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DATA COMPRESSION IN DIGITAL ANGIOGRAPHY USING THE FOURIER TRANSFORM

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Abstract

While digital techniques in radiology develop rapidly, problems arise with archival and communication of image data. This paper reports on experiments on data reduction of digital image sequences of the heart and the brain. The time-intensity curves at every picture element are subjected to the Fourier transform and reconstructed from a number of coefficients smaller than the original number of images. The reconstruction error is assessed by visual inspection and by determining the mean square deviation of the original and the reconstructed curve. It is shown that compression factors between 5 and 10 may be achieved without loss of diagnostic information. It is furthermore demonstrated that storage of the images in the form of Fourier coefficients leads to advantages in fast retrieval, enhancement of morphology and quantitative analysis.

1. Introduction

Digital image processing techniques are becoming increasingly important in radiology, especially in the field of angiography. Three fields of application are of particular interest:

- visualizing vessel structures after intravenous injection ("Digital subtraction angiography")[1-3]

- quantifying the function of organs (e.g. functional imaging)[4-7] and

- communicating and archiving radiographic data[8].

Even using modern storage and communication technology the tremendous rates and amounts of data raise problems concerning

- storage and archiving capacity

- speed of retrieval

- speed of transmission

It is therefore worthwhile to develop methods of data reduction. Research in TV-coding has explored two basic approaches known as predictive coding and transform coding[9]. Compression is achieved in predictive coding by transmitting only differences from a value predicted from the proceeding picture elements. In transform coding the data are transformed from the time domain into a new coordinate system, such as the frequency domain, in which they may be described in a more dense form. Transform coding is suitable in cases where there is an ´a priori´ knowledge about the image content, as is true for angiographic imagery.

We report here on experiments with Fourier transform coding for intravenous ventriculograms and brain angiograms which will show that not only an appreciable data reduction may be achieved, but the compression algorithms may even enhance the display of organ morphology and function.

2. Material

Ventriculograms

After central venous injection of 25 ml of 76 % contrast medium a fluoroscopic sequence was taken at 10 μR per video frame using a Siemens high resolution image intensifier video unit. The video image sequence was stored on video tape. Subsequently a quarter of the full screen containing the left ventricle was digitized with a gray scale resolution of 256 and a spatial resolution of 128 x 128 pixels at a rate of 50 images/s. Up to 484 images where taken. Ventriculograms of the same patient before and after pacing were used for the investigations. This enabled us to see whether paradoxical motion (in case of pacing) influences the compression efficiency.

Brain angiogram

Here fluoroscopy was done after selective arterial injection of 25 ml of 60 % contrast medium at 1 μR/frame with a ten year old image intensifier unit. The image sequence was stored on video tape. 90 images were digitized with a resolution of 256 x 256 taking every 6th video frame (about 8 frames/s).

Digitisation was done in real time with the system CA-1 (Computer-Angiography One) [10,11], which incorporates an 8 Mbyte random access image sequence store. For the angiogram of the brain the computations have also been done with this system. In the case of the ventriculograms, the computations have been performed on our VAX/11-780 image processing computer which is linked to the CA-1 System in the Department of Radiology.

3. Method

Coding of an image sequence can be performed in the spatial domain and/or the time domain. Since we know, that the temporal structures in angiography are simpler and more regular than the spatial ones, the method is based on analysis of the time behaviour of the intensity at every picture element of the angiographic image. When looking through an angiographic image sequence in the time direction at every picture element of a ventriculogram we obtain typical intensity time curves (ITC) as shown in fig. 1b. Their structure is produced by the periodical movement of the contrast filled ventricle over the picture element. The rate of intensity change depends on the spatial gradient and the velocity of the moving object. Both of them have a characteristic behaviour. The situation is similar in the case of a moving bolus of contrast medium in vessels, e.g. in a brain angiogram.

The idea of using the 'a priori' knowledge about the ITC has already been applied by the authors for the computation of functional images [12]. It has also been applied for temporal filtering in digital angiography [13,14]. In this paper we use it to extract the relevant temporal structures for data reduction. One method for this is the approximation of the original curve by a sum of basis functions. Considering the sinusoidal form of the curves in fig. 1b makes it obvious that the Fourier transform should be very well suited. The discrete Fourier transform approximates the original curve F(t) as a sum of sine and cosine functions with corresponding coefficients a_i and b_i, where $\omega = 2\pi/T$ and T is the basic period length. i is the harmonic number.

$$F(t) \approx F_R(t) = \frac{a_0}{2} + \sum_{i=1}^{n} a_i \cos i\omega t + \sum_{i=1}^{n} b_i \sin i\omega t \quad (1)$$

This equation may also be written in terms of an amplitude A_i and a phase φ_i:

$$F(t) = \frac{a_0}{2} + \sum_{i=1}^{n} A_i \sin(i\omega t + \varphi_i), \quad (2)$$

where $A_i = \sqrt{a_i^2 + b_i^2}$, $\quad tg\,\varphi_i = \frac{a_i}{b_i}$

Since the A_i and φ_i are better suited for interpretation they are mostly used in this paper. By accessing the histogram of the amplitudes A_i, one can estimate the number of harmonics which can be expected to contribute significantly to F(t). With a chosen number n_R the function is reconstructed from the amplitudes and phases. The reconstructed sequence is then compared to the original

- by visual inspection of the sequence and/or the sequence of differences,

- by assessment of the mean square deviation of the reconstructed sequence from the original. It is defined as

$$S^2 = \frac{\sum_{t=1}^{N} (F(t) - F_R(t))^2}{N - 1}, \qquad (3)$$

where t is the discrete time, F(t) is the original ITC and N is the number of images in the sequence.

When only morphological information is to be drawn from the images, the reconstruction is judged to be optimum, when no significant deterioration can be perceived by the radiologist. For quantitative analysis the mean square deviation in relevant regions of the organ is taken as a measure of the reconstruction error. The ratio of the number of original images and the coefficient images needed for an appropriate reconstruction is defined as the compression factor.

4. Compression of periodic scenes (left ventricle of heart)

As shown in fig. 1b, the ITC of a left ventricular angiogram has a low frequency component caused by the contrast medium flow and components related to the periodic motion. In the frequency spectrum (see fig. 1c) this fact is represented by a peak at low frequencies and several repeating peaks at the heart frequency and higher harmonics. Fig. 2 shows for illustration the images of the Fourier coefficients a_0 to a_{11}. We are now interested in three types of processing.

- Compression and reconstruction of a single heart cycle (if image quality is acceptable and only the wall motion is to be inspected).

- Compression and reconstruction of a sequence of cycles (if blood flow is to be considered and/or the signal to noise ratio is to be improved).

- Compression of a sequence of cycles and reconstruction of one representative cycle for further data reduction.

Single cycle

We first inspect the frequency spectrum, as shown for a single cycle (T = 46 images) in fig. 3. We recognize a high peak at the heart frequency and a sharp decay of subsequent harmonics. It is obvious that not more than four harmonics contribute. In fig. 4 one image of the original sequence is shown with its reconstructions from 1, 3 and 5 harmonics. We recognize that the reconstructed images are less noisy and that there is almost no visible difference between the reconstructions with 3 and 5 harmonics. This is also supported by the mean square deviation images (fig. 5), where from the 5th harmonic on only artefacts of the ribs and the diaphragma are visible. It is also seen that on the apex, which showed a severe dissynchronization, no essential reconstruction error occurs.

The quality of reconstruction can also be assessed from the comparison of the original and reconstructed ITC (fig. 6). The overall dependence of reconstruction error on the number of harmonics is shown in fig. 7. We can state that a reconstruction with four harmonics preserves all relevant information and that artefacts of motion not due to the heart can be suppressed to some extent. In the case shown the resulting compression factor is 5.

Sequence of cycles

The method is the same in principle when a sequence of cycles is considered e.g. for the investigation of blood flow through the heart. From the amplitude spectrum of a sequence of 10 cycles

(T = 484 images) shown in fig. 1c we discern that the main contribution comes from the amplitude A_1 representing the motion of the contrast-medium and the heart frequency with its subsequent harmonics. Obviously not more than fourty frequencies contribute significantly to the result. This indicates that a compression by a factor of five is possible in this case, too. This can again be verified by the comparison of the reconstructed sequence with the original one. The results look very similar to those shown in fig. 4.

But since the frequency information is derived from several cycles a further reduction of noise can be recognized.

Representative cycle

A representative cycle is automatically reconstructed when only the harmonics of the heart frequency (e.g. the peak frequencies A_{10}, A_{20} ... in the histogram in fig. 1b) are taken and considered as A_1, A_2 ... . This technique lends itself to the integration of several cycles in intravenous angiography. Unfortunately it works well only when the heart motion is very reproducible. This is obviously not the case in our example, although the beat period length is stable. On the one hand the statistical noise is suppressed significantly, but the image sequence is blurred.

5. Compression of scenes containing only contrast medium motion (brain angiogram)

In static scenes the situation is simpler, since only one type of motion has to be considered. A frequency spectrum for an intraarterial brain angiogram (90 images) looks as shown in fig. 8. In the region of the artery the number of contributing frequencies is maximum since the bolus curve is fairly rectangular. In regions where smaller vessels and parenchyma are overlaid the number of frequencies drops down. In the region of the veins almost only the basic frequency remains.

Fig. 9 shows one original frame compared to reconstructed frames with two to four harmonics. Visual inspection shows that from the 3rd harmonic on vessels are visible at least as well as in the original. With higher harmonics the optical impression becomes even better.

The reconstruction error for the four reconstructions is visualized in fig. 10. It can be seen that the errors are concentrated on the region of the artery. It should be pointed out that these differences are on the order of one gray value. Inspection of the difference sequence shows that the artefacts are caused by oscillations of the reconstructed curves at times apart from the real appearance of the bolus. Therefore if one considers 4 harmonics a compression factor of 10 can be achieved without significant loss of information. It should be noted that for intravenous angiograms the results should be at least as good, because the high frequencies due to the rectangular bolus are absent.

6. Special Properties concerning image retrieval and analysis

Certainly the Fourier transform is not the only method of data compression one can think of. But it does exhibit some remarkable properties conducive to application in image data bases and/or further processing, which we seek to illustrate in the following examples.

Fast retrieval of image sequences

Let us assume that we have a hardware system at hand which performs the additions necessary for the reconstruction of the sequence from the Fourier coefficients in real time. A low resolution film of the image sequence can be displayed as soon as the first three coefficient matrices (A_0, A_1, φ_1) have been transmitted from the database. Further refinement takes place as the image sequence is inspected. Such a feature is well adapted to the needs of the radiologist, who first is given an overview and then can concentrate on special regions of interest, which become sharper and sharper in the course of time. Thus with fair transmission speeds the radiologist is not forced to wait. In case of ambiguities, the error image may be overlaid in order to verify whether an effect is due to morphology or is an artefact of the reconstruction.

Enhancement of morphological structures

Storage of the image sequence in the form of Fourier coefficients enables the user to apply any form of frequency filters on the ITCs just by applying weighting factors. As a simple but effective example of morphology enhancement we can just omit A_0 in the reconstruction, which results in the display of the background subtracted angiographic sequence.

Phase synchronos subtraction of two sequences, as required in intravenous ventriculography is simply accomplished by subtraction of the coefficients a_i, b_i. In fact each of the amplitude and phase images themselves are not merely abstract numbers, but can have a very practical meaning. The A_0 image is nothing else but the blurred background or 'mask' image (see fig. 11a) . In case of the brain the A_1 image is a good aproximation of a subtracted angiogram integrated over the observation time (see fig. 11b). In the case shown a minor perfusion of the occipital region is apparent, which is not visible in the original sequence.

Quantitative analysis

The advantages of the Fourier representation for quantitative analysis are next demonstrated with some examples.

It turns out that the φ_1 image is a good aproximation of the displacement of the contrast medium bolus in time. In the case of the brain the φ_1 image (see fig. 11c,11d) is very close to a functional image of the type "arrival time" (see also ref. 7). From this simple image cerebrovascular transit times may be read easily at any location.

The a_1 image clearly delineates the locations in which we have seen contrast medium. In the case of the heart (see fig. 2) the enddiastolic area, which might be used for ejection fraction calculations, is clearly defined. A major problem in calculating the ejection fraction arises in determining the location of the mitral valve. As shown in fig. 12 the φ_1 image is of great use because it directly displays the phase jump between atrium and ventricle.

7. Implementation aspects

The Fourier transform for a sequence of 128 images with a resolution of 128 x 128 pixels takes 12 minutes on a VAX-11/780 computer. If we consider that most imaging facilities have less powerfull computers and that in practice larger matrices are required, application at first glance seems impossible. There are, however, two arguments against this:

- the compression time is not relevent because transmission into the archive is not time critical, in general nobody waits for it;

- in the near future imaging modalities will be equipped more and more with special processors, which could perform this task quite rapidly.

Truly time critical is image reconstruction, which fortunately happens to be the easier task. A special processor, which performs the necessary summations in real time, is not too hard to implement. It should be pointed out that the coefficient matrices can even undergo further compression steps ranging from zero suppression to sophisticated prediction algorithms.

8. Conclusions

We have shown that the application of the Fourier transform can compress angiographic image sequences in a straight forward way by factors of 5 to 10. Thus these algorithms can be used for reduction of storage capacity and for speeding up image transmission in medical data bases. Furthermore coefficients display some striking advantages concerning image enhancement and quantitative analysis. Certainly special hardware is required to implement the algorithms. The expenses, however, are more than compensated by the resulting savings in storage and transmission capacity.

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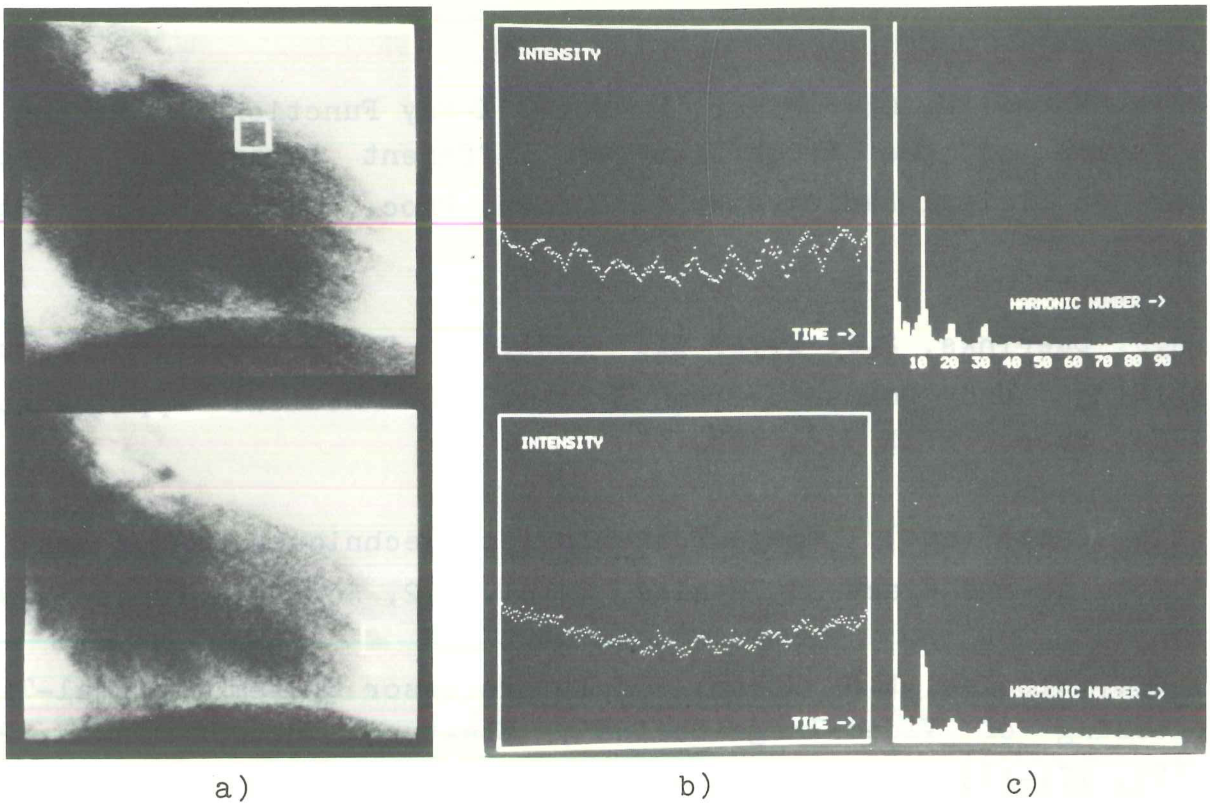

Fig. 1. Intravenous ventriculogram
a) Two frames with regions of interest
b) Corresponding intensity vs. time curves
c) Corresponding histograms of the amplitudes A_i

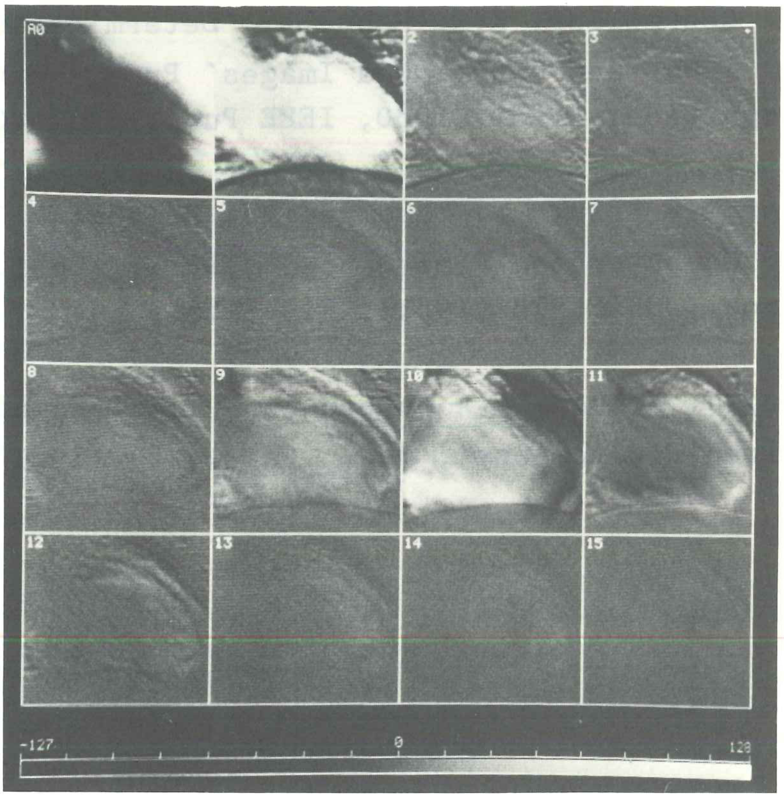

Fig. 2. Images of the coefficients a_i for the heart in fig. 1

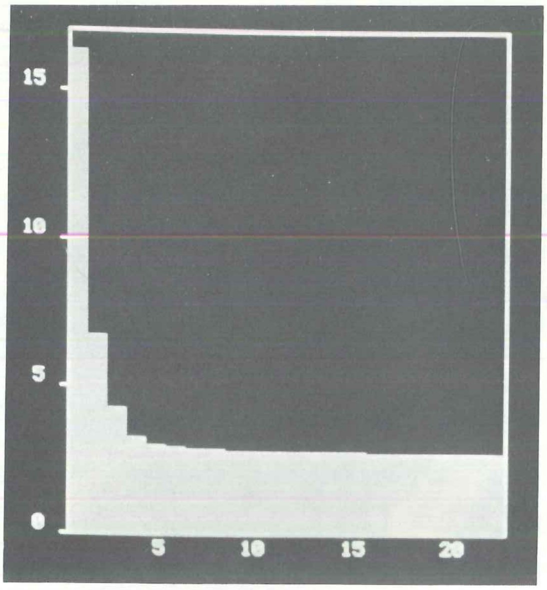

Fig. 3. Histogram of the amplitudes A_i for a single cycle

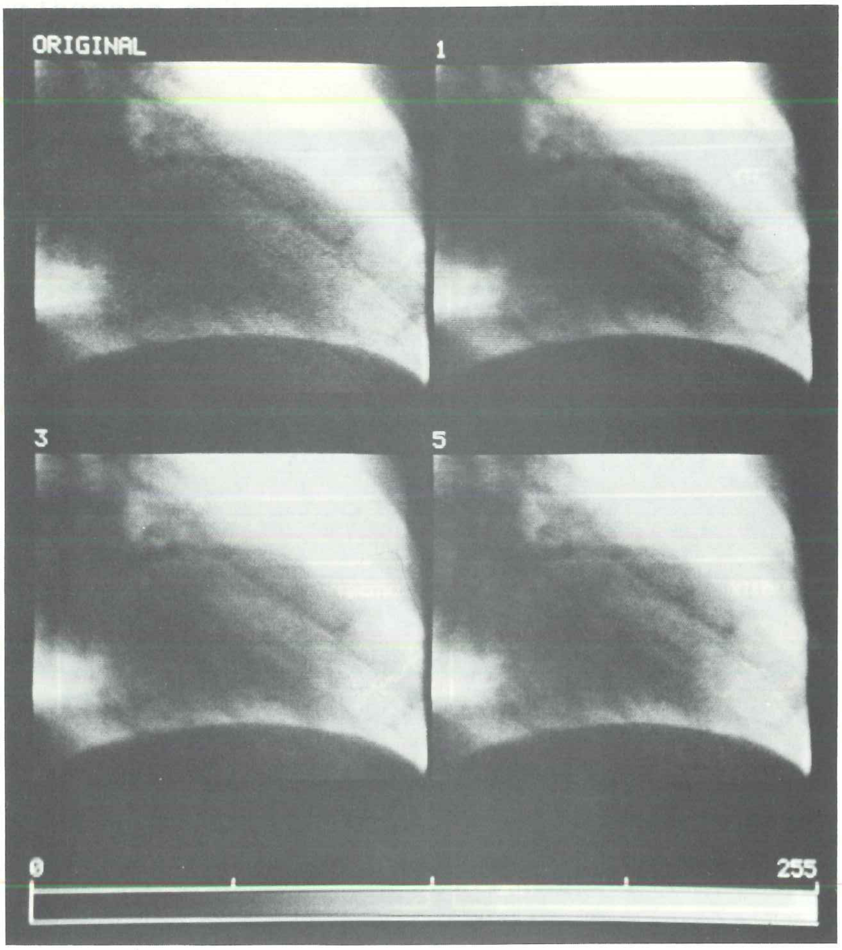

Fig. 4. Original frame of a ventriculogram together with the frames reconstructed with 1, 3 and 5 harmonics

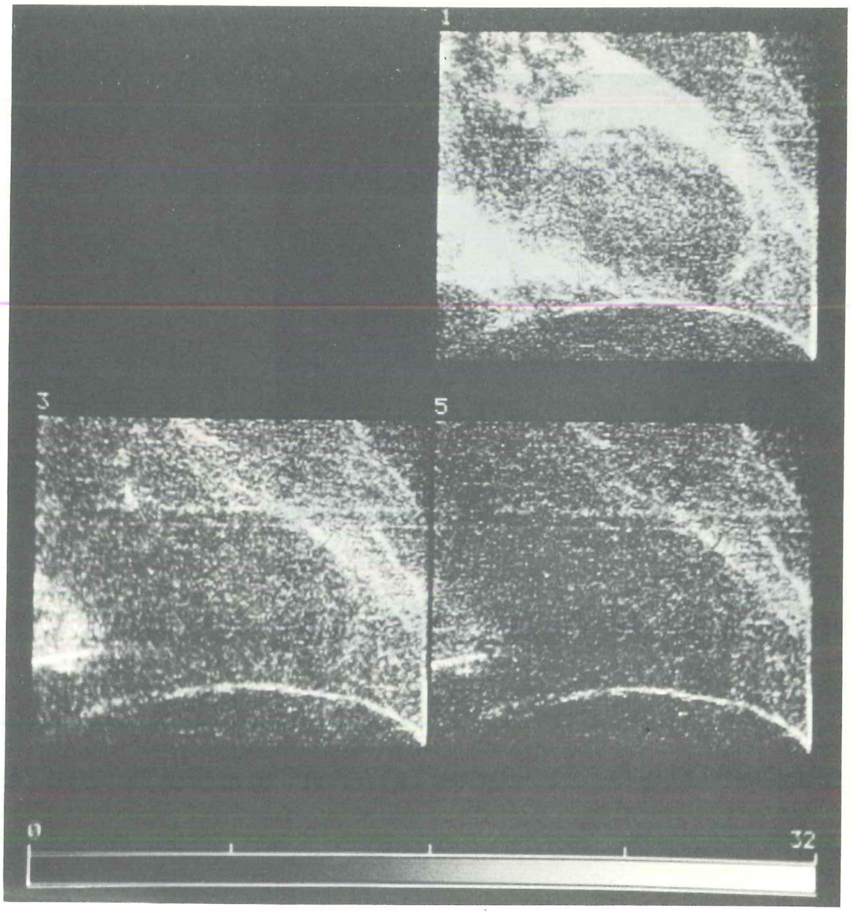

Fig. 5. Reconstruction error (S^2) images for reconstruction with 1, 3 and 5 harmonics

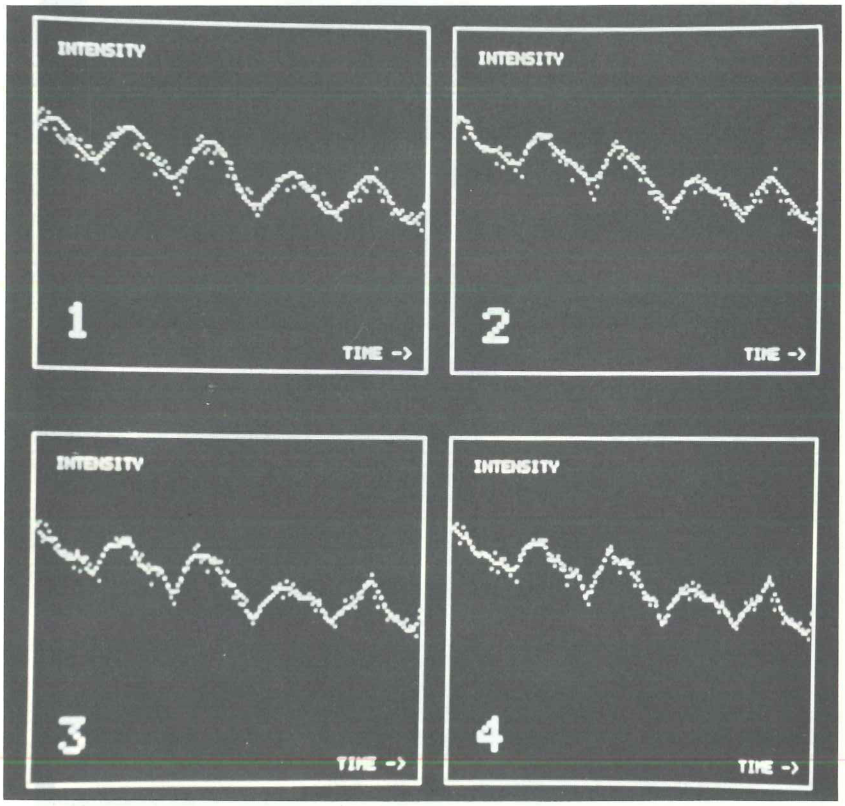

Fig. 6. Intensity vs. time curves of a ventriculogram (484 images) reconstructed with 10, 20, 30, and 50 coefficient pairs together with the original curve (dotted line)

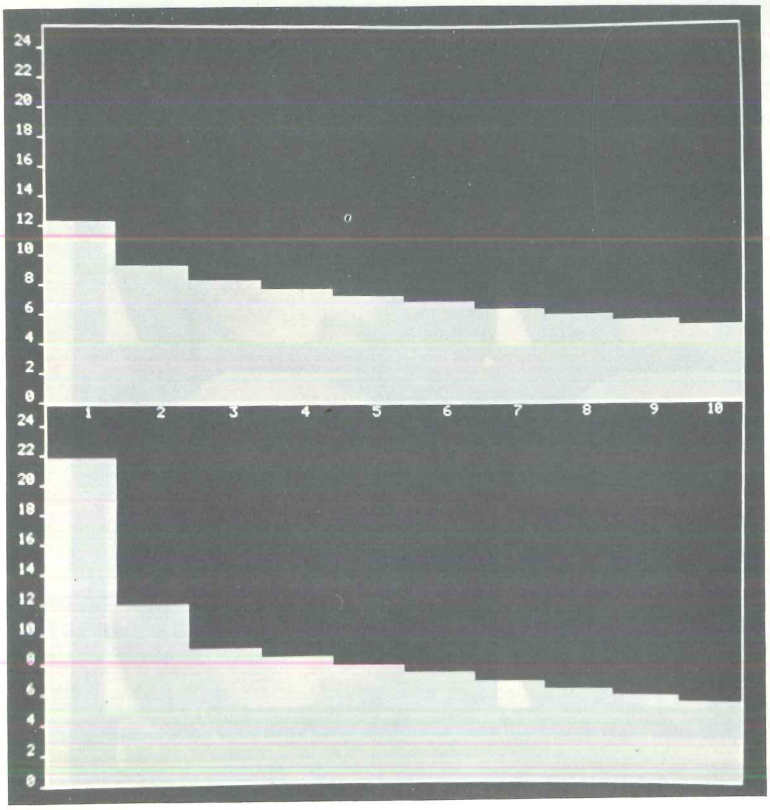

Fig. 7. Reconstruction error S² as a function of the number of harmonics used for reconstruction: for the whole image (upper half) and the heart wall (lower half)

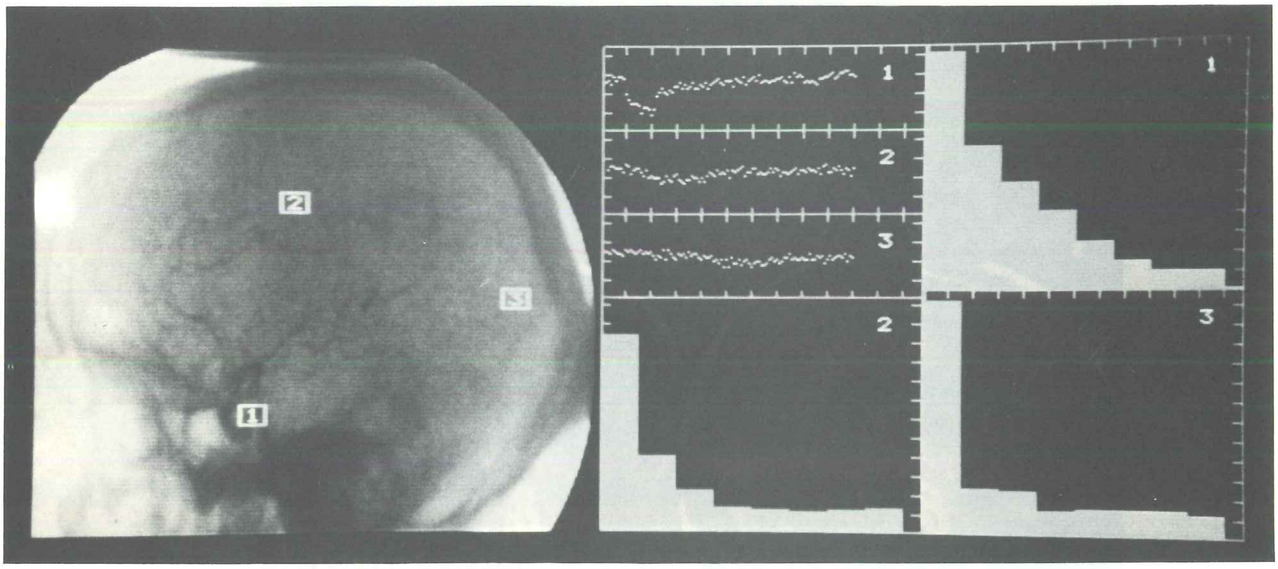

Fig. 8. Intensity vs. time curves and amplitude (A_i) histograms for several regions of a brain angiogram

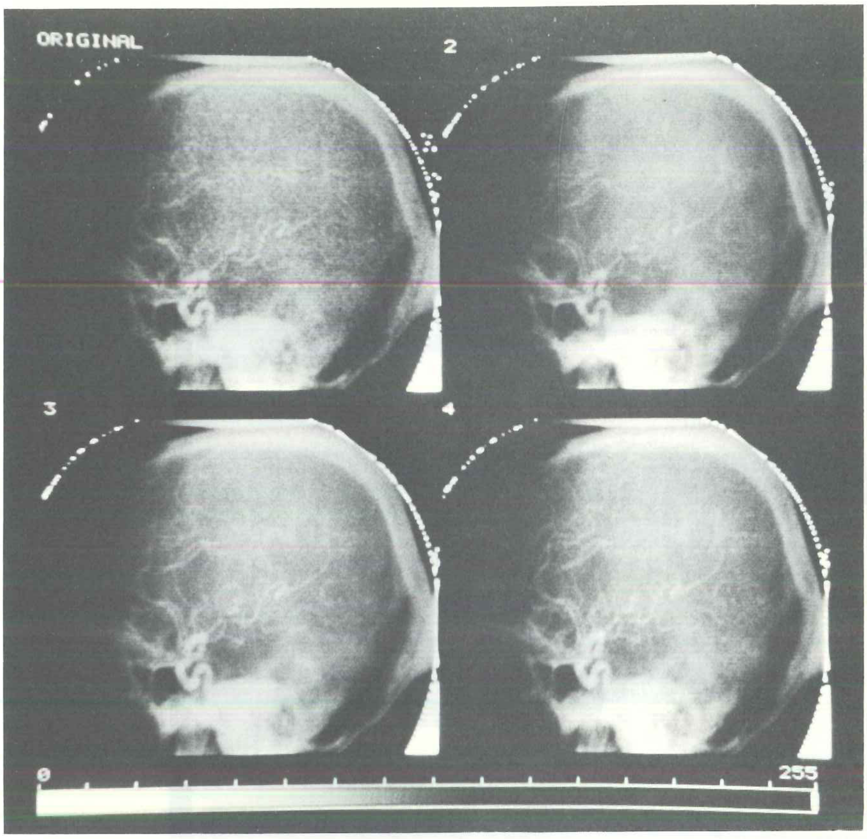

Fig. 9. Original frame of an angiographic sequence of a brain together with the same frame reconstructed with 2, 3, and 4 harmonics

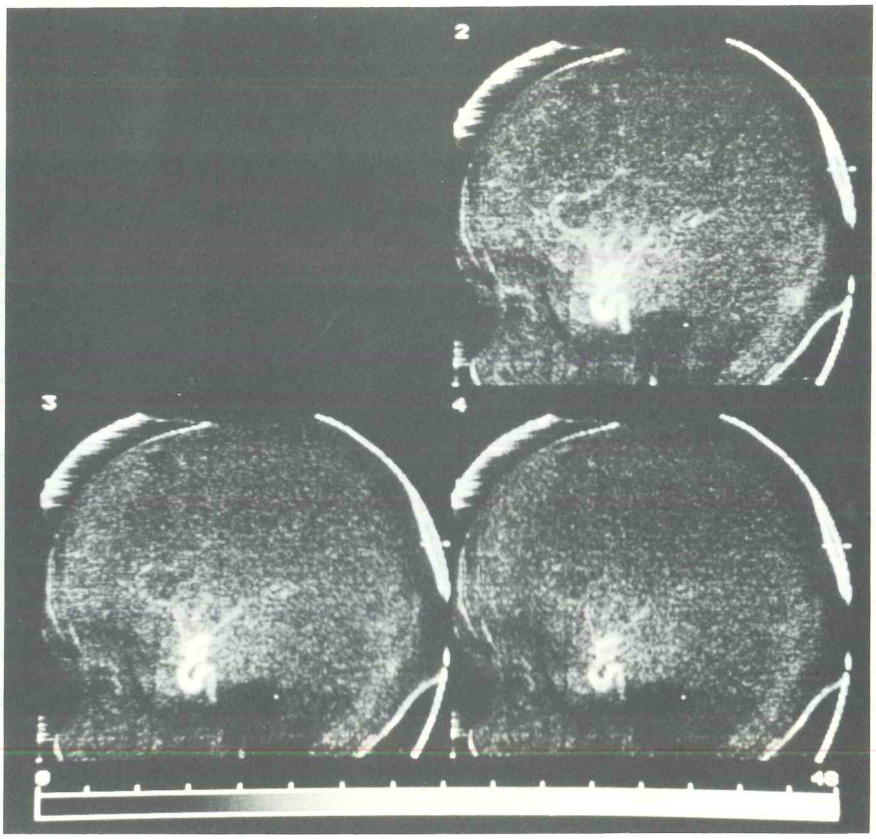

Fig. 10. Reconstruction error (S^2) images for reconstruction with 2, 3 and 4 harmonics

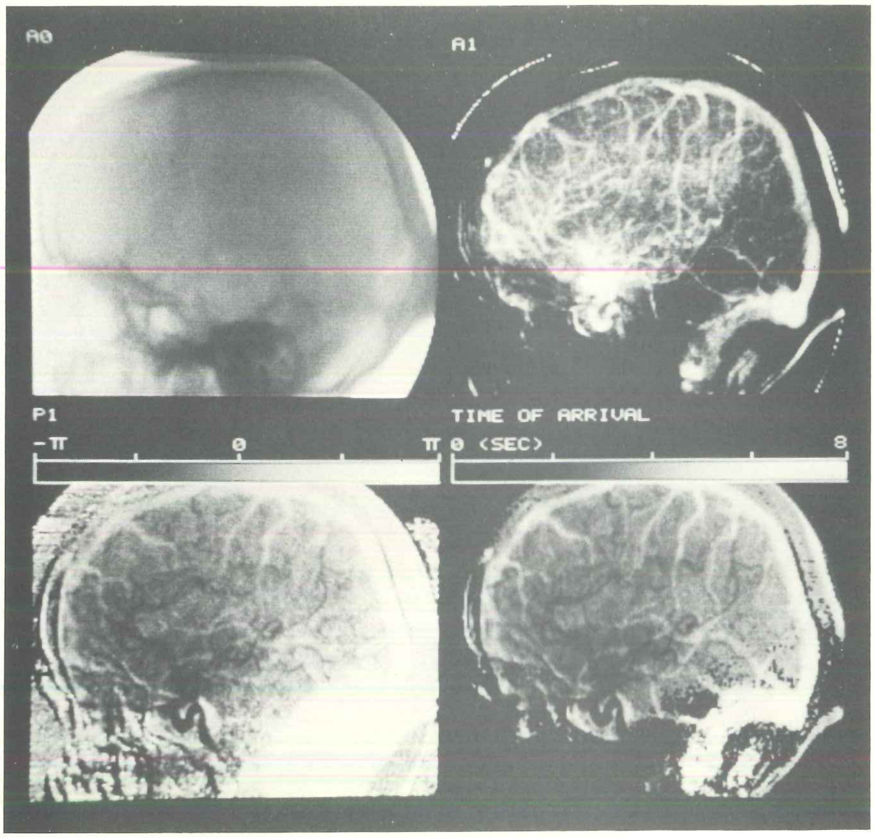

Fig. 11. Illustration of the meaning of Fourier coefficient images

a) A_0-image (= ´mask´-image)

b) A_1-image (= integrated subtraction-image)

c) φ_1-image (= ´arrival time´-image)

d) Arrival time image, shown for comparison

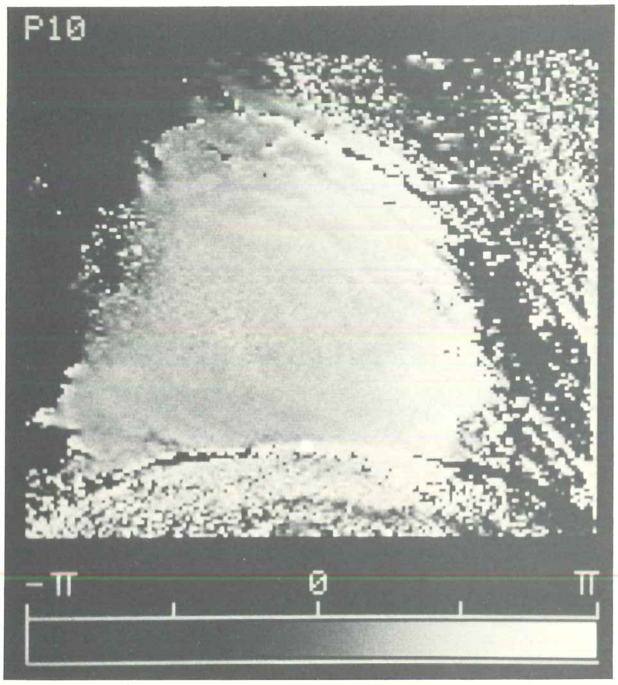

Fig. 12. φ_1-image of an intravenous ventriculogram