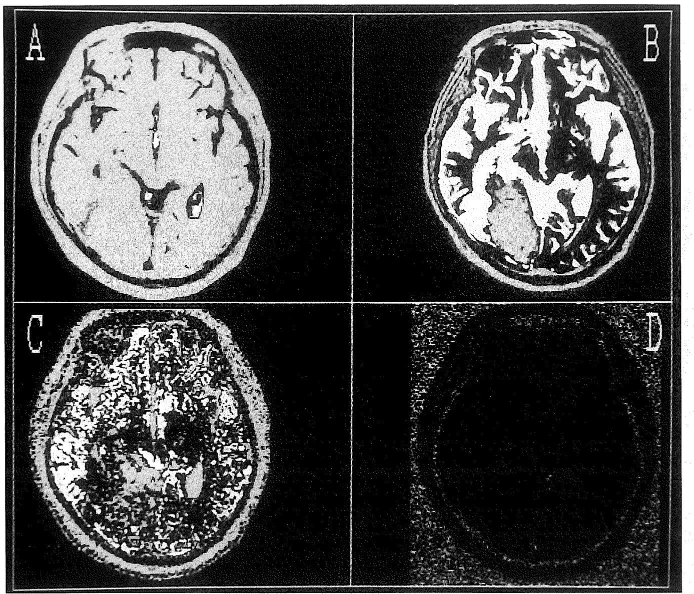

Fig.3. Four eigen value images calculated by the eigen value expansion technique from the four images in Fig. 1. (A) shows the first eigen value image, (B) the second eigen value image, (C) the third eigen value image, and (D) the fourth eigen value image and the ratio of contribution for each eigen value image to the sum image of these eigen value images is 60.7%, 38.2%, 1.02%, and 0.02%, respectively.

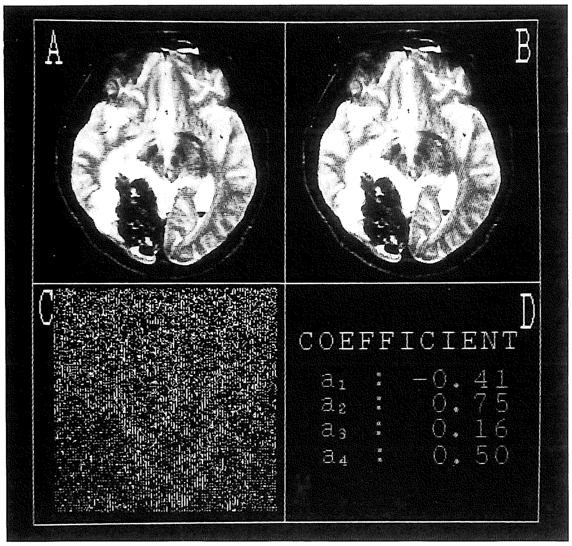

Fig.4. (A) shows the image which is identical with the image (A) in Fig.1. (B) shows the calculated image by a linear combination of the four eigen value images and the mean image. The coefficients are shown in (D). (C) shows the difference between (A) and (B), which is multiplied by 10 to clarify the difference.

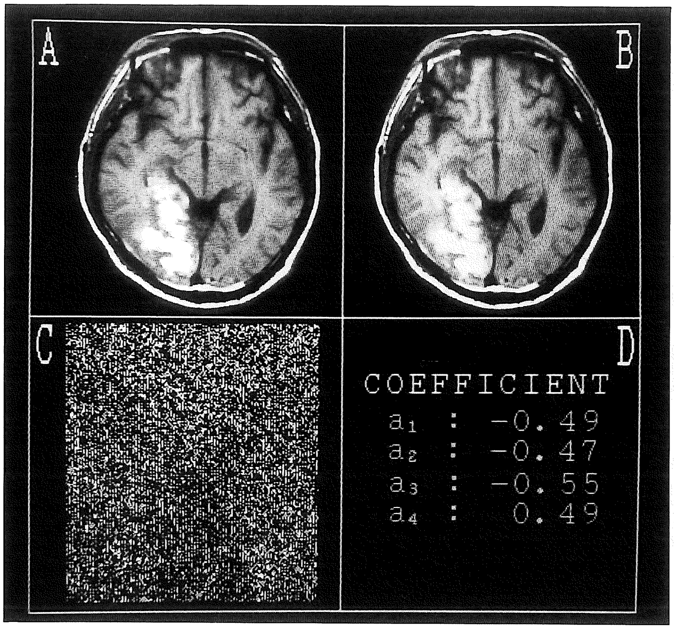

Fig.5. (A) shows the image which is identical with the image (C) in Fig.1. (B) shows the calculated image by a linear combination of the four eigen value images and the mean image. The coefficients are shown in (D). (C) shows the difference between (A) and (B), which is multiplied by 10 to clarify the difference.

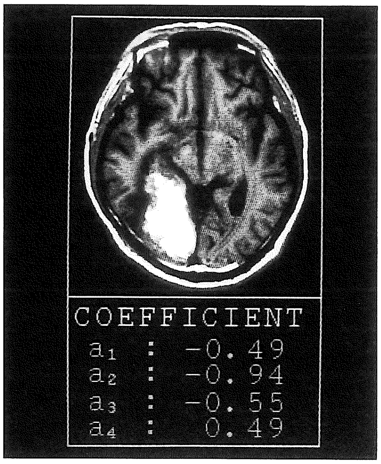

Fig.6. This is the result of an image enhancement by a linear combination of the four eigen value images and the mean image, where the coefficient for the second eigen value image is twice as much as one in case of the image (B) in Fig.5. The hemorrhaged region is clearly discriminated from the normal regions.

Detecting the abnormality in the CSF flow from a series of cinematic spinal CSF flow images was tried as the second example of the application of the eigen value expansion technique. In this case, seven ECG gated gradient refocused echo (GRASS) images of a patient with a cervical disk herniation were used for examinations. They were obtained with TR/TE/flip angle=50 ms/20ms/30degrees within the R-R interval.

Original seven images and the averaged image were shown in Fig.7, where images were arranged from 1 to 7 according to the cardiac cycle and the image 1 was the one at the end of ventricular systole and the image 4 was at the end of ventricular diastole. It is very difficult to find the differences among the original images at first sight. For the enhancement of the differences, the bases for these seven image vectors were calculated according to the eigen value expansion formula. These bases and the averaged image were shown in Fig.8, where the image A was the first eigen value image, B the second one, C the third one, and so on. The ratio of contribution for each eigen value image to the sum image of them was 23.1%, 20.9%, 17.0%, 13.8%, 13.1%, 11.9%, and 0.2%, restectively. As same as the above section, any image can be represented by a weighted sum of the averaged image and all of the basis images in Fig.8. To enhance the disturbance of CSF flow, each of images in Fig.7 was represented by a weighted sum of the averaged image and all of the bases. The components used of an image with respect to the

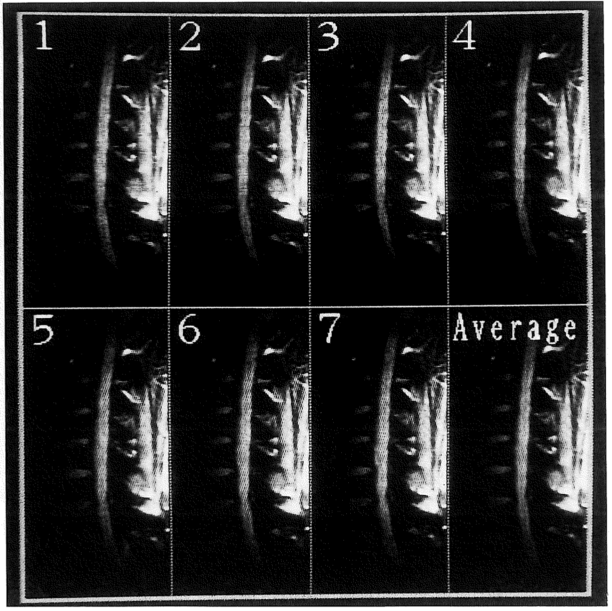

Fig.7. Seven ECG gated CSF flow images with a GRASS sequence which were used for detecting disturbance of the flow caused by a cervical disk herniation. The TR/TE/flip angle were 50ms/20ms/30 degrees within the R-R interval. The eighth image is the mean image calculated from these seven images.

bases were same as ones, which were obtained when original images were decomposed into the averaged image and the bases, but the component with respect to the second basis was multiplied by 10. Results images, where the disturbance of CSF flow were enhanced, were shown in Fig.9. The stagnation of CSF caused by the disk herniation can be found in Fig.9. Judging from this result, it becomes easy to find the abnormality of CSF flow compared with in Fig.7.

DISCUSSION

The signal intensity of a MR image depends on the proton density, T_1 and T_2. In the field of the conventional feature extraction processing of MR images, therefore, the proton density, T_1 and T_2 were calculated from some MR images and then any images, which were not taken but had appropriate features, were estimated with using their parameters. But this kind of feature extraction technique has some limitations. They are that it is difficult to find out the scan parameters for the best contrast between the region of interest and the other regions, it is impossible to enhance the region of interest at discretion, and so on.

There are also some difficulties in objectivity and reproducibility when the matched filter method is used to extract features, because its ability to extract features depends on the quality of data sampled for a

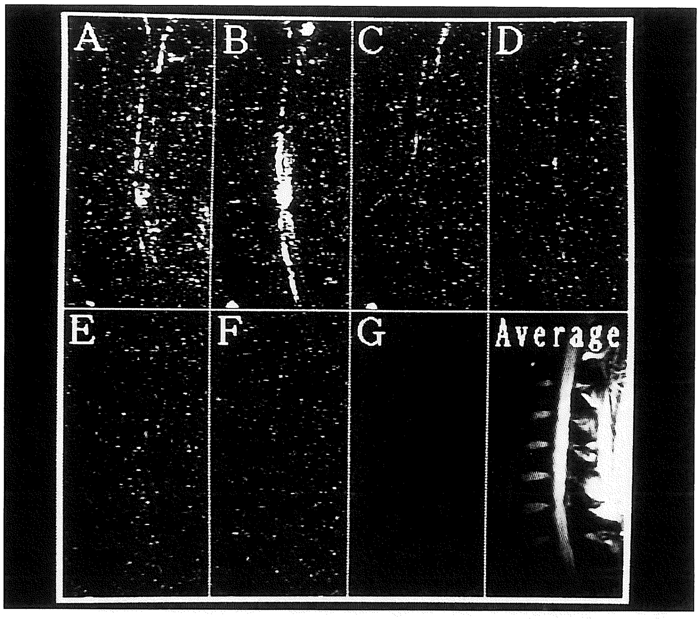

Fig.8. Seven eigen value images calculated from the seven images in Fig.7. (A) is the first eigen value image, (B) the second eigen value image, (C) the third one, and so on. The eighth averaged image is identical with the averaged image in Fig.7. The ratio of contribution for each eigen value image to the sum image of these seven eigen value images is 23.1%, 20.9%, 17.0%, 13.8%, 13.1%, 11.9%, and 0.2%, respectively.

template and there are no rules to sample data for a template from the region of interest in a image. Furthermore, the feature extaction technique with the matched filter method becomes ill-posed because all of data sampled for a template are similar in the signal intensity and the algebraic linear independence among them is very low. It is necessary for the matched filter method to introduce the new process to settle the illness of the condition in addition ot extracting features. To utilize the matched filter method in extracting features is, therefore, troublesome and not suitable for the daily routine.

On the other hand, the eigen value expansion technique, that is an orthonormal transformation method which decomposes a set of images into some linearly independent images, has some merits described as follows.

1. There are no restrictions on scan parameters of the MR images which are utilized for the feature extraction.
2. The eigen value expansion technique is already established theoretically and would produce the consistent basis images if the MR images are fixed.
3. The basis images obtained are statistically uncorrelated each other and it is possible to produce any images by a weighted sum of these bases. The properties of the image, which is produced by this way, depend upon the purpose for which the image is intended and the weight coefficients for the basis images are determined for this purpose.

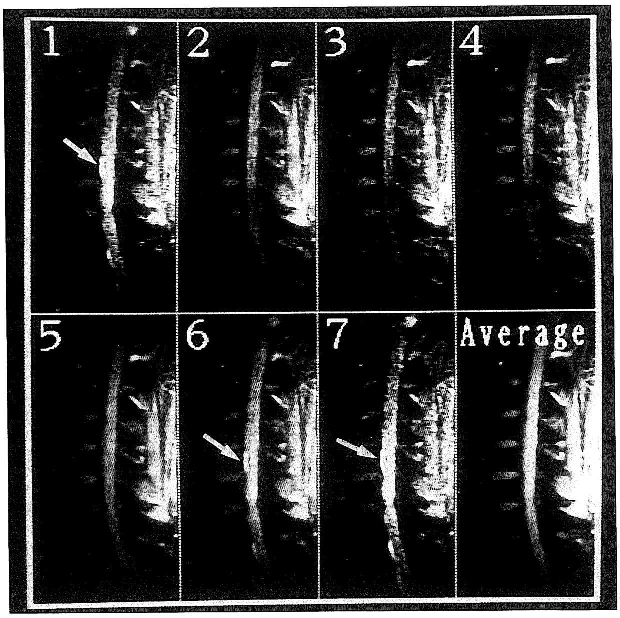

Fig.9. This is the result of an image enhancement to detect the disturbance of the CSF flow by a linear combination of the seven eigen value images and the mean image. It is easy to understand the stagnation of CSF (indicated by the arrow in the figure) caused by the disk herniation.

So, it is easy to have the image with any properties.

4. The standout of an eigen value expansion tehhnique is that if there is a region which is different from other images in signal intensity, it is possible to discriminate the region as a feature by using a eigen value expansion technique even though the difference of the signal intensity is a little. Conventional feature extraction or image enhancement methods do not have this kind of ability.

5. All of the procedures to extract features of MR images with a eigen value expansion technique are described in the form of a matrix and the size of the covariance matrix K, which is the most important matrix in the procedures, is equivalent to the number of images utilized and small, while the size of a image vector is very large. Consequently, the procedure is not time-consuming, not memory-consuming in a computer and easy to be implemented in a micro computer.

CONCLUSION

MR imaging has become an important technique in the diagnosis and assessment of various lesions. How well various lesions can be visualized upon the quality and the contrast of images.

In this article, we proposed the new feature extraction and contrast enhancement technique by using the eigen value expansion method with some MR images, which were obtained with various imaging parameters at the same anatomical site. Images of a hemorrhaged brain with a spin echo sequence and of a CSF flow with a GRASS sequence were selected for evaluating the ability of the feature extraction or contrast enhancement.

Results showed that proposed application of the eigen value expansion method to the feature extraction and the contrast enhancement of MR images was good enough to clinical use and superior to other feature extraction methods such as producing a calculated MR image with TR and TE or the matched-filter method in processing speed, the ability of the feature extraction and reproducibility of results.

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