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Factor Analysis in Gated Cardiac Studies

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Factor analysis of dynamic structures (FADS) can automatically provide "physiological" factors related to anatomical structures that have different temporal behavior, even if these structures overlap; it also yields images corresponding to the factors' spatial distributions. In normal patients, two significant cardiac factors, corresponding to the atria and the ventricles, may be extracted. A third significant factor can be obtained when additional dynamic structures exist. However, the method does not provide an estimate of the background. It becomes part of the factors, but it does not modify their shapes. FADS has been applied to 45 gated cardiac studies. Results obtained by FADS were compared with those obtained from the amplitude and the phase of first-harmonic Fourier analysis (FA). The joint results were compared with the final diagnosis, established by real-time echocardiography and/or ventriculography. In normal patients, good agreement was obtained between the two approaches. On the whole set of patients, FADS was significantly better than FA (by sign test: $p < 5\%$).

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A gated cardiac study is basically noninvasive. It is reliable in detecting abnormalities of contraction and conduction. To provide an easy interpretation of dynamic series, numerous image processing methods have been proposed. Most of these use parametric images (*1*) such as ejection fraction or stroke volume images (*2,3*). Fourier "functional" images are now often used (*4–6*), though their lack of specificity has been pointed out by several authors (*7–9*). When the first harmonic of the Fourier transform is used, it is assumed that the left-ventricular time-activity curve (LV TAC) can be fitted well by a cosine function. The phase indicates only the shift between the LV TAC and the cosine function. We must stress that the cosine function is only a rough approximation of the real LV TAC, and its unfaithfulness is more critical in some pathological cases. Also, the shape of the elementary TAC will no longer be maintained in overlapping regions, such as parts of the atria and the ventricles. In fact, the images to be analyzed are two-dimensional projections of three-dimensional count distributions.

It is assumed that any TAC is a weighted sum of a limited number of pure time-activity evolutions, called physiological components, which correspond to regions of similar temporal behavior in 3-D space. Our method, factor analysis of dynamic structures (FADS), permits the recovery of the physiological components through model formation from the superimposition pattern. It does not need any a priori hypothesis concerning the shape of these physiological components. The aim of the analysis, as described previously (*10–13*), is to obtain an estimate, under positivity constraints, of the physiological components and to reconstruct true functional images (factor images). The analysis was used for each individual patient study.

This approach—first introduced in the field of spectrophotometry by Lawton and Sylvestre in 1971 (*14*)—, was used to determine the shapes of two overlapping functions $f_1(x)$ and $f_2(x)$ from an observed set of additive mixtures of the two functions.

In this paper's first section, the concepts of physio-

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logical components, factors, and factor images are introduced. In the second section, clinical results obtained with FADS and Fourier analysis are presented. The third section presents a general discussion of both methods and of clinical results in an attempt to validate FADS in cardiac studies at equilibrium, with abnormalities of both contraction and conduction.

MATERIAL AND METHODS

Patients and data acquisition. The study consisted of 45 gated cardiac blood-pool examinations. The assessment of wall-motion abnormality was based on real-time echocardiography (33/45 patients) and/or ventriculography and coronary arteriography (27/45 patients). Of the patients studied, four were normal, 11 had congestive cardiomyopathy, 29 had coronary artery disease (CAD), 26 with previous infarction and one with a pacemaker.

There were eight patients with left bundle branch block and two with right bundle branch block. All patients were in normal sinus rhythm at the time of the test.

Equilibrium gated blood-pool scintigrams were obtained after i.v. injection of 15–20 mCi (550–740 MBq) of red blood cells labeled in vivo with Tc-99m (*15*). The acquisition was performed with a gamma camera,* equipped with a LEAP collimator and interfaced with a dedicated computer system. A 1.2 zoom was used. Cardiac cycles were divided into sixteen 64 × 64 frames with 200k counts per frame. A modified LAO projection with 15° caudal tilt was used in all patients, and 30° RAO projections or anterior views in 36 of 45.

In addition we studied four normal patients with a large total number of counts (20 million) by courtesy of the Department of Nuclear Medicine of the University of Illinois, Chicago.

DATA PROCESSING

Conventional analysis. RAO and LAO scintigrams were processed using a package provided by the manufacturer of the minicomputer. This package included calculation of global left-ventricular ejection fraction, mapping of ejection fraction and stroke volume, and first-harmonic Fourier analysis, performed after temporal and spatial filtering (*2*).

The concept of physiological components. Consider sequence of p (n × n) digitized scintigraphic images, the content of a pixel (i,j) of the kth image being $x_{ij}(k)$. The vector

$$\vec{X}_{ij} = [x_{ij}(1),x_{ij}(2), \ldots, x_{ij}(p)] \quad (1)$$

represents the temporal evolution of the content of the pixel (i,j). This elementary time-activity curve is called a TAC (time-activity curve) or a "dixel" (for dynamic-study pixel) by Barber (*10*), or a "tixel" by Munkner (*16*). The generalized term "3-ixel" or "trixel", previously proposed (*17*), is used in this paper, since time is not always the third dimension (it can be the energy, for instance).

The information contained in the n^2 trixels is the same as that in the p (n × n) images. To each pixel of an image there corresponds an underlying activity, which is the resultant of the activities of a number (low in general) of anatomical and functional structures. To aid in understanding the concept of physiological components, a simplified model of normal gated cardiac blood-pool scintigraphy at equilibrium can be introduced and written as follows for the (i,j) pixel of the kth image

$$x_{ij}(k) = v_{ij}V(k) + a_{ij}A(k) + b_{ij}B(k) + N_{ij}(k), \quad (2)$$

where V(k), A(k), and B(k) represent the elementary activities corresponding to the ventricles, the atria, and the background activity in associated surrounding structures, corresponding to the overlapping regions, essentially the lungs and large vessels. The time-independent coefficients v_{ij}, a_{ij}, and b_{ij} represent the contributions of each functional structure in the pixel (i,j), and they will differ from one pixel to another. In a pure ventricular area, $a_{ij} = 0$, and in a pure atrial region, $v_{ij} = 0$. $N_{ij}(k)$ is the random noise.

It may be seen that, for each k, the elementary activities V(k), A(k), and B(k) are essentially nonnegative, and for each pixel (i,j) the weighting coefficients v_{ij}, a_{ij}, and b_{ij} are also nonnegative.

The time evolution of a trixel (i,j) is

$$\vec{X}_{ij} = v_{ij}\vec{V} + a_{ij}\vec{A} + b_{ij}\vec{B} + \vec{N}_{ij} \quad (i = 1,n; j = 1,n), \quad (3)$$

where

$$\vec{V} = [V(1),V(2), \ldots V(p)],$$
$$\vec{A} = [A(1),A(2) \ldots A(p)],$$
$$\vec{B} = [B(1),B(2), \ldots B(p)]. \quad (4)$$

and

$$\vec{N}_{ij} = [N_{ij}(1),N_{ij}(2), \ldots N_{ij}(p)]. \quad (5)$$

Equation (3) describes 4096 trixels or elementary activity curves, for a spatial sampling 64 × 64. In order to improve the statistics and to decrease the computing time, an 8 × 8 sampling, corresponding to 64 trixels, is used for the processing.

The vectors $\vec{V}$, $\vec{A}$, and $\vec{B}$ are defined as physiological components. Each n × n set of coefficients, v_{ij}, a_{ij}, and b_{ij}, can be considered as an n × n image in which the content of the pixel (i,j) is proportional to the value of its own coefficient. The associated images I_v, I_a, and I_b, where

$$I_v = \{v_{ij}\}; I_a = \{a_{ij}\}; I_b = \{b_{ij}\} \quad (6)$$

are called functional images. From Eqs. (3) and (6), at time k

$$I(k) = V(k)\cdot I_v + A(k)\cdot I_a + B(k)\cdot I_b + N(k), \quad (7)$$

where N(k) is the distribution of the random noise in the kth image.

Therefore, Eq. (3) shows the decomposition of the initial acquisition into physiological components (time-dependent information) weighted by their associated functional images (spatial information). Equation (7) shows the decomposition into images weighted by associated physiological components.

In the case of contraction or conduction abnormalities one or more pathological functions can be introduced. Let $\vec{P}$ be a pathological component and $I_p = \{p_{ij}\}$ the associated pathological image. From Eqs. (3) and (7) a more general model can be written:

$$\vec{X}_{ij} = v_{ij}\vec{V} + a_{ij}\vec{A} + p_{ij}\vec{P} + b_{ij}\vec{B} + \vec{N}_{ij} \quad (8)$$

and

$$I(k) = V(k)\cdot I_v + A(k)\cdot I_a + P(k)\cdot I_p + B(k)\cdot I_b + N(k) \quad (9)$$

This model is a weighted sum of q + 1 functions, (being q physiological components plus the background function).

Each image I_v, I_a, I_p, I_b is essentially a functional image.

As a result of the heterogeneous spatial structure of the background, different methods of interpolative background subtraction have been proposed (*18*,*19*), but they still appear unsatisfactory.

At equilibrium, the concentration of Tc-99m RBC in the vessels is constant. In the background regions without cyclic motion, the activity remains constant during the cardiac cycle. The overall time-activity evolution in the regions having a cyclic motion must remain constant according to the hypothesis of equilibrium state. Therefore, the mean time-activity function, $\vec{F}_M$, defined below [Eq. (11)], is also constant and must be considered as a linear combination of the underlying physiological components. Thus the background activity $\vec{B}$, a constant like $\vec{F}_M$, is a linear combination of the q physiological components, and the model can therefore be reduced to rank q.

Principles of the factor analysis of dynamic structures (FADS). The first step carried out in FADS is the estimation, by means of principal component analysis (PCA), of the q most significant principal components, being the eigenvectors associated with the successive eigenvalues (monotonically decreasing) of the covariance matrix of the vectors $\vec{Y}_{ij}$, defined from Eq. (12), as follows

$$\vec{F}_{ij} = \frac{\vec{X}_{ij}}{\sum_{k=1}^{p} X_{ij}(k)} \quad \begin{matrix} j = 1,n;\ i = 1,n \\ k = 1,p \end{matrix} \quad (10)$$

$$\vec{F}_M = \frac{1}{N}\sum_{ij}\vec{F}_{ij} \quad (11)$$

$$\vec{Y}_{ij} = \vec{F}_{ij} - \vec{F}_M \quad (12)$$

All the trixels $\vec{Y}_{ij}$ are considered equally important. The main advantage from the standardization of the original data, as introduced in Eq. (12), is to reduce the rank of the study space to q − 1 (*10*); the disadvantage is the risk of giving too much weight to trixels that do not contain significant information. In such a case, the operator will have to reject them carefully.

The purpose assigned to FADS is to determine the rank q of the underlying model and a base of oblique factors in the q-space (study space). Since the aim of FADS is to separate the signal (physiological components) from the noise (random fluctuations), FADS belongs to the class of Factor Analysis methods. PCA is used as a mathematical instrument to extract the whole of the significant information. Under reasonable assumptions, PCA separates "significant" information from noise N(k). At this step in the processing, an 8 × 8 spatial sampling is used. It does not fundamentally modify the model described in Eq. (3). The principal components, which are orthogonal, are not yet the physiological components $\vec{V}$, $\vec{A}$, and $\vec{P}$, some of their values being negative. The changing of the orthogonal components into factors that are estimates of the physiological components corresponds to an oblique transformation of the orthogonal basis functions (*10*,*11*).

The oblique solutions can be obtained by rotating the q principal components (*12*). Alternatively, by using the method proposed by Barber (*10*), the factors can be computed in a space having (q − 1) dimensions after scaling and centering. We used this second method, modified in order to take into account the limits of that positive domain within which physiological components can exist (*20*). The factor images are reconstructed in the same format (64 × 64) as the raw data, and therefore correspond to the projections of the unfiltered original data (4096 trixels) in the transformed space. The contribution for each factor to the total information is then determined.

In the absence of background, the oblique solutions (or factors) provided by FADS should be solutions close to the physiological components of Eqs. (8) and (9). The presence of background, which does not increase the rank of the model (i.e., the number of independent components as shown above), can introduce a bias in the determination of these physiological components. Here the decomposition is made into such (biased) estimates.

However, the contribution of background to the final factor image does not fundamentally modify the temporal information and thus the interpretation of the factors, as illustrated by our results.

The software, as described in a previous paper (*13*),

was implemented on a clinical nuclear medicine system. It required 128k bytes and a computation time of about 4 min.

Only the first 13 frames were used, in order to avoid the artifact introduced by falling counts in last three frames.

As some trixels located at the image periphery do not contain significant information, their inclusion can generate artifacts. So a threshold procedure had to be applied in order to keep only significant trixels.

Three- and two-factor analyses were systematically performed on each patient; they were not time-consuming, since only one PCA is then necessary.

The factor images, after pseudo-Wiener filtering, were represented either as normal scintigraphic images or using a trichromatic display, assigning one color (blue, green, or red) to each factor. This enabled the topography of each individual factor image to be scrutinized. The factors (which are time functions) are represented superimposed on their corresponding factor image (weights).

Statistical evaluation. For each patient, the agreement between FADS and Fourier analysis with respect to the final conclusions was evaluated. The results were classified into four categories: 0 = no agreement, 1 = low, 2 = good, 3 = total agreement, as shown in Table 1. The index of classification takes into account (a) the qualitative agreement between the abnormality and the shape of the factors (in FADS) and the pattern of phase delay (in Fourier analysis); and (b) the location of the abnormality. The ventricular area was divided into six regions: the entire right ventricle, and the left ventricle subdivided into septal, apical, inferior, lateral, and anterior regions.

For the final diagnoses, real-time echocardiography and ventriculography were not reinterpreted, and initial reports were used.

The results obtained by Fourier analysis and FADS were first interpreted by two independent observers (FC,JPB) without knowledge of the clinical history, and a common score was established for each patient. The two views were evaluated separately.

To assess the degree of agreement between FADS and Fourier analysis, the statistical test we used is a bilateral sign test on the difference between results for FADS and Fourier analysis in each case, throwing out those cases in which the two methods gave the same score.

RESULTS

Clinical results. *Normal patients.* (Fig. 1). In the four normal patients, only two significant factors were extracted by FADS. The physiological meaning of the factors was given by their shape and their associated factor images. Thus it was possible to identify a ventricular factor, being maximal at end-diastole and minimal at end-systole. In LAO view, the factor image appeared to be very close to the stroke-volume image. The mean contribution of this factor to the total information was (30.0 ± 1.5)%. The second or atrial factor seemed to correspond to the atria plus surrounding structures. Its shape was in opposition to the ventricular factor, with a mean contribution to the total information of (70.0 ± 1.5)%. In the RAO and anterior views, both ventricles and atria were well identified even in regions of projectional overlap. In these normal patients, when FADS was performed with three factors, the third factor had a very low contribution and no anatomical or physiological significance.

In the series of high-count normal patients, the "atrial" factor could be resolved into two separate factors, the first corresponding to the atria and the second (with a very flat shape) to the large vessels (Fig. 2). However, the ventricular factor was not modified and the clinical diagnosis would be performed using either a two- or three-factor analysis.

Using the results of a FADS in a normal patient, the ventricular factor image was divided into two large regions, one for each ventricle. Using these regions, two independent FADS analyses were performed on the raw dynamic series. The two resulting ventricular factors were synchronous, as expected. This result confirms the stability of the analysis.

The stability of FADS was also tested by using a repeat examination of a patient in both LAO and anterior views. The factors found were very similar. The factor images correspond to projections of the same 3-dimensional distribution (Fig. 1).

Pathological cases. Akinetic segments always appeared to follow the "atrial" factor. When this factor could be decomposed into the two separate factors described above, the akinetic segment followed the vascular factor. In the eight patients with only akinesia, FADS provided two significant factors in four cases (Fig. 3), and three in four cases.

TABLE 1. SCHEME FOR RATING AGREEMENT BETWEEN FADS OR FOURIER ANALYSIS (TABLES 2-6) AND THE FINAL DIAGNOSIS

Agreement	Existence of disease	Type of disease	Location
Total (3)	+	+	+
Good (2)	+	+	±
Poor (1)	+	−	±
No (0)	−	−	−

Note: agreement (+), disagreement (−), no agreement about the number of pathological segments (±).

In severe congestive cardiomyopathy, the center of the left ventricle was occupied by the "atrial" factor, with the ventricular factor as a surrounding ring corresponding to the free wall and the septum (Fig. 4, upper left, p 1072).

In conduction abnormalities such as bundle branch block, in pacemaker rhythm, and in wall-motion abnormalities such as hypokinesia or dyskinesia, a third significant factor could always be extracted. Its pathological significance was given by its location on the factor image and the shape of the factor.

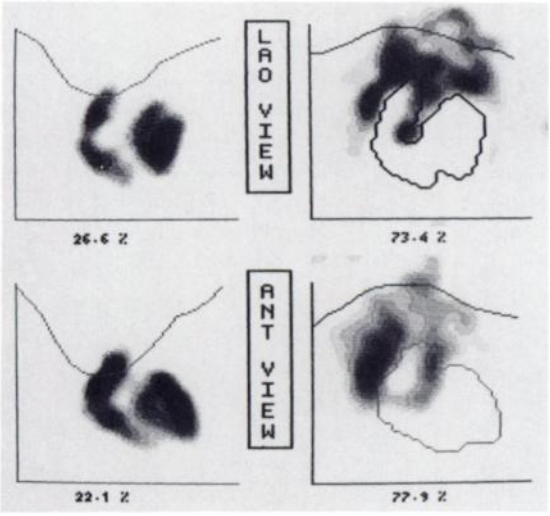


FIG. 1. FADS results from normal patient. Dynamic study is described by 2 factors. LAO view: upper left = ventricular factor, upper right = atrial factor. Anterior view: lower left = ventricular factor, lower right = atrial factor. Note stability of FADS between two views.

Conduction abnormalities. In patients with bundle branch block, the ventricles could be described by two factors, with a temporal shift of the same order of magnitude as that shown by the ECG (Fig. 4, upper left, lower left, p 1072).

The identification of two separate ventricular factors was also possible, in spite of partial overlap in the RAO view (Fig. 4, lower left, upper right, p 1073).

Pacemaker rhythm. In the one patient with a pacemaker, FADS also showed two ventricular factors, the first corresponding to the site of the pacemaker location, in advance of the second factor.

Wall-motion abnormalities. In patients with an aneurysm, dyskinetic segments were identified as a third factor that was maximal during systole and slightly in advance of the atria. The trichromatic representation allowed a good estimation of the size and the exact location of the dyskinesia (Fig. 5).

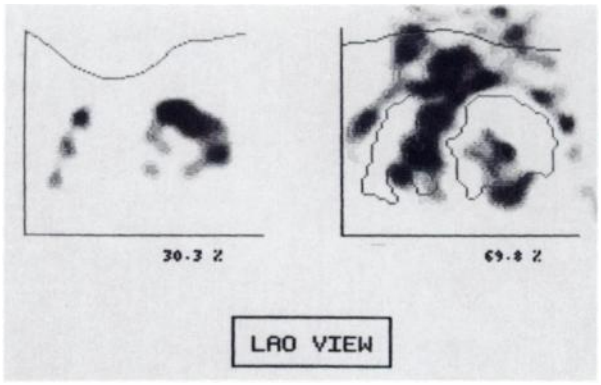


FIG. 3. Akinesia described by two factors, in LAO view. Left = ventricular factor, right = atrial factor.

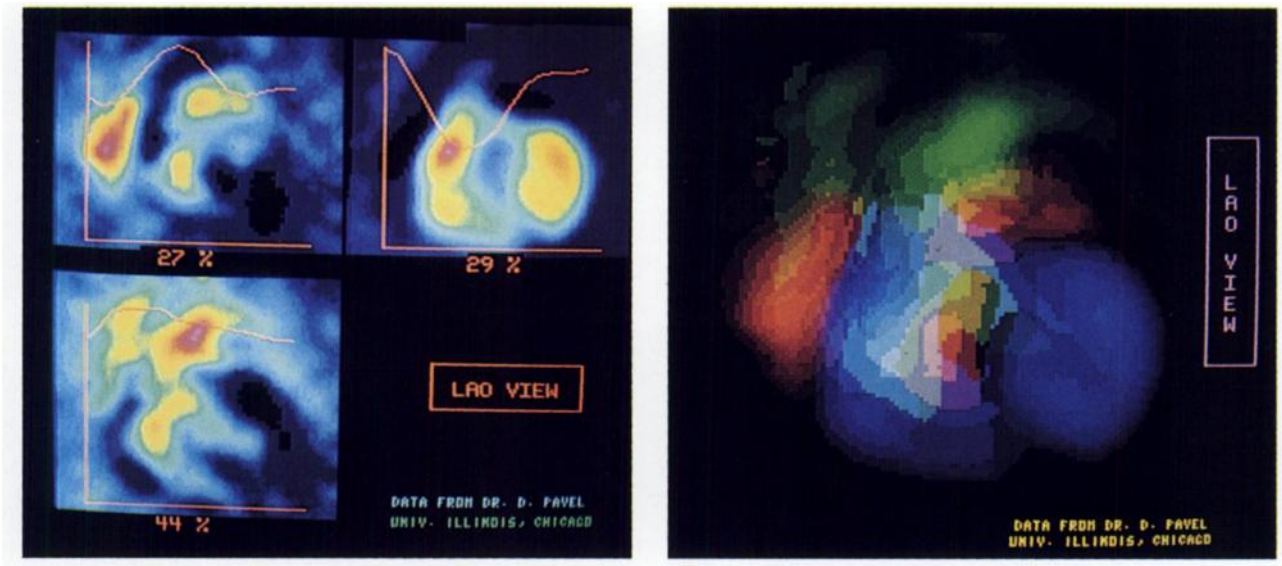


FIG. 2. Normal "high-count" patient in LAO view. Dynamic study is described by three factors in this example. Left: upper left = atrial factor, upper right = ventricular factor, lower left = vascular factor. Right: Superimposition of 3 factor images.

Hypokinetic segments had also a characteristic factor shape, with a plateau during the first third of systole and followed by normal ventricular factor shape. In these cases, additionally, the superimposition of the three-factor images allowed good evaluation of the size of the hypokinesia (Fig. 6).

VALIDATION OF FADS

In order to validate FADS, factor images giving the spatial information were essentially compared with the amplitude image of the first harmonic of Fourier analysis. Temporal information was compared using both the factors and the phase images.

Both results were compared with ventriculography, the real-time echography reports, and with the clinical history.

In normal patients, the "ventricular" factor image closely resembled the amplitude image from Fourier analysis. In congestive cardiomyopathy, the central area of the left ventricle usually corresponded to a region of decreased amplitude having a phase delay. In the other pathological cases, where dynamics could be described by three factors, the third factor, in hypokinesia and dyskinesia, corresponded to an area of decreased amplitude with a phase delay on Fourier analysis, which was evaluated only qualitatively.

Using the category assignments defined in Table 1, FADS and Fourier analysis were compared. The results for the whole set of patients, in LAO and RAO views, are shown in Table 2. FADS was significantly better than Fourier analysis in LAO view (sign test: $p < 5\%$) and in RAO view ($p < 5\%$).

For the LAO view, the two methods were in agreement in 27/44 cases. Neither method detected a wall-motion abnormality in two CAD patients. In seven cases

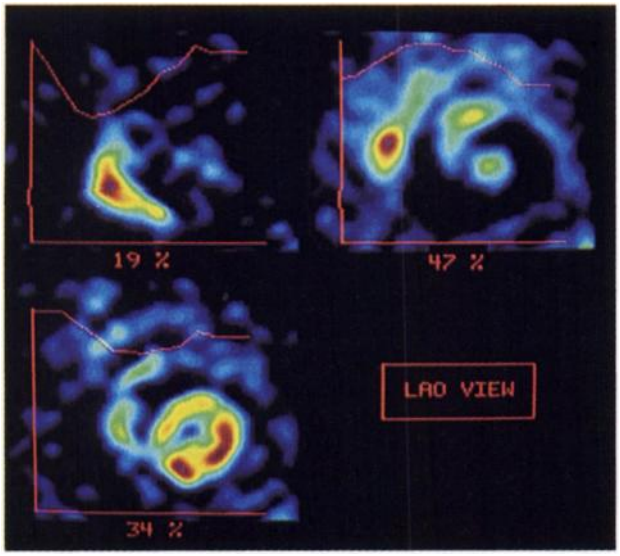
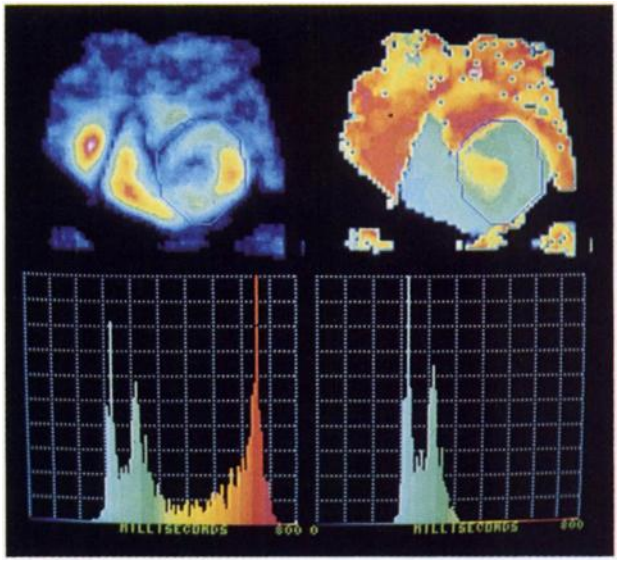


FIG. 4. Left bundle branch block in patient with congestive cardiomyopathy. Left: LAO view: FADS results (upper left = right-ventricular factor, upper right = atrial factor, lower left = left-ventricular factor). Note presence of atrial factor at center of left ventricle corresponding to an akinetic area. Lower left: LAO view: FADS results, superimposition of the three-factor images. Lower right: LAO view: Fourier analysis. Bundle branch block is well identified, as well as central akinesia.



the agreement between the two methods and the final diagnosis was good, and was complete in 18 cases.

In the RAO view, the two methods were in agreement in 25/37 cases. In two cases, the agreement between the two methods and the final diagnosis was poor, but was good in four cases, and complete in 18.

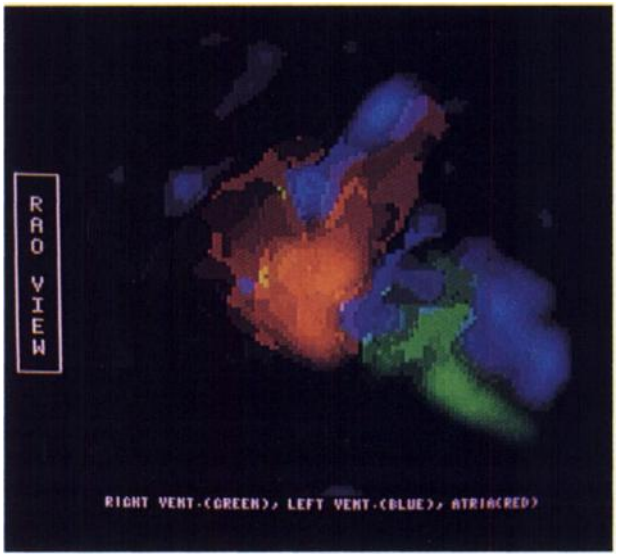
In patients for whom both views were obtained, a global score for the whole examination can be obtained by summing the individual score of each view (Table 3).

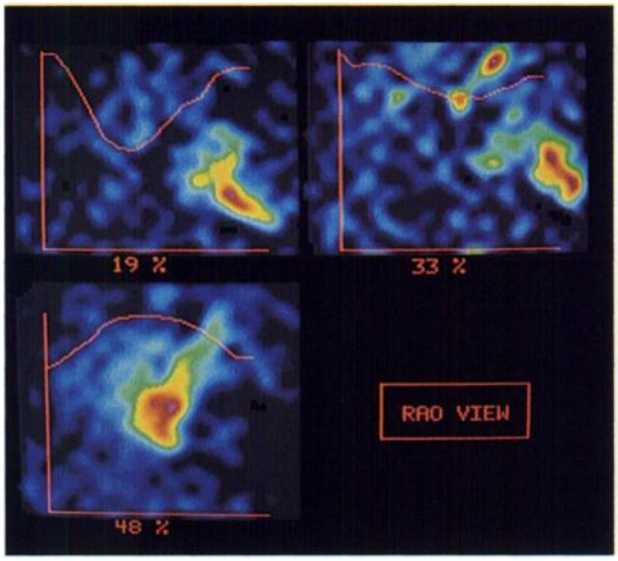
Fourier analysis was better than FADS in two cases. In one case, FADS failed to detect a septal hypokinesia. In the other case, FADS diagnosed an akinesia instead of a hypokinesia.

FADS was better than Fourier analysis in 11 cases. In four cases (three CAD and one congestive cardiomyopathy), due to severe cardiac insufficiency, Fourier analysis was of poor quality. In three other CAD patients, the phase image was normal: it did not show a hypokinesia in one case, the extension of the hypokinesia was inaccurate in another; and in the last one, with an aneurysm, the phase showed a wall-motion abnormality but it was difficult to make out its type. In the four other cases, a conduction abnormality was barely diagnosed, whereas it was obvious using FADS.

The difference between the two methods is significant (sign test: $p < 5\%$).

Among seven patients who were imaged only in LAO view, FADS was superior to Fourier analysis in four cases. In two CAD patients with limited hypokinesia, the phase image was nearly normal. In one, an aneurysm was not obvious. In a case with severe cardiac insufficiency, the phase and amplitude images were of very poor quality.





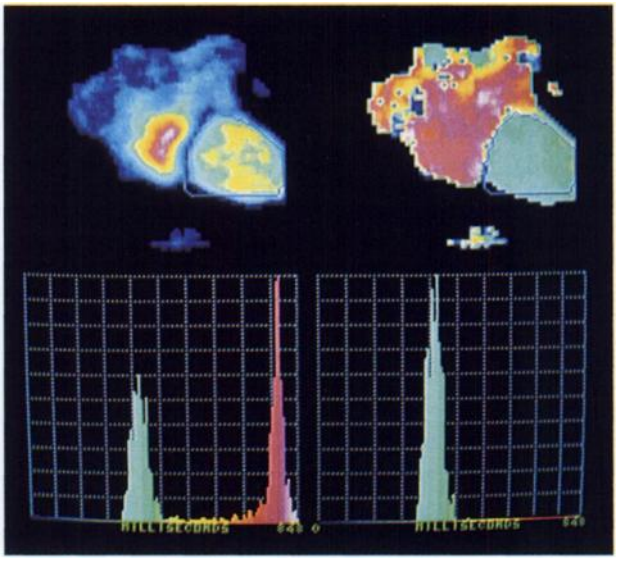


FIG. 4. (continued). Lower left RAO view: FADS results (upper left = right-ventricular factor, upper right = left-ventricular factor, lower left = atrial factor). Upper right: RAO view: FADS results, superimposing the three-factor images. Note stability of FADS results. Lower right: RAO view: Fourier analysis. Bundle block branch is not identified on this view.

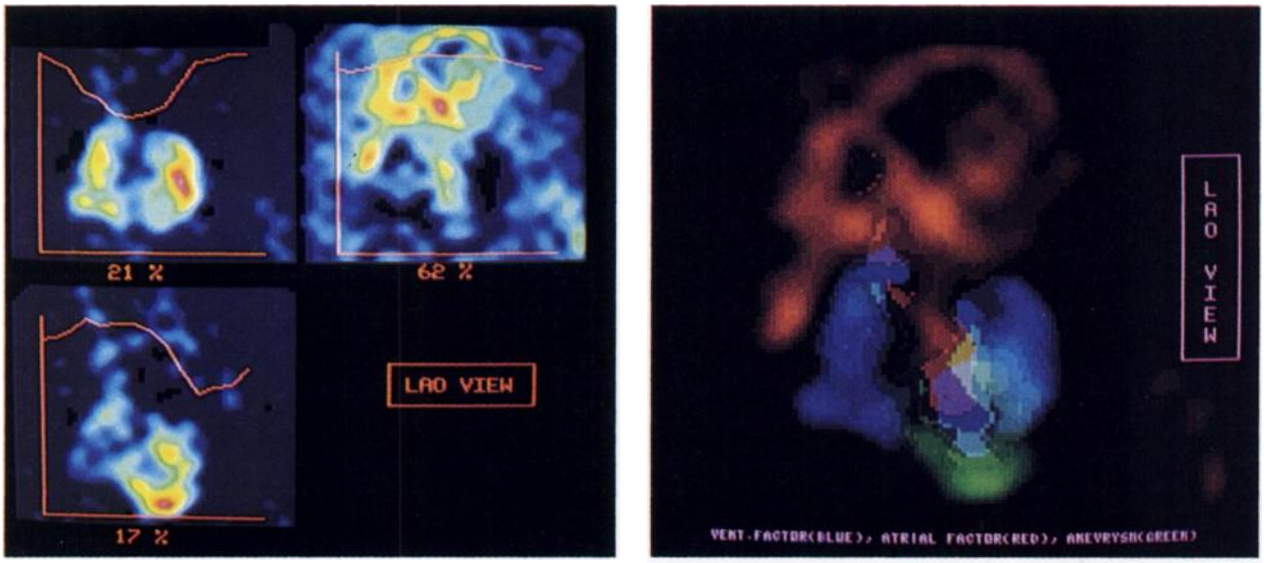


FIG. 5. Apical aneurysm, LAO view, FADS results. Left: upper left = ventricular factor, upper right = atrial factor, lower left = pathological factor. Right: Superimposition of 3 factor images.

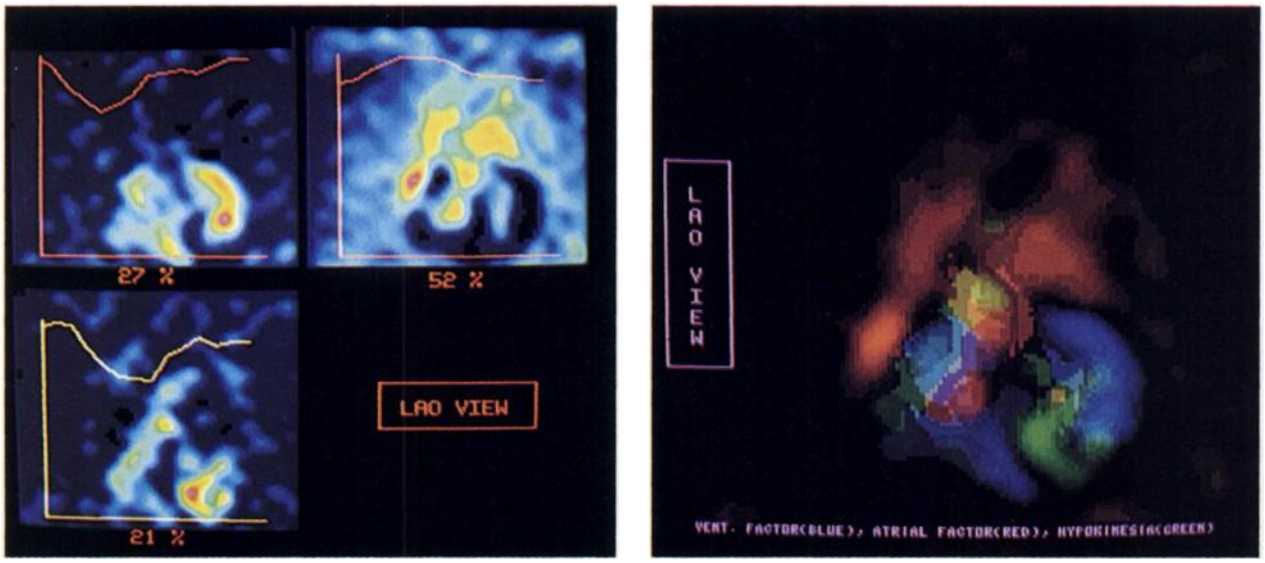


FIG. 6. Septal hypokinesia, LAO view. Left: FADS results (upper left = ventricular factor, upper right = atrial factor, lower left = pathological factor). Right: FADS results. Superimposition of the 3 factor images.

The agreement between the two methods in each condition is given in Tables 4, 5, 6. Due to the small size of each group, the sign test could be used only in the conduction abnormalities, in RAO view ($p < 2.5\%$).

DISCUSSION

Factor analysis has been used by several authors. Schmidlin (*21*) proposed its use to extract orthogonal factors characterizing populations of renograms. In the same way, factor analysis can be used to classify each individual study according to the characteristic of the global population. Schmidlin (*21*) concluded that "one cannot expect that the factors produced by this algorithm will correspond to anything which has a direct anatomic interpretation or physical meaning." This point has also been discussed by Goris (*1*), who stressed the difference between functional and parametric imaging.

Oppenheim et al. (*22*) were mainly interested in using PCA to smooth the original time-activity curves, using orthogonal factors obtained on a population of renograms in order to obtain better "functional" images.

Chatfield et al. (*23*) concluded that PCA was not a powerful technique for analysis of time-series data. The emphasis of the time and spatial data structure being information of major importance results from our ex-

TABLE 2. COMPARISON BETWEEN FOURIER ANALYSIS AND FADS USING CATEGORY ASSIGNMENTS DEFINED IN TABLE 1, FOR WHOLE SET OF PATIENTS

Fourier analysis

FADS	0	1	2	3	Total
0	2	0	0	1	3
1	1	0	0	0	1
2	0	1	7	3	11
3	0	3	8	18	29
Total	3	4	15	22	44

LAO VIEW

Fourier analysis

FADS	0	1	2	3	Total
0	0	0	0	0	0
1	1	2	0	0	3
2	0	2	4	2	8
3	0	2	6	18	26
Total	1	6	10	20	37

RAO VIEW

TABLE 3. COMPARISON BETWEEN FOURIER ANALYSIS AND FADS, FOR WHOLE SET OF PATIENTS. SCORES ARE OBTAINED BY SUMMING THOSE OBTAINED FOR EACH VIEW

Fourier analysis

FADS	0	1–2	3–4	5–6	Total
0	0	0	0	0	0
1–2	1	1	0	0	2
3–4	0	1	4	2	7
5–6	0	2	7	19	28
Total	1	4	11	21	37

perience and especially our approach in terms of physiological components. This information leads to a unique interpretation of results. Our approach—which includes physical and physiological a priori knowledge in the estimation of the dynamic and spatial components (positivity constraints) and in the assessment of results—is more exhaustive than the approach restricted to statistical considerations. Nevertheless, the statistical properties of original data must be considered in order to improve the stability of the estimation procedure.

FADS (factor analysis of dynamic structures) is intended to extract, from a dynamic series, estimates of the physiological components and of their associated functional images—that is, the spatial contributions corresponding to anatomical structures with different temporal behavior.

Due to the limited statistics of our dynamic series (200k counts per frame), the maximum number of factors that could be obtained was three. In each case, three- and two-factor analyses were performed. The third factor was retained when it led to a physiological interpretation and when the two- and three-factor analyses gave consistent results. It is obvious that when the contribution of the third factor to the total information is extremely low (<1%), the two-factor analysis is retained. In a general way, if an analysis is performed with n factors, its results must be consistent with the results of n-1, n-2, . . . , 2 analysis.

The shape of the factors obtained may be used to confirm that assumption. The ventricular factor is similar to the usual ventricular time-activity curve (TAC); it preserves the different phases of ventricular emptying and filling and the asymmetry of the curves. When three factors can be extracted in normal patients, the so-called atrial factor is resolved into a pure atrial factor and a vascular factor resembling a carotidogram.

The shapes of the pathological factors were also in agreement with physiopathological data. Bundle branch blocks were studied mainly to test the method. The time shift between the two ventricular curves was of the same

TABLE 4. CONDUCTION ABNORMALITIES COMPARISON BETWEEN FOURIER ANALYSIS AND FADS) IN LAO AND RAO VIEWS

Fourier analysis

FADS	0	1	2	3	Total
0	0	0	0	0	0
1	1	0	0	0	1
2	0	0	1	0	1
3	0	2	3	4	9
Total	1	2	4	4	11

LAO VIEW

Fourier analysis

FADS	0	1	2	3	Total
0	0	0	0	0	0
1	1	1	0	0	2
2	0	2	0	0	2
3	0	2	3	2	7
Total	1	5	3	2	11

RAO VIEW

TABLE 5. CONGESTIVE CARDIOMYOPATHY COMPARISON BETWEEN FOURIER ANALYSIS AND FADS IN LAO AND RAO VIEWS

Fourier analysis

FADS	0	1	2	3	Total
0	0	0	0	0	0
1	0	0	0	1	1
2	0	0	1	2	3
3	0	1	3	3	7
Total	0	1	4	6	11

LAO VIEW

Fourier analysis

FADS	0	1	2	3	Total
0	0	0	0	0	0
1	0	0	0	0	0
2	0	2	0	0	2
3	0	1	3	3	7
Total	0	3	3	3	9

RAO VIEW

order of magnitude as that measured on the ECG. Paradoxical kinetics were well identified by the shape of the corresponding factor, which is maximal during ventricular emptying. A delay of contraction (tardokinesis) was found in ischemic myocardium. Johnson (*24*) showed that mean volume changes in ischemic zones were smaller than in healthy zones during the first third of systole. In patients with hypokinesia, the pathological factor demonstrated the tardokinesis as a plateau during the first third of systole. The akinetic segments were associated mainly with the atrial factor, when described by only one factor. When resolved into two factors, the akinetic segments corresponded to the "vascular" factor. It seems that these areas moved passively with very low amplitude; thus they are not completely akinetic but present a very moderate paradoxical motion.

While these data show that FADS provided a valid representation of wall-motion and conduction abnormalities and were easy to interpret, some limitations must be considered. The quality of the results obtained and the number of significant factors extracted by FADS depend on the signal-to-noise ratio (S/N) of the original

TABLE 6. CORONARY ARTERY DISEASE COMPARISON BETWEEN FOURIER ANALYSIS AND FADS IN LAO AND RAO VIEWS

Fourier analysis

FADS	0	1	2	3	Total
0	2	0	0	1	3
1	1	0	0	0	1
2	0	1	5	1	7
3	0	1	5	11	17
Total	3	2	10	13	28

LAO VIEW

Fourier analysis

FADS	0	1	2	3	Total
0	0	0	0	0	0
1	1	1	0	0	2
2	0	1	3	2	6
3	0	0	3	12	15
Total	1	2	6	14	23

RAO VIEW

dynamic series. However, FADS is a powerful image-filtering instrument (being a mixed time and space filtering), which improves the S/N. Furthermore, typically more than 95% of the total variance is contained in the first three components; thus FADS can also be used as a powerful method for data compression (*13*).

The factor images and their associated factors seem to have a physiological meaning more straightforward than amplitude and phase images of the first harmonic of a Fourier transform. The phase is influenced by the shape of the entire ventricular time-activity curve, and simply describes how much one must shift a cosine in order to make it fit the ventricular curve as closely as possible. As a result, alterations in different timing parameters of the ventricular curve may cause similar changes in the amplitude of the first harmonic (*7,8*). The influence of curve symmetry on the phase has also been shown by Wendt (*9*) in a phantom study, as well as the effect of translation, rotation, and overlapping of the chambers. Using a multiharmonic approximation as proposed by Goris (*25*), a more accurate approximation of the ventricular curve can be obtained, but the problem of overlapping remains. However, phase analysis of the first harmonic gives satisfactory results in many instances (*26–32*). Some clinical limitations were stressed, particularly in cases of severely impaired left-ventricular function (*33*) and in the akinetic or severely hypokinetic segments (*31*).

When cardiac kinetics were described by two factors, FADS and Fourier analysis led to similar conclusions. In these cases the two factors are, by nature, quasi-orthogonal. When three factors are present, for instance in bundle branch block, the two ventricular factors have a similar shape but differ by their temporal shift, and are far from being orthogonal. In such cases, results obtained by Fourier analysis were globally of poorer quality compared with those obtained by FADS. This was particularly true in the RAO view, where the problem due to the overlapping of the chambers is added, and FADS can naturally resolve the problem of the structure superimposition. Despite these limitations, however, Fourier analysis is actually one of the most commonly used techniques in cardiac data processing.

In order to assess the potential usefulness of FADS, results obtained with the two procedures were compared. FADS gave significantly better results than Fourier analysis (sign test) for the whole set of patients. In the various groups of conditions, the number of patients well classified using FADS was always greater than with Fourier analysis. In the few cases where FADS was inferior to Fourier analysis, the major disagreement observed concerned a CAD patient: FADS was normal, whereas Fourier analysis showed a septal hypokinesia. In that case, however, the two "gold standards" were not in agreement: the echocardiogram showed a hypokinesia whereas ventriculography was normal. In two cases, the diagnosis of FADS was akinesia instead of hypokinesia. In these two patients, due to poor statistics, FADS could extract only two significant factors, the hypokinetic segments appearing on the atrial factor image. In one case, the pathological factor obtained in the RAO view suggests an akinesia instead of the dyskinesia clearly seen in LAO view.

When Fourier analysis had a lower score than FADS, it corresponded to limited hypokinesia in four cases. It was in agreement with the findings of Botvinick (*26*), who showed that, in many hypokinetic segments, no

significant phase delay was demonstrated. In four cases, due to severe cardiac insufficiency, the phase and amplitude images were of poor quality. This is one of the limitations of Fourier analysis (*33*). The inferiority of Fourier analysis in the RAO view is related to the superimposition of the two ventricles. The phase obtained corresponds to a mean phase. This was shown in a phantom study (*9*).

CONCLUSION

The aim of FADS is to extract temporal and spatial factors that are as close as possible to the responses of an unknown underlying model. As the solutions of a physiological model are typically not orthogonal, the desired factors cannot be orthogonal. FADS gives oblique solutions according to the physiological constraints of positivity, i.e., positivity of the factors and of their spatial contribution (*20*).

FADS gave satisfactory results for the diagnosis of contraction and conduction abnormalities. Globally, results were slightly better with FADS than with Fourier analysis, especially in conduction abnormalities. As with Fourier analysis, FADS can also be used automatically. Its main advantage seems to lie in its versatility. It can be used without modification for a variety of other dynamic studies. Factor analysis of dynamic structures (FADS) also appeared to provide an accurate means of revealing anatomical structures with different temporal behavior in hepatobiliary studies (*34*) and in the interpretation of dynamic scintigrams of transplanted kidneys (*35*). Moreover, FADS can be interpreted by inexperienced physicians.

FOOTNOTE

* Opticamera CGR.

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