Should a Fixed External Reference System Be Used to Analyze Left Ventricular Wall Motion?

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SUMMARY To investigate whether a fixed external reference system should be used to most accurately describe regional left ventricular wall motion, we used vectors to analyze a simple model of ventricular contraction. If measured in a fixed external reference system, motion of implanted radopaque midwall markers may contain translational as well as contractile components. Therefore, comparisons of different reference systems that use marker motion measured in a fixed reference system as a standard will be biased unless proper corrections are included. We conclude that evidence to date does not indicate that the use of a fixed reference system is superior to other methods for analyzing regional ventricular wall motion.

THE USE of contrast ventriculography to quantify left ventricular segmental wall motion has resulted in the development of methods to measure regional endocardial movement. As the methods have proliferated, the accuracy of these alternative approaches in separating abnormal from normal wall motion has been compared.1-4 These comparisons are difficult to evaluate for the same reasons that have led to the development of multiple methods of analysis: (1) By examining a two-dimensional silhouette of the three-dimensional ventricle, one cannot determine with certainty which segments exhibit truly abnormal motion and to what extent the motion is abnormal. (2) There is a choice between external and internal reference systems. (3) The ventricle has multiple landmarks that may be used to superimpose a reference grid system. (4) There are choices between measurements (segmental area, hemispherical lengths, and radial lengths), the number of radii, chords or regions to be measured, and the frequency of the measurement (end-diastole and end-systole or frame-by-frame).

Ingels and co-workers5 reported that left ventricular midwall dynamics were measured most accurately in the 30° right anterior oblique plane by a fixed external reference system using polar co-
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five coordinates. Their conclusions were based on a study in which five methods for describing wall motion were evaluated for measurement accuracy. To assess differences between fixed and internal reference systems, they used the motion of surgically implanted midwall radiopaque markers as a standard. They compared the magnitude of "error" between measurements of marker motion obtained in a fixed external reference system and measurements of marker motion defined by the alternative systems. However, measurements of marker movement using internal reference systems were not corrected for translation of that reference system within the fixed system. We feel that this procedure added an extra component to the calculated error for all internal systems and biased the results of their study.

Methods and Results

To facilitate understanding of the issues involved, we will use an example to show that marker motion measured in a fixed external coordinate system may not agree with marker motion due to contraction if there is movement of the entire ventricle. Then, we will show how the error defined by Ingels et al. includes (rather than excludes) any motion of the reference system that is being evaluated. We will use vectors to illustrate the concept that marker motion measured in a fixed external coordinate system consists of contractile and translational components.

Figure 1 is a simplified model of ventricular contraction, with four markers at specific locations around two circles. In this model, there is contraction ($r_2 = 0.90r_1$) as well as translation (the center of the circle moves from $P(1)$ to $P(2)$). Using a fixed external reference system, the motion of the four markers is represented by the vectors $\vec{a}$, $\vec{b}$, $\vec{c}$ and $\vec{d}$, and the motion of the center of the circle is denoted by the vector $\vec{p}$. If there is no translation of the circle, then $\vec{p} = 0$, and the points $P(1)$ and $P(2)$ coincide. If there is translation of the circle, the magnitudes of the vectors representing marker motion in the fixed external reference system are not equal (e.g., $|\vec{a}| \neq |\vec{c}|$). However, since both contours are circles, actual contractile motion for each marker must be equal.

Figure 2 illustrates an approach which may be used to reconcile this discrepancy. The vector $\vec{a}$, which represents the motion of marker A in the fixed external coordinate system, can be represented with respect to two alternative reference systems: the origin of the fixed external reference system or a reference point (such as the center of the circle) that is defined internally using ventricular landmarks that may move with respect to the fixed coordinate system. Using the fixed external reference system, the marker motion may be expressed as

$$\vec{a} = \vec{A}_2 - \vec{A}_1$$  (1)

where the vectors $\vec{A}_2$ and $\vec{A}_1$ are drawn from the origin.

**Figure 1.** A simple model of ventricular contraction in which there is also translation of the entire ventricle with respect to the laboratory. The radius of the smaller circle is 10% less than that of the larger circle. The center of the circle moves from $P(1)$ ("end-diastole") to $P(2)$ ("end-systole") in the fixed external coordinate system. The motion of four markers in the fixed system is represented by vectors $\vec{a}$, $\vec{b}$, $\vec{c}$ and $\vec{d}$. Although the contractile motion for each marker should be equal, the magnitudes of the four vectors are different when measured in the fixed reference system. These differences are attributable to the translation and can be resolved by subtracting the vector $\vec{p}$ from each marker vector.
The location of the marker in the fixed reference system can also be specified by drawing a vector from its origin to the internal reference point, and then from the internal reference point to the marker:

$$\vec{A}_2 = \vec{P}_2 + \vec{L}_2$$  \hspace{1cm} (2a)

and

$$\vec{A}_1 = \vec{P}_1 + \vec{L}_1.$$  \hspace{1cm} (2b)

The magnitude of the vector $\vec{L}_1$ is the distance from the internal reference point $P(1)$ to the position of marker $A$ at end-diastole and the magnitude of the vector $\vec{L}_2$ is the distance from the internal reference point at end-systole to the marker position at end-systole. When an internal reference system is used instead of a fixed external reference system, the difference between $\vec{L}_2$ and $\vec{L}_1$ is the measured marker motion.

The equation for the motion of the internal reference point is $\vec{P} = \vec{P}_2 - \vec{P}_1$. Combining this equation with equations $2a$ and $2b$, equation $1$ may be rewritten as:

$$\vec{a} = \vec{L}_2 - \vec{L}_1 + \vec{p}.$$  \hspace{1cm} (3)

which also can be written

$$\vec{p} = \vec{a} - (\vec{L}_2 - \vec{L}_1).$$  \hspace{1cm} (4)

In the work of Ingels and co-workers, "error (E) was defined as the absolute value of the difference between standard marker motion (marker motion measured in a fixed external [laboratory] reference system) and marker motion measured by each method." Using the nomenclature applied to figure 2, the absolute magnitude of vector $\vec{a}$ (designated $|\vec{a}|$) is the standard marker motion, and the difference in length between vectors from an internal reference point to the marker is measured marker motion $|\vec{L}_2| - |\vec{L}_1|$. Their definition of the magnitude of error due to measurements for a single marker is thus written

$$E = |\vec{a}| - |\vec{L}_2| - |\vec{L}_1|.$$  \hspace{1cm} (5)

By comparing the scalar equation $5$ with the vector equation $4$, one can see that if there is motion of the internal reference system with reference to the fixed external reference system ($\vec{p} \neq 0$), there will automatically be a contribution to the error term (E) that was defined by Ingels et al. This contribution will be equal to the magnitude of $\vec{p}$ and will be added to other components which originate because scalar rather than vector quantities are used. Therefore, measurements of marker motion made when using an internal reference system will contain an added component of "error" when they are compared to measurements made with a fixed external reference system; the magnitude of this contribution to the "error" term will be equal to the movement of the origin of the internal system measured in the external system. Ingels et al. compared angiographic measurements to those of the markers made with the external system; thus, it is not surprising that the angiographic measurements made with the external system had the smallest total error and those made with internal reference systems had larger total errors.

**Discussion**

Using a simple spherical model of contraction, we have attempted to show that marker motion measured in a fixed external reference system does not correspond to actual contractile motion if there is translation of the entire ventricle in the fixed external coordinate system. Using vector notation, we have also illustrated that any motion of an internal reference system was directly added to the error term when Ingels et al. compared different reference systems using measurements with a fixed external
system as their standard. Because one of the primary purposes of ventriculography is to examine contraction and relaxation of the ventricle, we think it is appropriate to judge alternative methods by their ability to describe the contractile component of motion rather than total motion. Therefore, translational motion of the ventricle should be compensated for. We conclude that Ingels et al. have not shown that fixed external reference systems are superior to internal moving reference systems.

We have used a simple circular model of the ventricle to illustrate the concepts discussed in this paper. Such a model, although not suitable for actually describing segmental wall motion, was used because it provides an easy means of identifying a reference point. However, all of the models for internal reference systems used to describe segmental ventricular wall motion do define (implicitly or explicitly) a reference point. This reference point generally moves to some extent, as the ventricular landmarks move due to translation, rotation and contraction or relaxation.

In previous studies that compared alternative reference systems, the goal was to determine which scheme (if any) for defining the reference point provides the most accurate measurement of contractile motion.

Aside from some additional issues (rotation in and out of the silhouette plane) originally discussed by Ingels et al., we feel that the implanted marker approach provides some clearcut advantages for a comparison study. Equations 3 and 4 are exact vector equations that introduce no measurement errors, because translation of the ventricle is taken into account. A substantial proportion of measurement error apparently occurs when scalar quantities representing the magnitudes of vectors are added or subtracted without regard to the direction of the vectors. If vector equations were used, there would be no preferred point for the origin of a fixed external reference system. We speculate that Ingels' choice of 69% of the distance along the long axis of the end-systolic frame as the optimal origin for a fixed reference system resulted because this location happened to minimize the differences between the scalar and vector descriptions of motion. Because the definition of error used to find this optimum reference point was the same as was used in the comparison paper of Ingels et al., we believe that the original results regarding optimal reference points should be reevaluated.

We believe that the scalar quantity \(|\mathbf{L}_2\bullet - |\mathbf{L}_1\bullet|\) as the measured motion in any reference system is appropriate because, by definition, one must always compare measurements for a specific chord, radius or hemiaxis. Because of this constraint, the vectors \(\mathbf{L}_2\) and \(\mathbf{L}_1\) should be in the same direction, and scalar subtraction would be justified. Ingels et al. noted that when the vectors are constrained to be in the same direction, some error is encountered because the vectors will not always exactly follow the markers.

Given that the use of scalars may be appropriate to define the measured marker motion (with respect to a given reference system), we will discuss what Ingels et al. characterized as standard marker motion. The motion of the markers as measured in the fixed external system is a combination of contractile and translational motion. To separate translational from contractile motion, standard marker motion should be redefined as the vector difference \(\mathbf{a} - \mathbf{p}\). If this convention were adopted, the resulting formula for error would be \(E = |\mathbf{a} - \mathbf{p}| - |\mathbf{L}_2\bullet - |\mathbf{L}_1\bullet|\). If \(\mathbf{p}\) were subtracted from each of the four vectors (\(\mathbf{a}, \mathbf{b}, \mathbf{c}\) and \(\mathbf{d}\)) in our model, the result would be four vectors of equal magnitude equivalent to the amount of radial contraction. A comparison of reference systems using this correction would be based primarily on the contractile component of standard marker motion.

Another problem of using measured marker motion as a standard is caused by rotation of the ventricle in the plane of the angiogram. If the smaller circle in figure 1 was rotated clockwise through a large angle, the true contractile motion of the markers would not be represented by the magnitude of the vectors alone. Rotation out of the plane of the silhouette presents similar problems. Even though both types of rotations may cause error, these errors were discussed by Ingels et al., and it is not evident that they could systematically bias a comparison study to the extent caused by the problems discussed in this paper.

In summary, conclusive evidence is not available that indicates that any particular reference system is superior to others.

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