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A HEURISTIC SEARCH PROCEDURE
FOR THE AUTOMATED ANALYSIS OF DYNAMIC CARDIAC SCINTIGRAMS

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RESUME

Le but de cette comunication est la déscription d'un procédé pour l'extraction du contour des objets convexes dans des images avec bruit. Cette opération peut être realisée comme une recherche d'un chemin optimal dans un graphe avec coût minimal en utilisant des techniques propres à l'Intelligence Artificielle. Cette approche devient plus facile en changeant la représentation de l'image de coordonnées cartésiennes à polaires avec origine dans le centre approximatif de l'objet et en reliant chaque point de l'image à un noeud du graphe. Cette recherche est effectué par l'algorithme A*, qui recherche le chemin avec coût minimal par la fonction d'évaluation suivante:

$$\hat{f}(n) = g(n) + \hat{h}(n)$$

où

g(n) est le coût du chemin avec coût minimal du noeud initial au noeud n;

et

$\hat{h}(n)$ est l'estimation du coût du chemin minimal du noeud n au noeud final.

Cet algorithme devient optimal lorsque des convenables fonctions sont choisies. Le traitement proposé à été appliqué à l'extraction du contour du ventricle gauche (VG) dans une séquence des scintigraphies. Le centre approximatif du VG est déterminé comme le centre de gravité du signal le long de l'axe du ventricle. Ce centre devient l'origine pour la transformation des coordonnées. La deuxième derivée partielle du signal le long de la coordonnée radiale peut donner une contribution utile à la fonction d'évaluation g(n). Ulterieures contributions à g(n) peuvent être ajoutées en tenant compte de la connaissance à priori de la courbure du contour du ventricle et de sa position par rapport à son centre. L'extraction du contour est effectuée au débout dans l'image diastolique, ensuite presque le même procédé est appliqué dans les images suivantes, en modifiant la fonction g(n) pour limiter la zone de recherche par rapport au contour de l'image précédente.

SUMMARY

The proposed contribution describes a procedure for the boundary extraction of convex objects in noisy images. This task can be performed as an optimal search of the minimal cost path in a graph by means of techniques that are peculiar of the Artificial Intelligence. This approach is made easier changing the representation of the image from cartesian to polar coordinates with origin in the approximated centre of the object and relating each point of the image to a node of the graph. The search procedure makes use of the A* algorithm, that searches for a minimal cost path by means of an evaluation function:

$$\hat{f}(n) = g(n) + \hat{h}(n)$$

where

g(n) is the cost of the minimal cost path from a starting node to the node n;

and

$\hat{h}(n)$ is an estimate of the cost of the minimal path from the node n to a goal node.

The algorithm becomes optimal if proper function g(n) and $\hat{h}(n)$ are selected.

The proposed procedure has been applied to the extraction of the boundary of the left ventricle (LV) in a sequence of gated equilibrium blood-pool scintigrams. The centre of the LV is determined as the centre of gravity of the counts along the approximated axis of the ventricle. The second partial derivative along the radial coordinate can give an useful contribution to the cost g(n) in the evaluation function. Other contributions to g(n) can be added taking in account the a-priori knowledge about the boundary curvature and the boundary position related to the centre of the ventricle. The boundary extraction is firstly performed in the end-diastolic frame, then a similar procedure is used in the successive frames, modifying the function g(n) in order to bound the search within an area depending on the boundary of the previous frame.

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INTRODUCTION

The estimation of convex object boundaries in noisy images often arises within the context of the analysis and interpretation of medical images. The most common approaches found in literature perform the boundary evaluation by means of edge detection techniques. The noise influence can be reduced by suitably filtering the original image. This procedure makes possible the object detection, however, as a filtering consequence, a shape distortion of the edge is achieved, that cuts down the accuracy in the reconstruction of the object.

In order to avoid this shortcoming, techniques, that aim at the boundary evaluation without that preprocessing, have been produced. An higher accuracy can be reached, provided that more complex algorithms are produced and the a-priori knowledge about the object under investigation is exploited. In this context, take place the algorithms developed by Montanari, Martelli, Cooper, and others [1-4]. These authors accomplish the boundary evaluation by dynamic programming or graph-search strategies.

The proposed procedure is based on graph-search algorithms, in which all the available information about the shape, the size, and the possible displacement within the image is exploited.

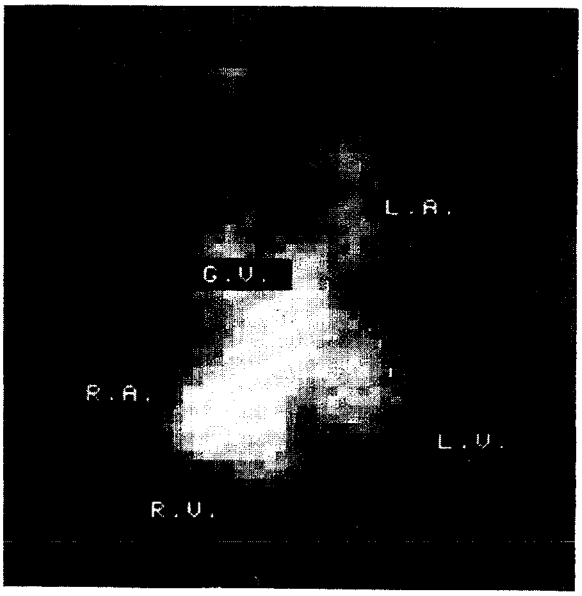

Fig. 1 - The cardiac scintigram image: L.V. left ventricle, L.A. left atrium, R.V. right ventricle, R.A. right atrium, G.V. great vessels.

The procedure has been carried out on scintigraphic images, in order to evaluate the boundary of the left ventricle in the cardiac gated equilibrium blood-pool scintigrams. This clinical test permits the visualization of the distribution of a radioactive tracer in the heart chambers. The supplied images present a low signal-to-noise ratio because of the statistical behavior of the fundamental phenomena that make possible this visualization (such as the gamma ray emission and detection). The superimposed noise can be regarded as a Poisson distributed random variable, since the image formation is a process that counts the gamma-rays that fall upon the detector. The aim of the scintigraphy is the evaluation of the wall motion and the computation of the ejection fraction, that is the ratio

$$\frac{N_{cd} - N_{cs}}{N_{cd}}$$

where N_{cd} and N_{cs} are the number of counts within the ventricle boundary respectively at the end-diastolic frame and at the end-systolic frame.

The a-priori knowledge about the shape of the object under investigation and about the statistical properties of the counts within the object and in the background area, makes possible the use of those procedures, that evaluate the boundary elements by optimizing a figure of merit (FOM), function of the boundary itself. This figure of merit is evaluated so that it assumes its greatest value on the exact boundary.

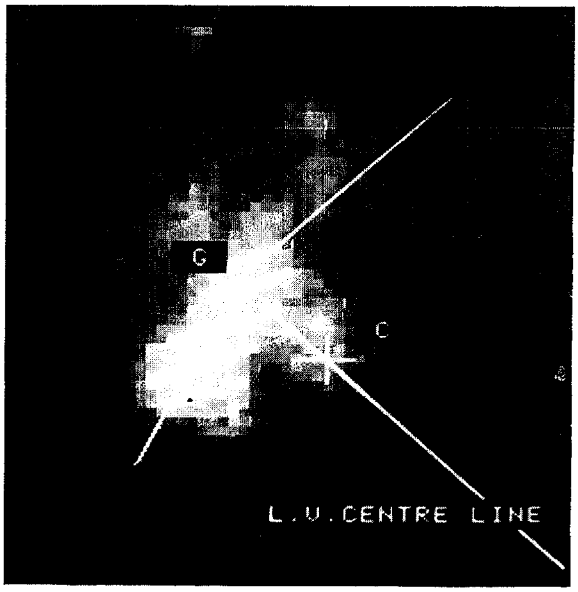

Fig. 2 - The restricted search area and the centre line of the left ventricle. G: centre of gravity of the image, C: approximated centre of the ventricle.

Montanari [1] performed this task by means of dynamic programming, embedding the a-priori knowledge in the figure of merit, while Martelli [2] showed that the FOM optimization approach can be improved representing the problem as the shortest path-search in a graph. This last technique has been later developed by other authors as Askhar and Modestino [3] and Cooper [4].

Several techniques have been developed in order to optimize this computation [5]. The A* algorithm appears to be very promising, provided that some conditions are checked.

DEFINITION OF THE LEFT VENTRICLE SEARCH AREA

The gated blood-pool scintigrams provide a total image of the heart with atria, ventricles and great vessels as shown in fig. 1.

In order to perform the boundary evaluation of the ventricle, the search area must be bounded so that the other structures can be neglected and their influence on the search procedure is restricted. This task is performed in successive steps: firstly, the centre of gravity of the whole image is computed (it falls normally near the line that divides the ventricles and the atria), then, regarding this point as the new origin of the cartesian coordinate system, only the restricted area of the image included between /4 and -5 /8, as shown in fig. 2 is taken into account, so that the left ventricle has a great probability of lying in this area. In the succesive step the centre line of the ventricle is estimated by computing the sums of the counts along 42 equally spaced radii in the restricted area. Representing in the graphic of fig. 3a these values versus the angular coordinate, the resulting curve presents two minima corresponding to the separation between the left atrium and the left ventricle (A) and between the left and the right ventricle (B). The maximum value placed between these two minima corresponds with a good approximation to the centre line of the ventricle. The analysis of the count values along this line (fig. 3b) makes possible the determination of the left ventricle centre as the weighted mean value of the counts lying between the first relative minimum (C) that comes starting from the centre of the image and the successive relative minimum (D) corresponding to the separation of the ventricle from the background or the spleen.

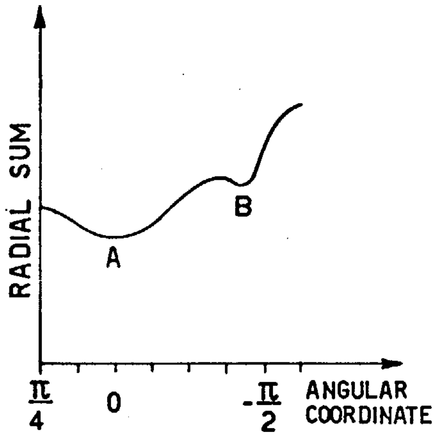

Fig. 3a – Curve of the radial sums versus the angular coordinate.

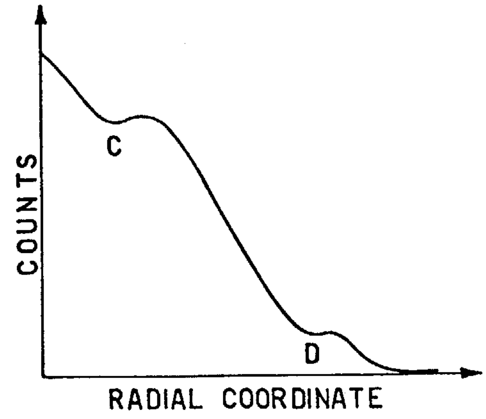

Fig. 3b – Curve of the count values on the centre line of the ventricle.

SEARCH PROCEDURE

In order to have a defined direction of search and an ordered and directed graph, in which all the successor nodes are strictly tied to the parent node, the transformation from cartesian to polar coordinates, with origin in the approximated centre of the left ventricle, is performed as suggested by Reiber [6]. This transformation is accomplished sampling at discrete angular and radial values the cartesian image. 64 angular samples and 32 radial samples are taken, overcoming the sampling uncertainty with interpolation techniques. The result of this transformation is shown in fig. 4a.

(a) (b)

Fig. 4 – a) Polar representation of the scintigram.
b) Second partial derivative of a).

The boundary becomes in the polar representation a single value function of the angular coordinate, since the left ventricle has a convex shape. Furthermore, by means of this transformation, each point I(i,j) can be thought as a node n_{ij} of a directed graph G, where the angular coordinate j of each point corresponds to the depth of the associated node in the graph as shown in fig. 5. Each node is linked to the adiacent nodes by arcs. Each arc has a value that represents the cost of applying a rule in order to go from one node to the other.

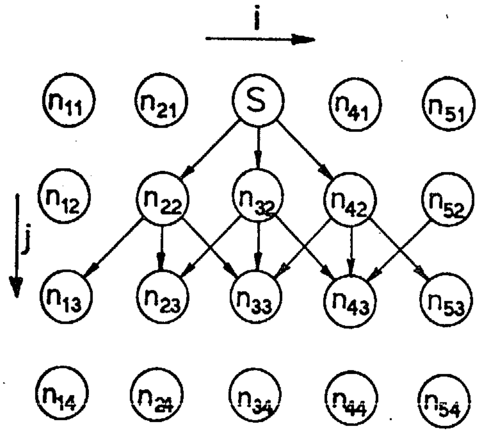

Fig. 5 - The image to graph correspondence.

This cost is related to an operator that emphasizes the separation between the object and the background. The first and the second derivatives are good operators for the edge extraction, since the maximum value of the first derivative corresponds to the point of maximum slope in the transition area and the maximum of the second derivative corresponds to those points of greatest change in the transition area. To make use of the first or of the second operator, depends on the definition of the boundary that best fits the problem under examen. The proposed technique makes use of the second derivative, for its best corrispondence to the actual left ventricle profile. This radial second derivative of the polar representation is shown in fig. 4b.

The value of the cost, associated to each arc linking a parent node to its successors, is given by:

$$c(n,m) = a(m) + K(n,m) \cdot \bar{a}$$

where

$c(n,m)$ is the cost of the arc linking the node n to the node m;

$a(m)$ is the complement to the maximum value of the second partial derivative versus the radium calculated on the polar representation in correspondence of the node m;

$\bar{a}$ is the average value of a on the full graph G;

and

$K(n,m)$ is a positive weighted coefficient (lower than 1) that include the a-priori knowledge about the boundary curvature; it is related to the morphology of the left ventricle as it appears in the scintigraphic images.

If a starting point is identified, the boundary can be computed as the best path that divides the object from the background. In order to estimate this best path, an evaluation function is associated to each node. This function contains the a-priori knowledge and the heuristic information, and so, makes possible the boundary detection without performing an exhaustive search and the number of involved nodes is very small.

The starting node S is determined as that corresponding to the element in the polar representation that lies on the angular origin and is characterized by the first relative minimum value of the complement of the second derivative beginning from the centre of the left ventricle.

Starting from the node S, the searching algorithm generates, step by step, all the possible successors of the candidate parent node. In order to bound the searching area these successors are those associated with points of coordinates (i-1,j+1), (i,j+1), and (i+1,j+1), if the parent node coordinates are (i,j) as shown in fig. 5.

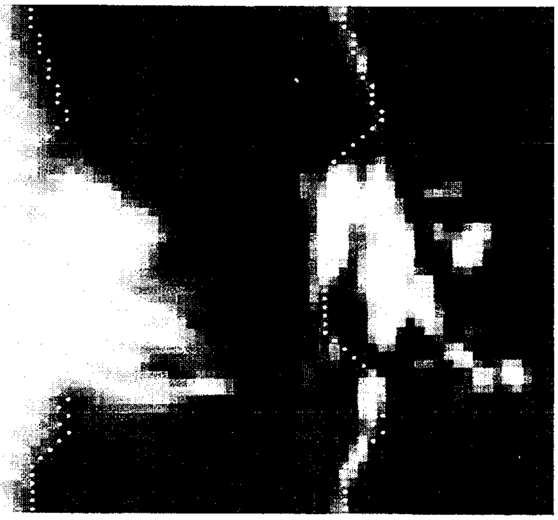

Fig. 6 - The extracted boundary placed on the polar representation and on its second derivative.

Pointers are connected to each successor node to relate this node to its parent, in order to make possible the backtracking of the path up to the starting node G. A more detailed description of this procedure (A*) algorithm is provided in [2,5].

The optimal path is selected at each step according to the evaluation function $\hat{f}(n)$ expressed by:

$$\hat{f}(n) = g(n) - \hat{h}(n)$$

where

$g(n)$ is the cost of the minimal cost path from S to n and is given by:

$$g(n) = g(n-1) + c(n-1,n)$$

and

$\hat{h}(n)$ is an estimate of the cost of a path to reach the goal node from the n node with minimal cost, and is given by

$$h(n) = a_{min} \, [P-p(n)]$$

where

a_{min} is the minimum of the complemented second derivative over all the points;

P is the total depth of the graph and $p(n)$ is the depth of node n.

It can be proved that, because of the choise of this evaluation function, the proposed search algorithm is always "admissible" i.e. for each graph the search always stop with an optimal path from S to n [5] and moreover, being

$$\hat{h}(n-1)-\hat{h}(n) \quad c(n-1,n) \quad n-1,n \quad G,$$

when the algorithm selects a node, it has just found an optimal path to that node.

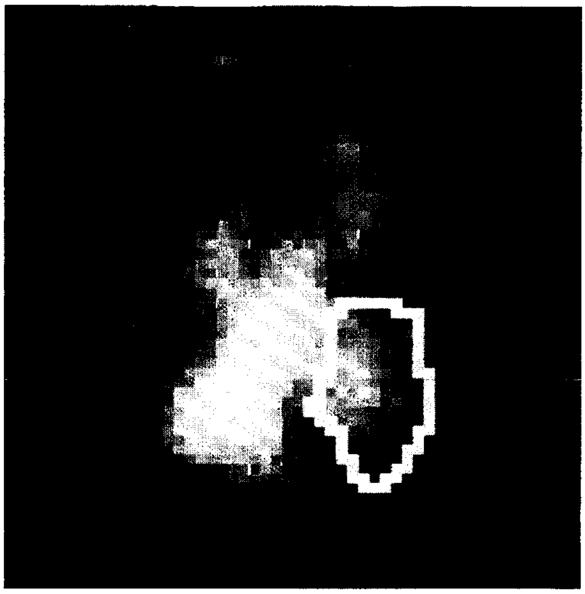

Fig. 7 - The extracted boundary placed on the scintigram in the cartesian repreesentation.

RESULTS

The extracted boundary is placed on the second derivative and on the polar representation of fig. 6, while the fig. 7 shows the same boundary superimposed to the original image. The movement information is achieved applying the same procedure to the complete sequence, starting from the end-diastolic frame. In order to avoid ambiguities in the evaluation of the boundary in the systolic frames, the costs associated to each arc in the graphs of the frames succeding the first are modified according to a bell-shaped function centered on the boundary of the previous frame. In this way the information of the previous boundary contributes to bound the number of possible paths, improving the efficiency of the algorithm. The result of the evaluation of the activity (sum of counts within the LV boundary) in the sequence of cardiac scintigrams is shown in fig. 8.

These results seem to be very promising and the proposed procedure is still under test in order to improve the use of the a-priori knowledge and to gain a clinical validation.

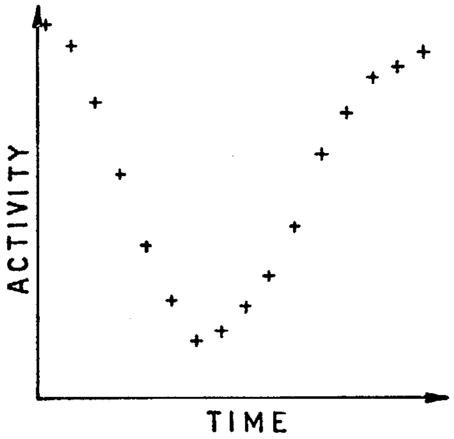

Fig. 8 - Time-activity within the left ventricle boundary on a complete cardiac cycle.

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