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Computer Assessment of Left Ventricular Wall Motion: The ALVEN Expert System

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The current limited success of computer-assisted analysis of left ventricular (LV) dynamics is due to three main reasons: (1) there is a strong tendency to remain within the realm of mathematical modeling for LV dynamics, and it is not at all clear that this is an adequate approach; (2) in places where mathematical models alone may be insufficient, current computer science research into more sophisticated schemes is not yet complete, and thus, more basic research is required, particularly into artificial intelligence, representations of knowledge, and interpretation control structures, before applications such as LV performance can be solved, a view also stated in M. Boehm and K. Hoehne (*in* "Digital Image Processing in Medicine" (K. Hoehne, Ed.), Springer-Verlag, New York/Berlin, 1981); (3) there is a distinct lack of knowledge about LV dynamics, in conjunction with disagreements about what is important to model and what terminology is to be used. Although each of these issues is addressed, the first two issues are concentrated on. Furthermore, a language for the expression of definitions for terminology has been designed, and a system for LV dynamics interpretation has been implemented.

1. INTRODUCTION

The evaluation of left ventricular (LV) performance by computer from cine representations of LV dynamics is a difficult and long-studied problem. A large number of heuristics have been proposed for measuring shape changes (*2*), following anatomical landmarks (*3*), computing segmental volume contributions (for a comparison, see (*4*)), etc., all performing with varying degrees of success, but being applied independently of each other. Although such heuristics are indeed valuable quantitative measures, we propose that their limited performance is due to two key considerations: (1) it is unlikely, given the complexity of the domain of LV dynamics and the amount of training that a clinical specialist in this area receives, that any single heuristic can capture all the important facets of the evaluation and be successful in all applications; (2) the heuristics are purely quantitative in nature, contrasting with the fact that clinicians, and for that matter humans in general, deal in qualitative or descriptive terms combined with numerical quantities. That is, relational quantities are

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necessary components of the interpretation process, while numerical ones are secondary. The key here is that a computer system that is to solve the difficult problems present in the domain of LV dynamics interpretation must integrate the above-mentioned numerical heuristics as well as consider the symbolic processing aspects of the interpretation. We distinguish our approach from those whose goal is to provide some intermediate visual representation that must still be subjectively interpreted by a clinician (the work described in (*5*) is a particularly good example of such a representation). Our goal is to perform this interpretation, in much the same way as the clinician does, and to do it in an objective and consistent manner. We have designed the framework for a computer system that can perform such an integrative process, and have implemented it in a system called ALVEN.

The premise used in the design is that if we wish to build a computer system that can perform at levels equal to expert human performance in some domain, then that computer system must contain the same knowledge employed by the human expert and must use the knowledge in much the same ways as the human expert does. The design and implementation is described in (*6–9*).

Briefly, the important concepts on which the computer system is based are as follows. We have designed and implemented a knowledge-base expert system for motion understanding that incorporates several novel features. A frame-based representation, which includes exception handling via similarity links and the organizational primitives IS-A (generalization/specialization) and PART-OF (part/whole) is used to construct a knowledge base of temporal concepts. A language has been designed that is used to create LV dynamics knowledge packages (classes), and thus, since the knowledge is interpreted by the computer, these knowledge packages can provide a set of formal definitions for our terminology. In addition, these definitions are easily examinable and modifiable by others. We believe that this will provide an approach to the solution of the terminology problem pointed out in (*10*); however, the problem of determining what the knowledge is, is still a major one. An iterative refinement solution is possible within this framework. This knowledge base drives the recognition process that integrates the paradigms of hypothesize-and-test and competition and cooperation among conceptually similar hypotheses.

2. Using the Representation and Knowledge Base: Control Strategy

In (*11*), three incarnations of the PUFF system were compared each with the same knowledge, but different control schemes. The result of the comparison was that for PUFF's specific problem domain, expectation driven (what is called hypothesis driven below) was the best strategy, yet it too had drawbacks. Its analysis was strongly influenced by the initial hypothesis, and was not able to recover from bad initial states, and moreover could not respond to all input data, only that which was required by the model. The control scheme of ALVEN does not rely on a single mechanism. We recognize that a single

scheme may not be adequate for all situations, and thus several interacting dimensions are included. Specifically, our control scheme does not suffer from the above-mentioned drawback because of its incorporation of model-driven, data-driven, and lateral failure-driven search, reflecting traversals of the knowledge base along the IS-A, PART-OF, or SIMILARITY dimensions.

ALVEN employs hypothesize and test as the basic recognition paradigm. The activation of a hypothesis sets up an internal goal, that is, that the class from which the hypothesis was formed tries to verify itself. However, activation of hypotheses proceeds along each of four dimensions concurrently, and hypotheses are considered in parallel rather than sequentially. These dimensions are the same class organization axes that are described above. Hypothesis activation is a cyclic process beginning with hypothesis-driven activation and then alternating with data-directed, temporal and lateral activations, and back to hypothesis-driven activation. For a given set of input data, in a single time slice, activation is terminated when none of the four activation mechanisms can identify an unactivated viable hypothesis. Termination is guaranteed by virtue of the finite size of the knowledge and the explicit prevention of reactivation of already active hypotheses. Because of the multidimensional nature of hypothesis activation, the "focus" of the system also exhibits levels of attention. That is, in its examination, the focus can be stated according to desired level of specificity or resolution (the two are related), discrimination set, or temporal slice.

Each newly activated hypothesis is recorded in a structure that is similar to the class whose instance it has hypothesized. This structure includes the class slots awaiting fillers, the relationships that the hypothesis has with other hypotheses (its "conceptual adjacency"), and an initial certainty value determined by inheriting or sharing the certainty with the hypothesis that activates the new hypothesis.

The matching result of a hypothesis for the purpose of hypothesis ranking is summarized as either success or failure. Matching is defined as successful if all slots that should be considered for filling are filled and no matching exceptions are raised. Otherwise, the match is unsuccessful. Using this binary categorization of matching, and the conceptual adjacencies among hypotheses, a certainty updating scheme based on relaxation processes (*12*) is used. Details of this scheme appear in (*6, 9*). Basically, hypotheses that are connected by conceptual adjacencies that imply consistency support one another, and those linked by adjacencies that imply inconsistency compete with one another by removing support. The IS-A relationship is in the former group, while the similarity relationship is in the latter group. The focus of the system is defined as the set of best hypotheses, at each level of specificity, for each set of structural components being considered in the given time slice. The focus, due to the slow change of certainties inherent in relaxation schemes exhibits inertia, or procrastination, i.e., it does not alter dramatically between certainty updates. Both global and local consistency is enforced throughout the contributions of hypotheses to one another via their conceptual adjacencies.

3. LV Dynamics Knowledge and Its Representation

Although there is still much work to be done in the determination of the knowledge of LV dynamics, much can be found in current literature which can be incorporated into our formalism. Two examples will be given. Both examples present LV dynamics knowledge derived from experimentation and measurements of echocardiograms. It should be clear that the contrast images we are interested in do not possess the same characteristics. This knowledge is used as a starting point for knowledge base construction only. Moreover, although the exact numerical quantities may differ between imaging techniques, the ***qualitative*** descriptions do not.

In the series of papers by Gibson and his colleagues (for example (*13, 14*)), several investigations were carried out that determined quantitative aspects of specific LV motions. In the second paper quoted, the segmental motions of the LV during isovolumic relaxation were examined in normal and ischemic LVs using echocardiography in order to determine dynamic differences between these two cases. Without describing technical details of their method, we will briefly summarize their findings. They discovered that in normal LVs an outward wall motion of 1.5–3.0 mm could be present in any region during isovolumic relaxation. In abnormal cases, i.e., patients with coronary artery disease, affected areas show inward motion, 2 mm or more for posterior or apical segments, and any at all for anterior regions, and nonaffected areas, due to a compensatory mechanism, may exhibit an increased outward motion of up to 6 mm over normal. The key feature to note here is that the description given does not have a mathematical form at all—it is a combination of quantitative and qualitative measures. The term "outwards" does not specify any precise direction as long as the motion of the segment is away from the inside of the LV. It is not impossible to set up a mathematical model of this; however, the model will be both cumbersome and will bury the pertinent facts in its equations, so that inspection by a nonsophisticated user becomes impossible.

The alternative is to devise a representational scheme that can incorporate both modeling aspects. Let us look at the form of the representation for the example cited above. A knowledge package in our scheme is called a ***class***. Each class has a name, a number of prerequisite components that provide part of its definition, a number of dependent quantities that are computed from the prerequisites, and a number of similarity links that relate the defined motion to other motions via the set of possible differences, or anomalies that can be present. So, the definition of a normal isovolumic relaxation phase is partially given by:

```
class N_ISORELAX is-a NO_VOLUME_CHANGE with prerequisites
  subj : N_LV such that [

        (find ant_mot : NO_TRANSLATION where [
          ant_mot.subj = self.subj.anterior,
          ant_mot.time_int = self.time_int
          ]
```

```
 or
 find ant_mot : OUTWARD where [
  ant_mot.subj = self.subj,
  ant_mot.time_int = self.time_int,
  dist(ant_mot.subj.centroid @ ant_mot.time_int.st,
    ant_mot.subj.centroid @ ant_mot.time_int.et) < 3
   exception [TOO_MUCH_MOTION with seg ← "anterior",
                        direction ← "outward",
   disp ← dist(ant_mot.subj.centroid @ ant_mot.time_int.st,
            ant_mot.subj.centroid @ ant_mot.time_int.et)]
  ]
) exception [TOO_MUCH_MOTION with seg ← "anterior",
                        direction ← "inward"],

(find post_mot : NO_TRANSLATION where [
  post_mot.subj = self.subj.posterior,
  post_mot.time_int = self.time_int
  ]
 or
 find post_mot : INWARD where [
  post_mot.subj = self.subj,
  post_mot.time_int = self.time_int,
  dist(post_mot.subj.centroid @ post_mot.time_int.st,
    post_mot.subj.centroid @ post_mot.time_int.et) < 2
    exception [TOO_MUCH_MOTION with seg ← "posterior",
                        direction ← "inward",
  disp ← dist(post_mot.subj.centroid @ post_mot.time_int.st,
           post_mot.subj.centroid @ post_mot.time_int.et)]
]
or
find post_mot : OUTWARD where [
  post_mot.subj = self.subj,
  post_mot.time_int = self.time_int,
  dist(post_mot.subj.centroid @ post_mot.time_int.st,
    post_mot.subj.centroid @ post_mot.time_int.et) < 3
  exception [TOO_MUCH_MOTION with seg ← "posterior",
                        direction ← "outward",
  dist(post_mot.subj.centroid @ post_mot.time_int.et,
    post_mot.subj.centroid @ post_mot.time_int.et)]]
),

(find ap_mot : NO_TRANSLATION where [
  ap_mot.subj = self.subj.apical,
  ap_mot.time_int = self.time_int
  ]
 or
 find ap_mot : INWARD where [
  ap_mot.subj = self.subj,
  ap_mot.time_int = self.time_int,
  dist(ap_mot.subj.centroid @ ap_mot.time_int.st,
    ap_mot.subj.centroid @ ap_mot.time_int.et) < 2
    exception [TOO_MUCH_MOTION with seg ← "apical",
                        direction ← "inward",
    disp ← dist(ap_mot.subj.centroid @ ap_mot.time_int.st,
```

```
                    ap_mot.subj.centroid @ ap_mot.time_int.et)]
        ]
        or
        find ap_mot : OUTWARD where [
          ap_mot.subj = self.subj,
          ap_mot.time_int = self.time_int,
          dist(ap_mot.subj.centroid @ ap_mot.time_int.st,
            ap_mot.subj.centroid @ ap_mot.time_int.et) < 3
          exception [TOO_MUCH_MOTION with seg ← "apical"
                                direction ← "outward",
            disp ← dist(ap_mot.subj.centroid @ ap_mot.time_int.st,
                  ap_mot.subj.centroid @ ap_mot.time_int.et)]]
      )
      ];
dependents
  time_int : with time_int ← (dur of TIME_INTERVAL with
                  dur ← default(0.093*(30/(0.8*HR))) )
      such that [
        time_int.st ≥ 0.24*(30/(0.8*HR)),
        tim_int.et ≤ 0.43*(30/(0.8*HR)),
        time_int.dur ≥ 0.08*(30/(0.8*HR)),
        time_int.dur ≤ 0.12*(30/(0.8*HR))
          exception [TOO_LONG_ISORELAX]
       ];
similarity links
  sim_link1 : ISCH_AP_ISOVOL_RELAX
    for differences:
      d1 : TOO_MUCH_MOTION where [
        seg = "apical",
        direction = "inwards",
        time_int = ap_mot.time_int ];

      d2 : TOO_MUCH_MOTION where [
        seg = "anterior",
        direction = "outwards",
        disp < 9,
        time_int = ant_mot.time_int ];

      d3 : TOO_MUCH_MOTION where [
        seg = "posterior",
        direction = "outwards",
        disp < 9,
        time_int = post_mot.time_int ];;

  sim_link2 : ISCH_ANT_ISOVOL_RELAX
    for differences:
      d1 : TOO_MUCH_MOTION where [
        seg = "anterior",
        direction = "inwards",
        time_int = ant_mot.time_int ];

      d2 : TOO_MUCH_MOTION where [
        seg = "apical",
        direction = "outwards",
```

```
            disp < 9,
            time_int = ap_mot.time_int ];
        d3 : TOO_MUCH_MOTION where [
            seg = "posterior",
            direction = "outwards",
            disp < 9,
            time_int = post_mot.time_int ];;

  sim_link3 : ISCH_POST_ISOVOL_RELAX
    for differences:
        d1 : TOO_MUCH_MOTION where [
            seg = "posterior",
            direction = "inwards",
            time_int = post_mot.time_int ];
        d2 : TOO_MUCH_MOTION where [
            seg = "anterior",
            direction = "outwards",
            disp < 9,
            time_int = ant_mot.time_int ];
        d3 : TOO_MUCH_MOTION where [
            seg = "apical",
            direction = "outwards",
            disp < 9,
            time_int = ap_mot.time_int ];;
end
```

The definition states that for a normal isovolumic relaxation phase to be recognized, normal motions for each segment must be present. There are three main clauses in the ***prerequisites*** component of the definition. The first defines the expected normal motion of the anterior segment, the second for the posterior segment, and third for the remaining segment, the apical one. So for example, in the first clause, the definition reflects Gibson's characterization: the anterior segment during this phase, must either not display any translational movement, or could display an outward motion of displacement less than 3 mm. A larger displacement than this in the outward direction would be recorded as the exception TOO_MUCH_MOTION, with specific additional contextual information recorded as well. In the matching of class definitions to actual observed motions, matching failures are recorded as ***exceptions***. Exceptions are stored with sufficient information so that the similarity links (sim_link1, for example) can determine which other class definition to try in a hypothesize-and-test manner. If the anterior segment were displaying motion and it were not outward, then it must be inward and this fact too would be recorded as an exception. The ***dependent*** portion specifies relevant timing information for the temporal placement of the phase within the left ventricular cycle. ***HR*** is in units of beats/second so that the right-hand side of the timing expressions is in units of number of images. Also, using the information derived from (*14*), the similarity links provide definitions of the constraints that must be found if a possible ischemic segment is to be recognized. Note that only the connections to possible ischemic states detectable by considering only the

characteristics of the isovolumic relaxation phase are included above; a set of similarly formed constraints would have to be present for other disease states as well, for those cases where the isovolumic relaxation phase plays a role in their definition. "sim_link2" relates the normal phase to the motion of an abnormal apical segment exhibiting the effects of ischemia. This, according to Gibson's definition, is shown by either the apical region itself having too much inward motion during this phase, and/or one of the other regions (posterior or anterior) exhibiting too much outward motion during the phase. Note that the set of differences does not define a necessary set; any one of the conditions is sufficient.

It should be clear that the above is not complete; it requires the remainder of the definitions for the other phases and motions since the entire definition of each class of LV motion is defined as a hierarchy of abstraction, each level adding more detail to the previous one. Some of the types of information that are represented are volume changes where known for normal phases, ejection fractions, for example; measures of degrees of abnormalities, derived heuristically; and others. The above is operated upon as if it were a programming language (a compiler, that converts this syntax into PSN, a knowledge representation formalism (*15*), and an interpreter, have been implemented for this language).

A second body of knowledge of the form necessary for interpretation can be found in (*16*). These researchers investigated, again by echocardiography, eight different clinical cardiac disease states with the intent of discovering posterior wall motion differences and similarities among the diseases, as well as global LV characteristics. The diseases were pericarditis, congestive cardiomyopathy, hypertrophic cardiomyopathy, valvular aortic stenosis, aortic insufficiency, mitral stenosis, mitral insufficiency, and systemic hypertension. Normal LVs were also studied. The measurements made for each of the above LV states were stroke volume, rapid filling volume, slow filling volume, atrial filling volume, the percentage filling for each of the previous three phases with respect to the stroke volume, posterior wall excursion in total, and for each of the three phases of diastole, as well as the percentage excursion in each phase, diastolic posterior wall velocity, rapid filling rate, LV end diastolic dimension, and ejection fraction. It is, of course, difficult to verify their results. However, they are important—they provide at least a starting point for the further elaboration and verification of such detailed dynamic information. In addition to the large amount of numerical information that they derived, they attached to the significant findings qualitative descriptors—such as whether or not this quantity should be higher or lower than in the normal case. This was rather fortunate from our point of view: the representational formalism that we had designed can handle description via common components and differences very well, and uses such information to advantage during the decision phases of the interpretation. Of course, a serious question does remain—how is this information related to that which can be derived from cine representations as opposed to echo representations? For this reason, we are using the numerical information

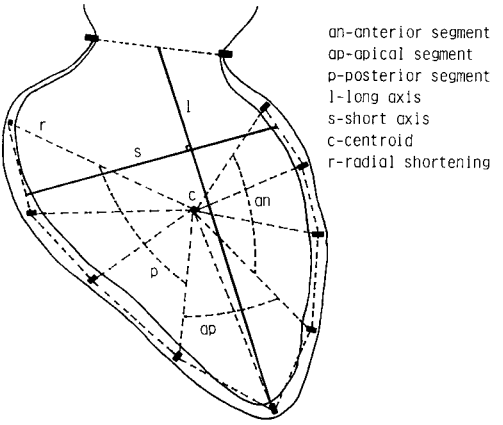

FIG. 1. Basic LV measurements.

as a starting point only and expect to iterate on it in order to converge to appropriate values. We do expect, however, that the qualitative descriptors will not differ between imaging schemes. It should be clear from the previous example how such information would be included into the representation, and this fact alone raises another important advantage of this scheme. The addition of information into a mathematical model may require a complete redefinition of the model. In our case, information is easily inserted, as long as one understands the semantics of the language.

4. Evaluation of Tantalum Marker Dynamics

The first domain of application of ALVEN is that of the evaluation of the dynamics of tantalum marker implants. The goal is to analyze both preoperative (without markers, using contrast media) and postoperative marker films (following coronary bypass surgery), to evaluate the efficacy of surgery, locally and globally, quantitatively and qualitatively, over the recovery period (several months) and to evaluate the effects of drug interventions. It is crucial for such comparisons of perhaps subtle changes that a rich representation involving both qualitative and quantitative be obtained for each film. Other examples of computer analysis of marker implants are (*4*), and (*17*), which addresses the problem of point of reference.

The initial evaluation is done on a cine contrast representation; each patient has a permanent volume correction factor for both diastole and systole that accounts for the shell of muscle enclosed by the contour created by connecting the markers (*18*). Linear interpolation is used for variations in this correction over time. Nine markers on the LV wall, and two on the aortic valve edges constitute the LV outline on which computations are based. A number of basic measurements are made throughout the LV cycle. These are depicted in Fig. 1 and include major and minor axes, volumes (with interpolated correction fac-

tors for muscle shell), 2D areas of segments, segmental volume contributions, circumferential dimensions, and changes in radial axis lengths. Figure 1 shows a typical LV outline, the myocardial location of the markers, the aortic clips, and the various measurements that are made in dashed lines, with major and minor axes in solid lines. The long dimension is distance between the apex and the midpoint of the line connecting the aortic clips. The short axis is the line with the longest dimension perpendicular to the long axis that intersects with the lines connecting the markers circumferentially. LV volume is computed using an area–length formula as in (*19*) in conjunction with the previously mentioned correction factor. A center of mass is used for the radial shortening computation as well as for the apex of each segment for segmental area computation and thus in comparison with the LV area, proportional segment volume contribution. Circumferential dimensions are obtained by straight lines correcting markers. Each measurement is made for each image of the sequence.

Figure 2 displays an actual image with the stages of image analysis that lead to "blind" marker finding, that is, without any sort of guidance as to expected marker location. The first stage involves filtering the image with a Marr–Hildreth-like operator (*20*). Zero crossings with their standard definition, however, do not lead to useful image tokens due to the nature of the X-ray images and their low contrast. A specially tuned version of the Marr–Hildreth operator was then used to extract the markers. This operator was tuned such that the size and shape of the marker was reflected in the center of the operator with the surround enveloping this center. The results of this are then superimposed on the original image to highlight the markers. These two steps are expanded in Figs. 2b and c.

Guidance, however, is an integral feature of the framework, namely, during the hypothesization of motion classes, the hypotheses themselves can be used to predict expected motion characteristics for the markers, segment, and entire left ventricle. Figure 3 then shows the kind of predictions that an "outwards" motion hypothesis creates and the guidance it provides. Note that for this example, "outwards" refers to outward motion of the marker with respect to the segment, not to the ventricle. Clearly, for this case the marker is not found on that path. The hypothesis structure is then modified to enclose a larger space, corresponding to a relaxation of the constraints of the hypotheses, until it is found. The same marker-finding process described earlier is used, but only in the prediction window. Four images are shown corresponding to the four predictions generated until this marker is found. In addition to the examination of a very small image subset for each marker, this process of prediction verification also provides important feedback for other levels of the system. This marker-finding process is guaranteed to always find a marker because the default process is the "blind" one referred to above. Figure 4 shows the sequence of marker motions for a complete cycle (a different cycle than the one from which the preceding images were taken).

ALVEN is capable of reporting on LV performance at marker, segment, and global LV levels of detail. Relative directions, motion extents, rates of change,

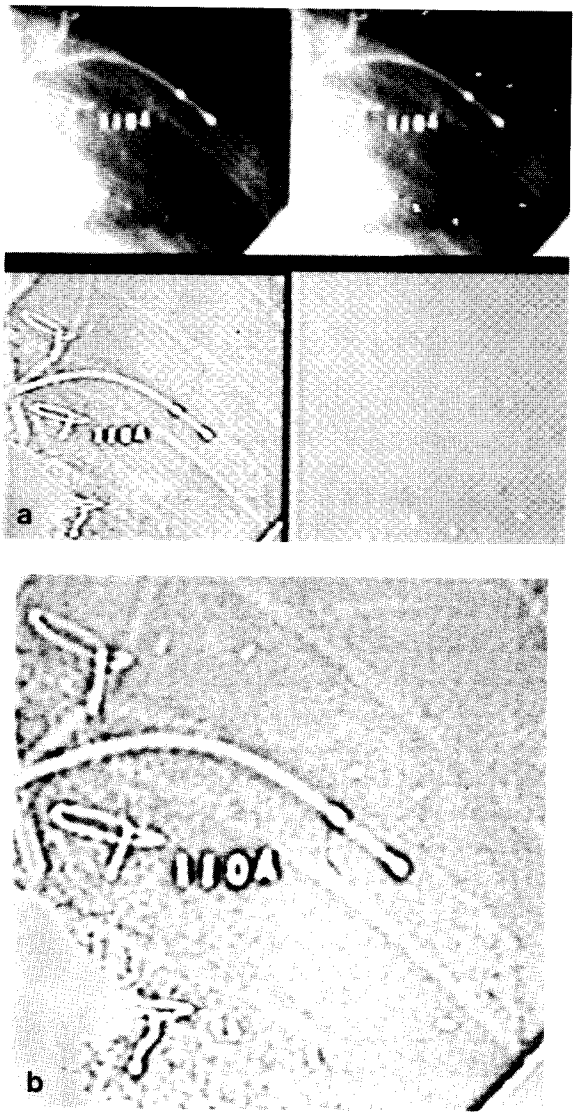

FIG. 2. A typical image and "blind" marker finding.

and temporal relationships are described both numerically and symbolically. Anomalies are detected by using the appropriate heuristic or by comparisons to accepted normal performance. Anomalies such as asynchrony, hypokinesis, dyskinesis, too slow or fast rate of change of volume with respect to the LV phase, too long or short phase duration, or degree of anomaly are considered.

An example of marker motions is shown in Figs. 4a and b, for a patient from our unit. Figure 4a shows the contraction phase, while 4b shows the expansion

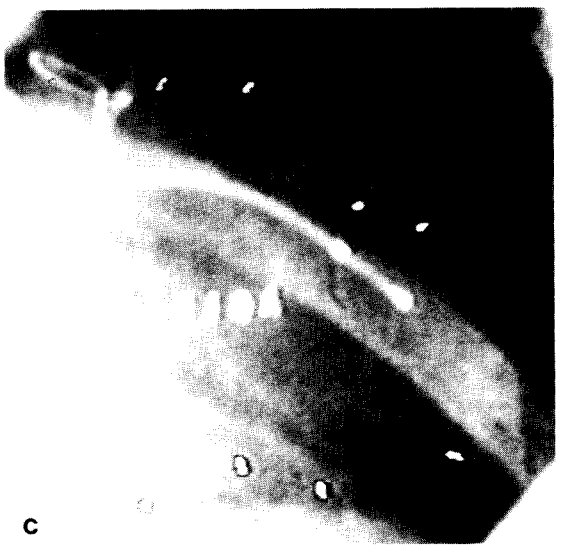

FIG. 2—*Continued.*

phase. This particular example was assessed by the radiologists with respect to motion anomalies: the radiologist reported that the anterior segment was hypokinetic, and the remaining segments exhibited normal motion. A portion of the output of the ALVEN system for this particular film (taken at 30 images/second, 17 images in all) is shown in the Appendix. Let us highlight some of the important points of this analysis. First, a short summary of how to read the example is necessary. For each physical entity that the system knows about, that is in this case, the markers, the segments, and the LV as a whole, a short summary of the motions observed is produced. This has been abbreviated due to space limitations in the following way: descriptions for the aortic clips were deleted, as were the descriptions for all of the markers save for marker 4. The remaining motions would have a form similar to those for the other markers. Each motion has a descriptive term, a possible referent where necessary (for example, "INWARD" motion is not semantically complete without saying inward with respect to some other object that has an inside, usually defined by the geometric centroid), quantitative values where appropriate (clearly a calibration phase is necessary), and a time interval or instant at which it was recognized. Time is noted in image units. The range of descriptive terms that ALVEN can understand is apparent from the example. Descriptions are shown for only one marker (5) for sake of brevity, and for each segment and for the left ventricle. The descriptions for the remaining markers are similar; the motion of marker 5 is of particular interest for this example.

Second, the example of the knowledge for isovolumic relaxation given earlier is relevant here. The motions exhibited by the anterior segment, that is, there is a small inward motion during that phase, as shown by the description at time

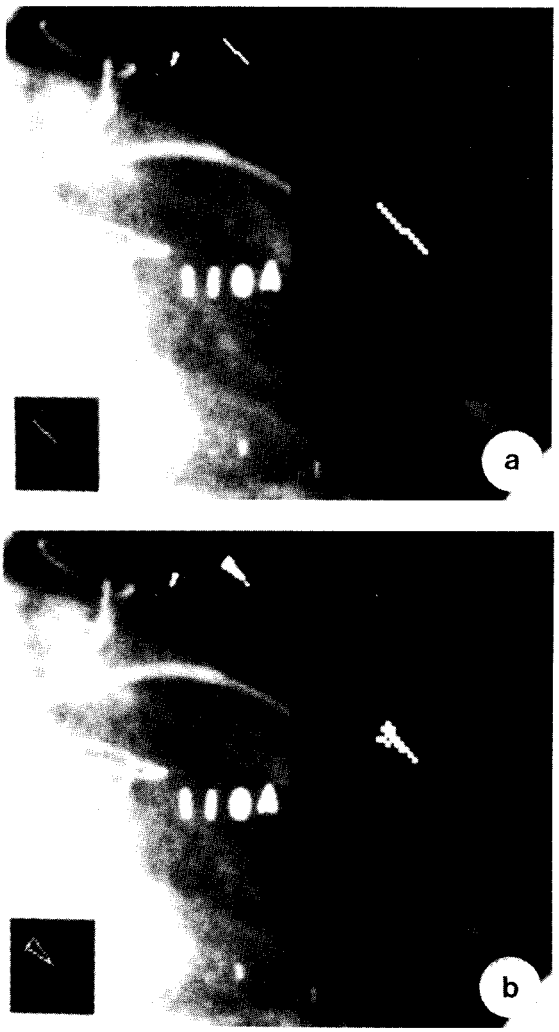

FIG. 3. Guidance for marker finding from hypotheses.

interval (6,7), due to an inward motion of marker 5 during that interval, and further evidenced by the volume contraction noted in the segment description, cause that chunk of knowledge to be activated and verified. The result is the descriptive term "ISCHEMIC ANTERIOR ISOVOLUMIC RELAXATION" which can be found in the description of the motions of the left ventricle. In addition, it will usually be true that if one segment is not performing up to par (notice the number of HYPOKINESIS instances detected—the great majority are present for the anterior segment thus confirming the radiologist's report), then the overall performance of ventricle must be impaired as well. This can be

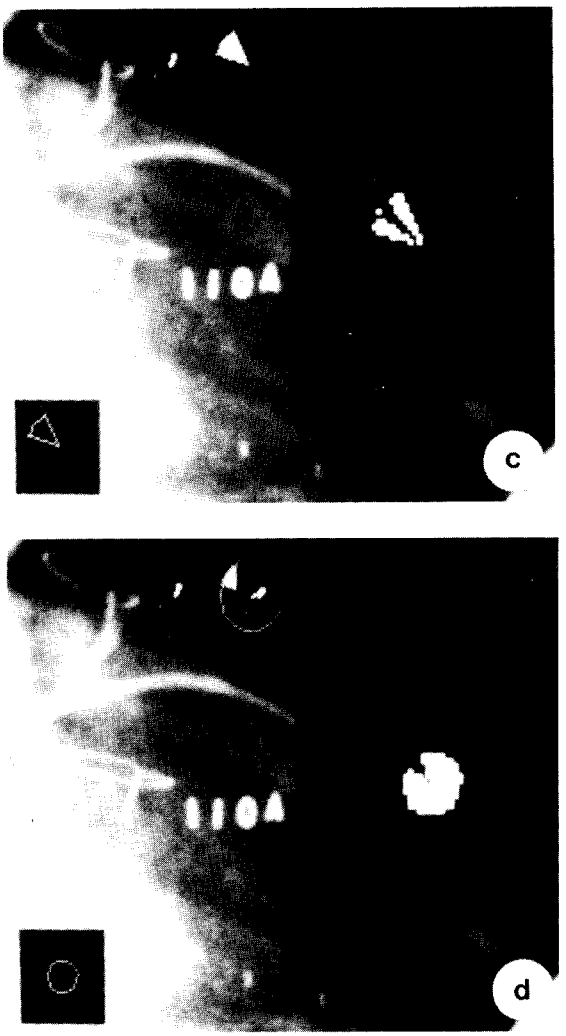

FIG. 3—*Continued.*

seen by the instances of "POOR SYSTOLE" that appear. These are confirmed independently using volume change information.

Some other interesting descriptive terms are briefly described. UNIFORM CONTRACT/EXPAND—for this to be detected, the object considered must have a decreasing volume, and all of its markers/segments (depending on the level of description) must be moving in the proper direction. So for a uniform contraction at the LV level, the three segments must all be moving inward and the overall volume of the LV must be decreasing. HYPOKINESIS—can only be noted if all markers/segments are moving in the same direction, and a comparison of their relative motions reveals one that is lagging behind. Note that

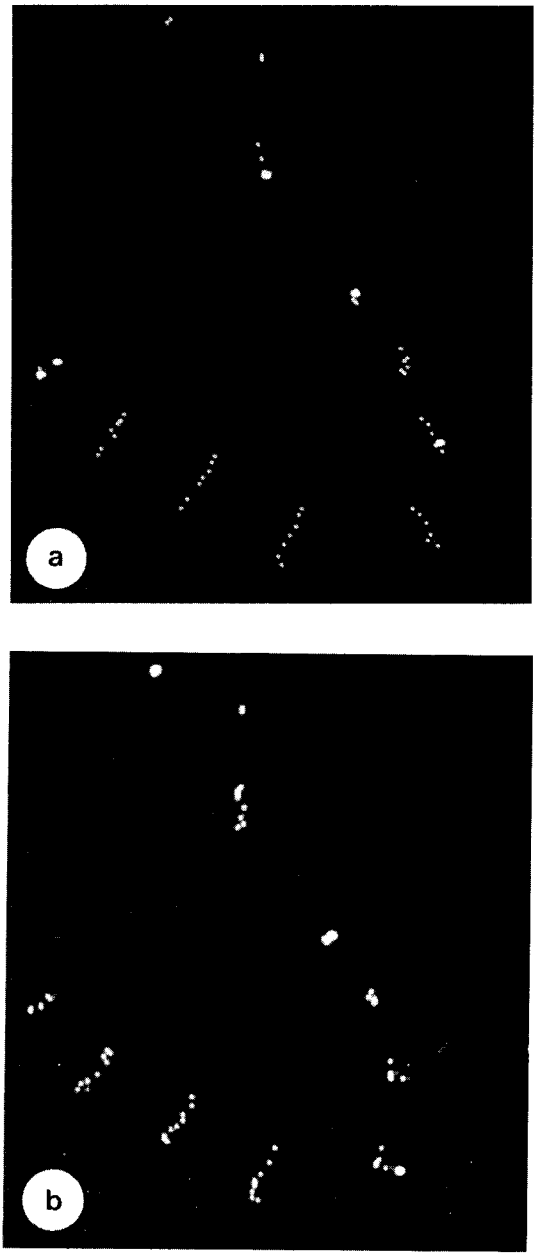

FIG. 4. Inward and outward motions of an LV cycle.

the use of the term hypokinesis does not make sense if all markers are not moving in the same direction, since this is a term describing anomalies of motion extent. If they are all moving too slowly, then no anomaly is detected at

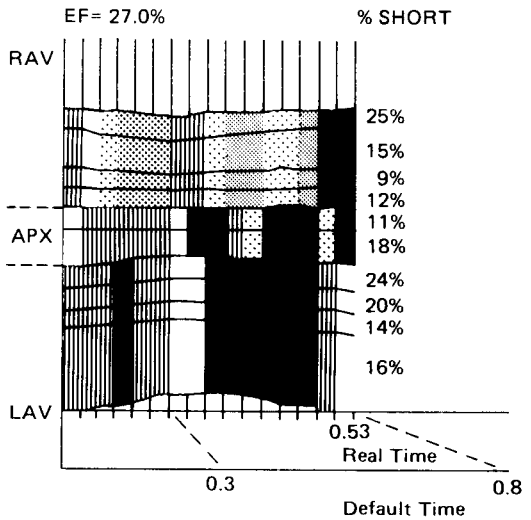

FIG. 5. ALVEN's graphic display of the evaluation in the Appendix. ⁘, severe hypokinesis; ▒, hypokinetic outwards motion; ▒, hypokinetic inwards motion; ||||, inward; ■, outward; □, no motion.

the marker level but it is detected at the segment level. If in turn, all segments are exhibiting small motion extents, no hypokinesis is noted at all; however, serious performance problems will be noted, because the volume changes will be lower than normal. The detection of hypokinesis is purely relational. Note, however, that it is not necessarily so. The data in (*16*) do provide some quantitative information on normal and abnormal extents for the posterior segment; these will be incorporated into the representation. However, the relational approach is a valid one when lacking information.

No constraints are currently in place for length changes—that is, normal or abnormal circumferential shortening, although examples are shown of how such changes are detected.

It should be apparent that the amount of information reported is large, and that this is not a desirable characteristic for a medical consultation system. Therefore, a simple, graphic display has been devised that captures much of the important information required for appropriate analysis. This display is presented in Fig. 5. A brief explanation is in order. Imagine that the ventricle is opened up along the circumference and laid flat along the vertical axis with the right side of the aorta on the bottom, the apex in the middle, and the left side of the aorta at the top. Time is the horizontal axis. For each time interval (image pair of the film), and for each segment, a summary is displayed in terms of whether or not the segment was moving inward, outward or was not moving. Remember that these are motions relative to the ventricular centroid. The yellow dotting represents hypokinesis with the more dense the dots representing increasing levels of severity. The black lines traversing the plot horizontally are the marker paths in time, useful for viewing circumferential shortening

effects. Finally, percentage shortening values for each marker with respect to the ventricular centroid are provided on the right side, along with ejection fraction. This display is particularly clear in revealing temporal relationships of a variety of types.

If these evaluations are compared with those of the radiologist, it can be seen that there is infinitely more detail present in ALVEN's evaluation, yet it is completely consistent with the radiologist's opinion. This has been borne out in several other examples as well as that have been tried. Moreover, this analysis is repeatable and objective. Although there is much knowledge refinement required before ALVEN's knowledge base is as competent in general as a good radiologist/cardiologist, the value of the enhanced evaluation is clear.

Conclusions

Current computer-assisted analysis of LV performance is limited by the state of the art in representation and interpretation of complex temporal data. This was motivated with examples of LV dynamics knowledge, showing that knowledge is not mathematical in nature but is a mixture of qualitative and quantitative facts, and that interpretation places stronger emphasis on relational attributes than on numerical ones. A representational framework for such knowledge was briefly described, and an example provided that showed that it is indeed capable of representing both numerical and relational information. An "expert" system that utilizes this representation called ALVEN has been implemented for the problem of left ventricular dynamics evaluation. An example of an analysis was provided. This kind of analysis provides most of the information that a radiologist can provide but also provides quantitative information, a simple graphical summary of the qualitative aspects and is consistent and objective. The approach described herein has resulted in a computer consultation system that goes far beyond other computer-assisted schemes for interpretation of LV dynamics from cine representations.

Appendix

Alven's Descriptive Output for the Motions in Fig. 4

Marker 5 exhibits:

TRANSLATING – time interval (0,5)
rate (mm/sec) → 60, 21, 33, 45, 51
trajectory (radians) → 4.71, 2.36, 0.46, 1.24, 2.18
specializations:
    OUTWARDS wrt ANTERIOR during (0,1)
    INWARDS wrt ANTERIOR during (1,2)
    OUTWARDS wrt ANTERIOR during (2,3)

TRANSLATING – time interval (6,10)
rate (mm/sec) → 15, 33, 42, 15
trajectory (radians) → 1.24, 4.19, 5.50, 1.24
specializations:

INWARDS wrt ANTERIOR during (6,7)
OUTWARDS wrt ANTERIOR during (7,9)

TRANSLATING – time interval (14,15)
rate (mm/sec) → 15
trajectory (radians) → 1.24
specializations:
INWARDS wrt ANTERIOR during (14,15)

others
NO MOTION during (5,6)
NO MOTION during (10,14)
NO MOTION during (15,16)
exceptions to normal detected:
MODERATELY HYPOKINETIC – CONTRACTION wrt ANTERIOR during (1,2)

ANTERIOR segment exhibits:
TRANSLATING – time interval (0,1)
rate (mm/sec) → 45
trajectory (radians) → 4.71
specializations:
INWARDS wrt VENTRICLE during (0,1)

TRANSLATING – time interval (3,8)
rate (mm/sec) → 30, 15, 21, 15, 15
trajectory (radians) → 1.24, 1.24, 2.36, 2.36, 4.71
specializations:
INWARDS wrt VENTRICLE during (3,8)

TRANSLATING – time interval (9,11)
rate (mm/sec) → 15, 15
trajectory (radians) → 1.24, 1.24,
specializations:
OUTWARDS wrt VENTRICLE during (9,11)

TRANSLATING – time interval (13,16)
rate (mm/sec) → 15, 15, 15, 15
trajectory (radians) → 0.00, 3.14, 0.00, 0.00
specializations:
OUTWARDS wrt VENTRICLE during (14,16)

VOLUME CHANGE – time interval (0,16)
rate (ml/sec) → −1.2, −66, 33, −48, −30, −12, −3, 27, 12,
−12, 21, 33, −6, −6, 2.1, 39, 39
specializations:
CONTRACTING during (0,1)
UNIFORMLY CONTRACTING during (0,2)

SYSTOLE during (3,6)
EXPANDING during (2,3)
UNIFORMLY CONTRACTING during (3,5)
CONTRACTING during (6,7)
DIASTOLE during (7,9)
CONTRACTING during (9,10)
DIASTOLE during (10,12)
CONTRACTING during (12,14)
DIASTOLE during (14,16)

PERIMETER CHANGE – time interval (0,8)
rate (mm/sec) → 45, −60, 30, −45, −45, −30, −30, 90
specializations:
LENGTHENING during (0,1)
SHORTENING during (1,2)
LENGTHENING during (2,3)
SHORTENING during (3,7)
LENGTHENING during (7,8)

PERIMETER CHANGE – time interval (9,10)
rate (mm/sec) → −30
specializations:
SHORTENING during (9,10)

PERIMETER CHANGE – time interval (13,16)
rate (mm/sec) → 30, −30, 45, 45
specializations:
LENGTHENING during (13,14)
SHORTENING during (14,15)
LENGTHENING during (15,16)

others
NO TRANSLATION during (1,3)
NO TRANSLATION during (8,9)
NO PERIMETER CHANGE during (8,9)
NO PERIMETER CHANGE during (10,13)
NO TRANSLATION during (11,13)
exceptions to normal detected:
SEVERELY HYPOKINETIC – CONTRACTION wrt VENTRICLE during (2,6)
TOO SHORT SYSTOLE during (7,7)
MILDLY POOR SYSTOLE during (7,7)
SEVERELY HYPOKINETIC – EXPANSION wrt VENTRICLE during (8,14)

APICAL segment exhibits:
TRANSLATING – time interval (1,6)
rate (mm/sec) → 33, 33, 60, 48, 33

trajectory (radians) → 2.08, 1.05, 1.24, 1.99, 2.08
specializations:
    INWARDS wrt VENTRICLE during (1,6)

TRANSLATING – time interval (7,10)
rate (mm/sec) → 60, 51, 15
trajectory (radians) → 4.71, 4.09, 3.14
specializations:
    OUTWARDS wrt VENTRICLE during (7,9)
    INWARDS wrt VENTRICLE during (9,10)

TRANSLATING – time interval (11,14)
rate (mm/sec) → 33, 15, 21
trajectory (radians) → 5.81, 4.71, 5.50
specializations:
    OUTWARDS wrt VENTRICLE during (11,14)

TRANSLATING – time interval (15,16)
rate (mm/sec) → 33, 33
trajectory (radians) → 5.81, 5.81
specializations:
    OUTWARDS wrt VENTRICLE during (15,16)

VOLUME CHANGE – time interval (0,6)
rate (ml/sec) → −12, −72, −24, −60, −42, −36
specializations:
    CONTRACTING during (0,1)
    UNIFORMLY CONTRACTING during (0,2)
    SYSTOLE during (1,6)
    UNIFORMLY CONTRACTING during (3,6)

VOLUME CHANGE – time interval (7,16)
rate (ml/sec) → 54, 24, 15, 15, 48, 36, 9, −15, 45, 45
specializations:
    DIASTOLE during (7,14)
    UNIFORMLY EXPANDING during (7,8)
    UNIFORMLY EXPANDING during (9,13)
    CONTRACTING during (14,15)
    DIASTOLE during (15,16)

PERIMETER CHANGE – time interval (0,6)
rate (mm/sec) → 15, −75, −30, −60, −45, −45
specializations:
    LENGTHENING during (0,1)
    SHORTENING during (1,6)

PERIMETER CHANGE – time interval (7,16)

rate (mm/sec) → 15, 30, 30, 30, 60, 45, 15, 15, 15, 15
specializations:
    LENGTHENING during (7,13)
    SHORTENING during (13,14)
    LENGTHENING during (14,16)

others
NO TRANSLATION during (0,1)
NO MOTION during (6,7)
NO TRANSLATION during (10,11)
NO TRANSLATION during (14,15)
exceptions to normal detected:
SEVERELY HYPOKINETIC – EXPANSION wrt VENTRICLE during (10,11)
SEVERELY HYPOKINETIC – EXPANSION wrt VENTRICLE during (14,15)

POSTERIOR segment exhibits:
TRANSLATING – time interval (0,6)
rate (mm/sec) → 15, 48, 33, 21, 33, 33
trajectory (radians) → 1.24, 0.95, 1.05, 0.77, 1.05, 1.05
specializations:
    INWARDS wrt VENTRICLE during (0,3)
    OUTWARDS wrt VENTRICLE during (3,4)
    INWARDS wrt VENTRICLE during (4,6)

TRANSLATING – time interval (7,16)
rate (mm/sec) → 15, 30, 21, 48, 21, 21, 15, 15, 15, 15
trajectory (radians) → 4.71, 4.71, 3.92, 3.92, 3.92,
                       3.92, 4.71, 0.00, 3.14, 3.14
specializations:
    OUTWARDS wrt VENTRICLE during (8,14)
    INWARDS wrt VENTRICLE during (14,15)

VOLUME CHANGE – time interval (0,6)
rate (ml/sec) → −33, −90, −15, −75, −96, −78
specializations:
    SYSTOLE during (1,6)

VOLUME CHANGE – time interval (7,16)
rate (ml/sec) → 5, 6, 27, 75, 111, 21, 15, 60, 21, 21
specializations:
    DIASTOLE during (7,16)
    UNIFORMLY EXPANDING during (9,12)

PERIMETER CHANGE – time interval (0,2)
rate (mm/sec) → −45, −15
specializations:

SHORTENING during (0,2)

PERIMETER CHANGE – time interval (3,6)
rate (mm/sec) → −30, −90, −15
specializations:
SHORTENING during (3,6)

PERIMETER CHANGE – time interval (7,12)
rate (mm/sec) → −45, −30, 30, 75, 75
specializations:
SHORTENING during (7,9)
LENGTHENING during (9,12)

PERIMETER CHANGE – time interval (13,16)
rate (mm/sec) → 15, 60, 15, 15
specializations:
LENGTHENING during (13,16)

others
NO PERIMETER CHANGE during (2,3)
NO MOTION during (6,7)
NO PERIMETER CHANGE during (12,13)

LEFT VENTRICLE exhibits:
TRANSLATING – time interval (0,6)
rate (mm/sec) → 15, 33, 15, 33, 1, 21
trajectory (radians) → 4.71, 1.05, 1.24, 1.05, 1.24, 2.36

TRANSLATING – time interval (7,15)
rate (mm/sec) → 15, 15, 15, 15, 15, 15, 15, 15
trajectory (radians) → 4.71, 4.71, 4.71, 3.14, 4.71, 3.14,
0.00, 4.71

VOLUME CHANGE – time interval (0,16)
rate (ml/sec) → −57, −216, −75, −168, −186, −138, 2, 120, 57, 54,
120, 162, 90, 27, 45, 90, 90
specializations:
UNIFORMLY CONTRACTING during (0,1)
SYSTOLE during (1,6)
UNIFORMLY CONTRACTING during (2,6)
UNIFORMLY EXPANDING during (7,11)
DIASTOLE during (7,16)
UNIFORMLY EXPANDING during (12,14)
UNIFORMLY EXPANDING during (15,16)

PERIMETER CHANGE – time interval (0,6)
rate (mm/sec) → 15, −150, 15, −165, −165, −105

specializations:
    LENGTHENING during (0,1)
    SHORTENING during (1,2)
    LENGTHENING during (2,3)
    SHORTENING during (3,6)

PERIMETER CHANGE – time interval (7,8)
rate (mm/sec) → 90
specializations:
    LENGTHENING during (7,8)

PERIMETER CHANGE – time interval (9,16)
rate (mm/sec) → 30, 75, 150, 60, 15, 60, 60, 60
specializations:
    LENGTHENING during (9,16)

WIDTH CHANGE – time interval (0,16)
rate (mm/sec) → −15, −15, −60, −15, −60, −60, −60, −60, −60, 60, 75,
45, 45, 45, 45, −15, −15

LENGTH CHANGE – time interval (0,16)
rate (mm/sec) → 30, −45, −15, −60, −60, −30, −30, 45, 15, 15, 15
45, 45, 45, 45, 45, 45

others
ISOMETRIC CONTRACTION during (0,1)
NO TRANSLATION during (6,7)
NO PERIMETER CHANGE during (6,7)
NO PERIMETER CHANGE during (8,9)
NO TRANSLATION during (15,16)
exceptions to normal detected:
MILDLY DYSKINETIC – CONTRACTION during (3,4)
ISCHEMIC ANTERIOR ISOMETRIC RELAXATION during (6,7)
SEVERELY POOR SYSTOLE during (7,7)
MODERATELY DYSKINETIC – EXPANSION during (9,15)

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