KNOWLEDGE-BASED IDENTIFICATION OF ARTERY BRANCHES IN CINE-ANGIOGRAMS

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ABSTRACT

This paper describes an image understanding system which interprets line segments detected In cine-angiograms, cine-film records of radiographic images of coronary arteries, into a model of the arterial system based on expert knowledge on the artery. A production system accesses rules on shapes and structures of the blood vessels to evaluate the geometrical parameters of sequences of segments, and a tree of hypotheses on the Identities of the individual segments in each view Is generated. Finally, the hypotheses obtained from different views are integrated to find a more reliable Interpretation of the images.

1. INTRODUCTION

Visual inspection of coronary arteries in cine-angiograms, cine-film records of radiographic images of beating hearts, has increased its importance to find diseased portions within the arteries and to assess the severity of the coronary diseases. Semi-automatic inspection systems have been proposed for quantitative analysis [11, but they need careful monitoring a large number of frames in the records and tracing the diseased parts by experts. Also it is a very difficult and time-consuming task for the experts to localize the detected lesions in the arterial structure, because the records consist of sequences of projections of the moving, complex, three-dimensional arterial system from different directions.

We have studied with Professor Abe's group of Medical School of Osaka University to develop an intelligent system which could help medical doctors by finding diseased portions of the arteries in the cine-angiograms and locating them in a model of the arterial system.

Since the arteriograms are much noisy, low contrasted, and time-varying images, the finding of the artery branches and tracking of their precise boundaries are very difficult image processing tasks. An attempt to automate this process has been already reported [2]. This paper describes higher level programs of the system, an expert system, for identifying the individual line segments detected in each view and constructing a model of the arterial system by integrating information obtained from different views.

Akita and Kuga [3] have studied an intellignet system which analyzes another type of images of blood vessels, color ocular fundus images. Their system classifies each segment of the blood vessel into an artery or a vein by utilizing knowledge on the shapes and patterns around crossing points of two segments. Our system needs much deeper understanding of the structure of the coronary arterial system. The arterial systems in the cine-angiograms show a wide variety of appearances because of (1) inter-individual varieties of shapes and structures of the arteries, (2) temporal changes in each cardiac cycle, and (3) significant changes in their shapps and structures by even a small amount of change in the direction of image projection. A number of medical studies have acculmutated knowledge on the anatomical structure of the coronary arteries, their appearances in the radiographic images taken from different directions, and techniques of interpreting the images. Expert medical doctors with much experience on the inspection nf the arteriograms can identify most of arterial branches, especially those important for diagnosis, by carefully examining the images and integrating information obtained from multiple views. Therefore, we follow the knowledge engineering approach [4,5] and design an image understanding system so as to easily transfer the expertise to the knowledge-base of the system and test its effectiveness and vaildity by experiments.

2. UNDERSTANDING OF IMAGES OF CORONARY ARTERIES

CORONARY ARTERIES AND ANTERIOGRAMS

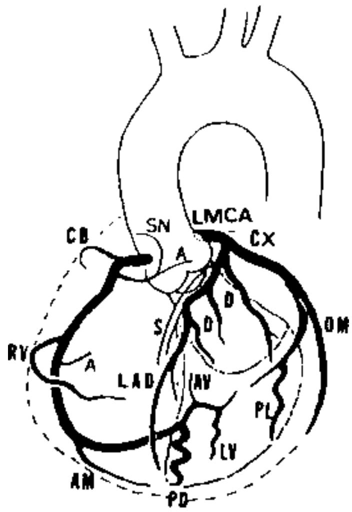
Anteriograms are 35mm cine-film records nf radiographic images of coronary arteries while X-ray opaque dye is intermittently injected through a catheter. The images are taken from several directions such as LAO (left anterior oblique projection) or RAO (right anterior oblique projection) to observe the three-dimensional structure of the arteries. The diseased portions, obstructing lesions, are detected as irregular and narrow or completely occluding portions in the vessels.

The coronary arteries have very complex structures. Fig.l illustrates a simplified diagram of the entire coronary arterial system which is based on representative coronary arteriograms of healthy subjects [7]. Images of the arterial systems, however, show a wide variety of appearances in both shapes and structures. The left coronary artery has 11 types of branches (the major branches are shown in Fig.1), and some branches vary in their numbers, lengths, sizes, directions, and the locations of their origins. Fig.2 shows two examples of the left arteries of two subjects in a 60 degree LAO view.

Another difficulty in analyzing the arteriograms is that we need to integrate information obtained from views of different directions, for example, LAO and RAO. This paper deals with only images of LAO views, but even a small amount of change in the direction of the projection sometimes causes significant changes in structure* of the images, and the system needs to compare the interpretations of two views in order to obtain a more reliable interpretation. We should also note that there exist temporal changes of the arteriograms in the shapes (and sometimes in the structures of images) in each cardiac cycle.

UNDERSTANDING OF CORONARY ARTERIES

An approach to analyze the images of such complex arteries is to utilize a three-dimensional model of the arterial system and interpret the images as projections of the model. The method, however, needs a very flexible model to



Flg.l Diagram of right and left coronary arteries as views 1n the left anterior oblique projection. The abbreviations of branches of the left coronary artery In this picture are as follows:

LMCA=)eft main coronary artery
LAD left anterior descending branch
CX =circumflex
D =diagonal branch
S =septal branch
OM =obtuse marginal branch
PL -posterolateral branch
CB =conus branch

Fig.2 Left coronary arteries of two different subjects, 60 degree LAO views.

cover the wide varieties of the arterial systems. Also it is very difficult to map the image data to the model because we deal with the images which were taken from different directions by a camera in different time courses.

Instead, we study another approach, the utilization of the expert Knowledge on appearances of the arteries in each view. The knowledge, as most of the expert knowledge of other fields, is not definitely defined, therefore the system must be flexible in such a way that we can easily transfer the expertise to the knowledge-base, test its validity and effectiveness by a series of experiments, and modify it. The production system which has been widely used in the consultation systems is also suitable for our purpose. We have constructed an image understanding system which acquires rules from'experts, analyzes input line images detected in the artriograms to generate hypotheses on the identification of the input segments, and reports the results. The expertise we use include both the heuristics for identifying each arterial branch and procedures for selecting suitable.arterial branch to be examined next.

I. *SYSTEM DESCRIPTION*

SYSTEM INPUT

In order to Concentrate fundermental problems of understanding the structures of the vessel system in the images, the system analyzes the line images of the arteries obtained from the arteriograms under an assumption that all line segments are found. Each line segement is represented by its starting point and terminal point (in a 256 by 256 image array), the mean width of the vessel, and the chain-coded segment. Fig.3 shows an example of the line image obtained from Fig.2 (a). We also assume that a user gives the system the direction of the image projection and points out the line segment corresponding to the catheter by using a cursor on a color display.

Fig.3 Segments of input line images obtained from Fig.2 (a).

SYSTEM DESIGN AND KNOWLEDGE REPRESENTATION

As mentioned in the previous chapter, we have designed an image understanding system for the anteriograms which is characterized by its flexibility to easily transfer the expert knowledge to its knowledge-base and modify it. We also consider it is very important to provide it with the capability of integrating information obtained from multiple sources. The system needs to compare hypotheses on the arterial structure deduced from each of multiple views and construct a model of the arterial system. Utilization of other information than the line images will be also useful to augment the capability of the system. The expert medical doctors effectively use such information for specific decision making. For example, the knowledge that anteriouly located vessels appear to move in a direction opposite to the posteriously located arteries is used to discriminate the anterious descending from the many ventricular branches in a RAO view, otherwise the task is very difficult even for the experts [7]. We have been developing such image processing programs which analyze temporal changes of the arteries in their locations or measure the velocity of blood flow in each branch in the images, and plan to add these programs to the system. Therefore, the system is designed so as to accept information sent from various types of image processing programs.

The main part of our expert system is schematically shown in Fig.4. It consists of (1) INFERENCE ENGINE, (2) RULES, (3) BLACKBOARD, and (4) INTERACTIVE SYSTEM. An expert gives the system his or her knowledge, rules represented in a simple

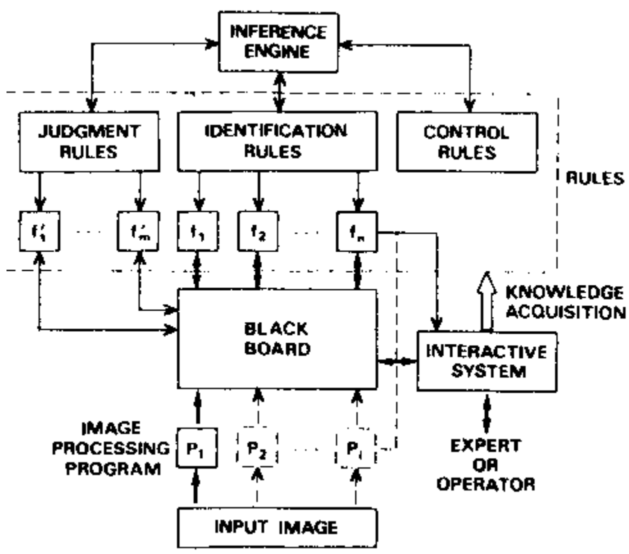


Fig.4 Image understanding system of cine-angiograms.

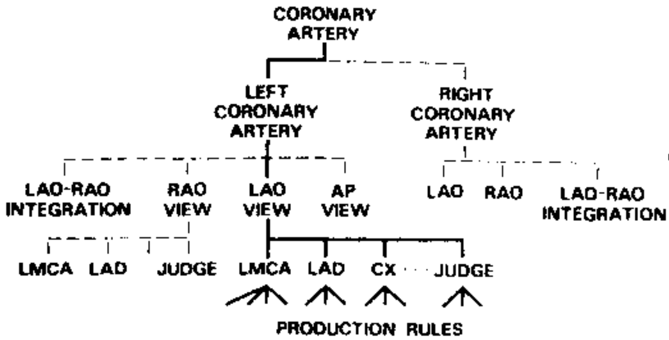


Fig.5 A tree of knowledge

English-like format, through INTERACTIVE SYSTEM. INFERENCE ENGINE accesses RULES, collects necessary data from the user, analyzes the line image data on BLACKBOARD, and generates hypotheses on the structure of the artery in the given image. The results are then shown on a color display.

BLACKBOARD is a data structure for collecting line image data obtained from different views of the coronary arteries and hypothesis trees generated for the views, which are then used to construct a model of the arterial system. It is designed so as to accept image data manipulated by the image processing programs which will be added in future.

The expert knowledge used in this system is a collection of modular type production rules as used in MYCIN and other consultation systems. In most cases, rules for identifying each arterial branch are independently used from those for the other branches and, therefore, we organize the rules in a context tree shown in Fig.5.

The rules are classified into three types: (1) control rules to specify a rule or a context of rules to be selected next, (2) identification rules to give conditions for reasoning whether a sequence of segments is a specified arterial branch, and (3) judgment rules to give conditions for judging which (or which part) of mutually contradicting hypotheses is more probable.

KNOWLEDGE FOR INTERPRETING ARTERIOGRAMS

The experts seem to have heuristics for interpreting the arteriograms. They first search the input images for large blood vessels which are easily and reliably detectable. For example, the left arterior descending coronary artery (LAD) is the vessel with the most constant origin, course, and distribution, and it is used as a key pattern for the interpretation. If LAD is found, the experts search for the next large vessel, for example CX (circumflex), which originates from the same vessel as LAD, by examining its shape, origin, and direction relative to the key pattern. Other branches are also detected by evaluating conditions on both their shapes and the relations to the arterial branches detected already.

Our system uses the same type of reasoning guided by the control rules proposing both a branch to be detected next and a context of identification rules to be used. At present, the system is provided with the expert's procedures for interpreting LAO views.

At first, the user is asked to point out the segment corresponding to the catheter by an identification rule accessed by a control rule. The context of LAI) detection is accessed next. It contains the following type of identification rules.

RULE Oil
IF THE CANDIDATE SATISFIES THAT
(1) IT BRANCHES AT 70 - 100% OF THE CATHETER, AND
(2) IT SATISFIES THE CONTINUITY CONDITIONS (AT BRANCHING POINTS), AND
(3) ITS WIDTH VARIATION (AT BRANCHING POINTS) IS 70 - 140%, AND
(4) ITS DIRECTION IS 80 - 100% OF THE LONGEST SEQUENCE,
THEN
(1) THE CANDIDATE IS DEFINITELY LAD CF*1.0), AND
(2) ADD THE CANDIDATE AS LAD TO HYPOTHESIS.

When this rule is accessed, the origin, continuity, width, and direction of each candidate, a sequence of segments, are examined, and all candidates satisfying these conditions are registered on the hypothesis tree with the highest certainty factor. The context contains another rule which finds less confident candidates for LAD. Candidates for CX are also examined by accessing the similar rules. MLCA (main left coronary artery) is a short blood vessel from which LAD and CX originate, and it is not observable in many LAO views. LMCA rules examine whether there exist a segment in each LAD's candidate between the end of the catheter and the point where the CX's candidate originates. If so, the segment is added to the hypothesis tree. If not, LMCA is an empty segment and is considered as the cross point of LAD and CX. Now we will show in more detail how the hypothesis tree is generated.

RULE 024
IF THE CANDIDATE SATISFIES THAT
(1) THE CANDIDATE BRANCHES AT 0% - 20% OF LAD, AND
(2) THE CANDIDATE BRANCHES FROM LAD AT 20 - 90 DEGREE, AND

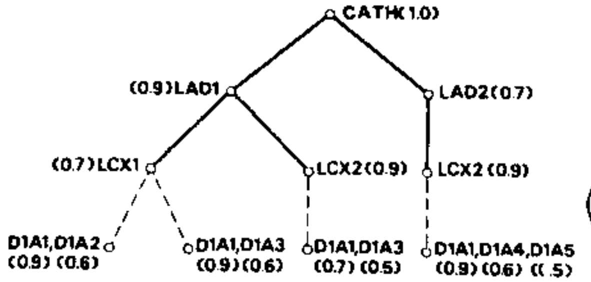
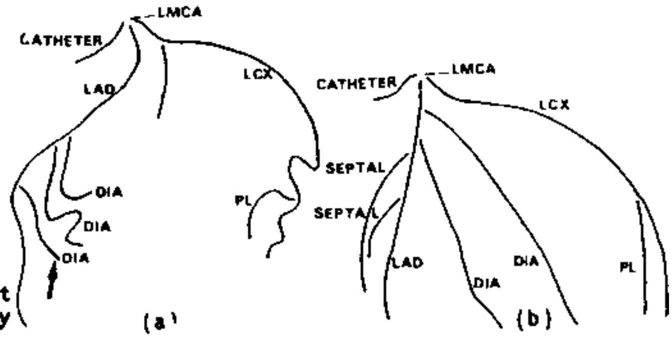


Fig.6 A hypothesis tree. MLCA is not shown because it was found as an empty segment.

(3) THE CANDIDATE IS SHORTER THAN LCX, AND
(4) THE CANDIDATE IS SHORTER THAN LAD, THEN
(1) THERE IS A STRONG EVIDENCE (CF-0.9) THAT THE CANDIDATE IS DIA, AND
(2) ADD THE CANDIDATE AS DIA TO

This is one of rules for finding DIAs (diagonal branches) which originate from LAD. (Since a large DIA sometimes originates directly from LMCA, we also implement rules for such cases in the knowledge-base.) Suppose that rules for finding three large vessels, LMCA, LAD, and CX, were accessed and several hypotheses on the identities of these vessels were already generated on BLACKBOARD as shown in Fig.6 with solid lines. In this example, CATH has been uniquely determined with CF=1, and there are three hypotheses on LAD and LCX: (LAD1 LCX1) (LAD1 LCX2) (LAD2 LCX2). When RULE 024 is accessed, all possible candidates for the diagonal branches are found on BLACKBOARD and are transferred to a short term memory, then individual premise conditions are evaluated for each candidate. Predicates in the rules are LISP functions which evaluate T or NIL by evaluating the specified geometrical attributes. Some LISP functions can access FORTRAN programs calculating complex shape parameters of which utilization considerably save the computing time. This link of production rules with FORTRAN programs will be useful for augumenting our system because the production system can control image processing . subroutine packages. At present, the system has functions examining attributes on the origin, length, direction, width variation, angle, curvature, continuity, and index of shape complexity of the candidate or the vessels detected already. If the candidate satisfies the premise, the action part is excuted and the result is added to the hypotheses on BLACKBOARD. The dotted lines of Fig.6 shows the hypotheses on DIA generated by the context containing RULE 024. Note that the system utilizes knowledge on the maximum number of each arterial branch such that LCX and LAD are single vessel but DIA are sometimes more than two branches.



F1g.7 Hypotheses with the maximum certainty factors generated for Images taken from different directions.

The rules for all branches in the context of LAO view are applied to the input image, and the hypothesis tree is completed for that view. The hypothesis having the highest certainty factor is displayed on the color display.

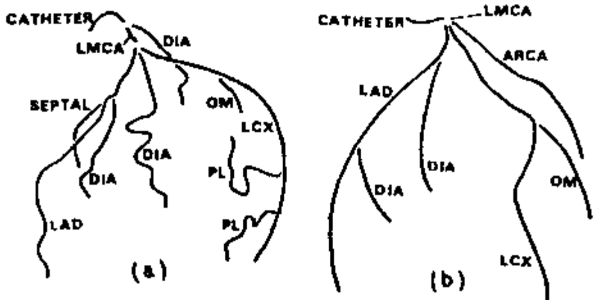
If the input anteriograms contain another LAO view of which direction, is different by a small angle, then another hypothesis tree is generated bv the same procedure. Then the judgment rules are applied to the trees and the most reasonable hypothesis is selected. The detailed process will be explained in the next chapter using an example.

4. EXPERIMENTAL RESULTS

We have implemented the system written in FLISP (a modified version of INTERLISPf and FORTRAN on a minicomputer HP2108A. About 50 rules are currently used for identifying the branches of left coronary arteries in LAO views.

The analysis of the line image with 12 segments obtained from an input image shown in Fig.2 (b) (a 60 degree LAO view) yields 6 hypotheses, and the interpretation with the highest certainty factor is shown in Fig.7 (a). The short line segment without any label is not given any identity, since the knowledge-base does not contain rules for such small branches. Most of the identities of the segments are identical to those by an expert and are considered as true. The branch identified as the third diagonal branch, however, is judged as a septal branch by the expert who examined other images taken from different-directions.

The cine-angiogram of this subject contains images taken from a direction different by a small angle; 55 degree LAO views. The system analyzes the line image obtained from one of them, and generates another hypothesis tree. The most confident hypothesis is shown in Fig.7



F1g.8 Examples of the Interpretations.

(b). The judgment rules are then applied to find correspondences between the two interpretations shown in Fig.7. Starting with the most reliable vessels (LAD in this case), the correspondence of the other arterial branches are examined. If the branches originate from the same vessel in the two views are not same, their certainty factors are re-examined. In this case, the third branch from LAD is assigned two different meanings; a diagonal and a septal branch. The system evaluates the certainty factors of both hypotheses on the identity of the branch for the two images. (b). We have CF[DIA,60*LA0]=0.6, CF[SEP ,60°LA0]=0 .3 CF[DIA,55°LA0]=0, and CF[SEP,F1g.4(b)] =0.5. Also the system searches the knowledge-base for descriptions on the branches of LAD and finds the knowledge that if LAD has more than two branches, there is suggestive evidence (CF=0.7) that LAD has the first DIA and the first SEP and the other. Since the two other branches are identified as DIA, then the rule gives CF[DIA]=-0.7 and CF[SEP]=0.7. By using the method for the inexact reasoning [5], the system concludes that the third branch is the first septal, and this interpretation is identical to that by the expert.

We have tested the performance of the system for a set of input images. The hypotheses with the highest certainty factor obtained from sample input images are shown in Fig.8. The system correctly identifies the major branches. I he computing time for the interpretation of one image ranges from 6 minutes to 20 minutes depending on the number of segemnts and the complexity of the structure Our experiences indicate that the utilization of the large computer such as FACOM M100 will shorten the computing time by a factor of 1/100.

5. DISCUSSIONS

The image understanding system for the anteriograms currently interprets the line images of the left coronary artery of a 60 degree LAO view. Also it can integrate the hypotheses generated for the images taken from a slightly different direction and obtain a more reliable model of the artery. Because of the modularity of the knowledge, it seems us easy to consruct the knowledge-base on other views of the left coronary artery and RAO and LAO views of the right coronay artery. The integration of hypotheses obtained from RAO and LAO views is more difficult and needs further research. The integration of other source of information such as temporal information is also important.

Although we use the rules on the structure of the artery of healthy subjects, the system can interpret the images containing diseased lesions if they appear as narrow portions of the segments. We consider the modification of the rules so as to find completly occluded portions would be easy if the invisible segments of the vessels are short. However, there exsit images in which total lack of visible parts beyond the diseased lesions is observed, and future research is needed to interpret these images.

We assume that the noise free line image is extracted from the raw image data, but it is very difficult to find small arterial branches in the cine-angiograms. The knowledge-based line finder [7] controlled by the production system will be useful for automatic inspection of the cine-angiograms.

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