Comparative Accuracy of Apical Biplane Cross-sectional Echocardiography and Gated Equilibrium Radionuclide Angiography for Estimating Left Ventricular Size and Performance

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SUMMARY To compare measurements of left ventricular size and performance obtained by apical biplane cross-sectional echocardiography (CSE) and gated equilibrium radionuclide angiography (RNA), we studied 70 patients, all of whom had single-plane and 30 of whom had biplane left ventricular cineangiography. Widescope, phased-array CSE images were obtained from two orthogonal apical views and left ventricular volumes were calculated using a microprocessor-controlled, video light-pen system programmed for a Simpson’s rule algorithm. The average CSE end-diastolic volume (EDV) for all 70 patients was less than the single-plane angiographic value of 176 ± 68 ml (p < 0.001, r = 0.80). The average CSE end-systolic volume (ESV) of 78 ± 57 ml was not different from the angiographic value of 84 ± 70 ml (r = 0.88). The average CSE and single-plane angiographic ejection fraction (EF) values of 55 ± 16% and 57 ± 19% were not different (r = 0.90). In the 30 patients who underwent biplane angiography, the average CSE EDV of 166 ± 62 ml was less than the biplane angiographic EDV of 217 ± 87 ml (p < 0.001, r = 0.81), and the average CSE ESV of 89 ± 69 ml was also less than the angiographic value of 114 ± 89 ml (p < 0.001, r = 0.92). The average CSE LV EF of 52 ± 19% was not different from the biplane angiographic value of 52 ± 17% (r = 0.87). In the 25 patients who underwent CSE, RNA and biplane angiography, the average LVEF values were 51 ± 20%, 46 ± 18% and 50 ± 17%, respectively, and the CSE and RNA values correlated with the biplane angiographic value (r = 0.90 and 0.93, respectively). Therefore, apical biplane CSE estimates of left ventricular volume correlate linearly with single-plane and biplane cineangiographic determinations, and this CSE technique compares favorably with gated equilibrium RNA for assessing left ventricular performance.

SEVERAL noninvasive techniques have been compared with contrast cineangiography for evaluating left ventricular size and performance. Calculations of left ventricular volumes and ejection fraction (EF) by standard time-motion (M-mode) echocardiography have compared reasonably well with measurements obtained by contrast ventriculography in patients with symmetrically contracting ventricles. Cross-sectional echocardiography has been shown to be more accurate than M-mode echocardiography for estimating left ventricular cineangiographic size and performance, especially in patients with coronary artery disease. However, these early cross-sectional echocardiographic studies were hampered technically by the necessity of tracing images from a video screen, by the necessity of overlapping tracings to create composite images of the left ventricle, and by the use of geometric assumptions and correction factors to compensate for the lack of ideal anatomic sections.

Time-activity radionuclide angiographic techniques, which are relatively independent of geometry, have also been shown to assess left ventricular function reliably in patients with various cardiac disorders.

The purposes of the present investigation were (1) to obtain two orthogonal apical long-axis views of the left ventricle using a wide-angle, phased-array, cross-sectional echocardiograph and to determine left ventricular size and performance using a commercially available, microprocessor-controlled, video light-pen system and a Simpson’s rule algorithm; (2) to compare these measurements with biplane and single-plane contrast cineangiographic determinations of left ventricular volumes and EF; and (3) to assess the comparative accuracy of cross-sectional echocardiographic and gated equilibrium radionuclide angiographic estimations of left ventricular cineangiographic EF.

Methods

Patients

Seventy patients were selected for this study on the basis of technically adequate left ventricular cineangiographic and cross-sectional echocardiographic studies. Sixty of these patients also had gated equilibrium radionuclide angiographic studies. Both
noninvasive studies were performed within 48 hours of catheterization without change in patient status or medical regimen. All 70 patients were male, ages 20–68 years (mean 52 years). Fifty-four of the 70 patients had coronary artery disease, and 30 of these had left ventricular wall motion abnormalities by cineangiography. In addition to coronary artery disease, eight patients had mitral regurgitation and four had aortic stenosis. Of the 16 patients without coronary artery disease, six had aortic regurgitation, three had mitral regurgitation, one had an idiopathic cardiomyopathy, and six had atypical chest pain syndromes with normal coronary arteries.

**Cineangiography**

Left ventricular contrast ventriculography was performed in all 70 patients in the 30° right anterior oblique (RAO) position with a power injection of 35–50 ml of Renografin-76 (meglumine diatrizoate) at 15 ml/sec and 400–500 lb/in². Thirty patients also underwent left ventriculography in the 60° left anterior oblique (LAO) position. Cine frames were exposed at 60 frames/sec. A grid of 1-cm squares was used to correct for magnification. The end-diastolic frame was chosen as that corresponding to the point of maximal outward displacement of the left ventricle and the end-systolic frame was taken at the point of maximal inward motion. The left ventricular long axis was measured from the apex to the midpoint of the aortic valve plane for both views. Single-plane 30° RAO angiographic volumes were calculated by the method of Kasser and Kennedy,18 and the biplane volumes were calculated by the method of Cohn et al.19 and corrected to true volumes using the regression equation developed by Wynne et al.17 EF was calculated in the standard manner.

**Cross-sectional Echocardiography**

Cross-sectional echocardiograms were obtained in all patients using a Varian V-3000 ultrasonograph with a 1.2 × 1.3-cm transducer composed of 32 precisely mounted piezoelectric crystals in a tight linear array operating at 2.25 MHz. The transducer was electronically controlled through an 84° minimum sector angle at 30 sweeps/sec at depths of 15 or 21 cm.

Two mutually perpendicular long-axis planes through the left ventricle were obtained in each patient from a single apical transducer position described by Silverman and Schiller19 and depicted with anatomic correlates by Tajik et al.18 Patients were positioned in the supine or left lateral decubitus position and the transducer was placed over the point of maximal apical pulsation. From this position, the apical four-chamber view was provided by a plane transecting the heart from apex to base perpendicular to the interventricular septum and below the aortic valve (fig. 1). Without changing the transducer position on the chest wall, the apical two-chamber view (RAO equivalent) of the left ventricle was obtained by rotating the transducer 90° clockwise. Thus, the beam transected the heart from apex to base parallel to the interventricular septum through the left-sided chambers (fig. 1). These two views of the left ventricle were chosen for volume calculations because (1) high-quality left ventricular images in both long-axis planes were obtained more frequently from this single transducer position (80–90% of all patients examined) than from other transducer placements; (2) the acquisition time for two high-quality left ventricular images from this single transducer position was less than 5 minutes; and (3) these two orthogonal views have a similar long axis, which best approximates the geometric requirements for volume calculations using the Simpson's rule algorithm. The clarity of left ventricular endocardial images in both views was optimized by adjusting the gray scale before recording the images on a Sanyo VTC 7100 video cassette recorder. All images were recorded in real time simultaneously with vertical and horizontal 1-cm calibration grids and an ECG.

Images were processed by the Varian V-3000 microprocessor-controlled light-pen system. This system was designed specifically for the Varian phased-array ultrasonograph and contains fixed programs. Calibration of the video light-pen system was performed for each cross-sectional left ventricular image being analyzed using the simultaneously recorded grid system. All images were viewed in real-time, slow-motion, and stop-frame format. Using the stop-frame mode and the reference ECG, an observer used the light pen to identify left ventricular end-diastolic endocardial borders and to define the long axis at the peak of the R wave, and end-systolic endocardial borders and long-axis measures near the end of the T wave at maximal inward motion of the left ventricle for both apical views. The visual integrity of endocardial images was slightly reduced during the stop-frame mode because of a loss of line information. In tracing the cross-sectional echocardiographic endocardial borders with the light pen, minor irregularities due to decreased visual integrity of the left ventricular endocardium were interpolated from the previously reviewed real-time and slow-motion images. The long axes were measured from the apex to the midpoint of the mitral valve plane for both apical views.

The end-diastolic and systolic endocardial borders identified by the light-pen system for each apical view inscribed two mutually perpendicular cross-sectional planar areas that were individually calculated and averaged for a minimum of three sinus beats, as were the end-diastolic and systolic long-axis length measurements for both views, using the programs in the microprocessor unit. From these measurements, a Simpson's rule algorithm was used to calculate end-diastolic volume (EDV) and end-systolic volume (ESV).20 This algorithm, also contained in the microprocessing unit, is derived by partitioning the average long-axis length into 20 increments, each of which defines a parallel slice through the left ventricle perpendicular to the common axis. This model assumes that each slice is one in a stack of elliptical cylinders of incremental height. Each cylinder has an elliptical cross-sectional area with major and minor axes defined by the average width of the original endo-
cardiac outlines obtained from the two mutually perpendicular apical cross-sectional views. The area of each of these ellipses is multiplied by the incremental height to obtain a volume for each slice, and the volumes of all slices are then summed to obtain the total left ventricular volume at end-diastole and end-systole. EF was then calculated in the standard manner. The average processing time for one left ventricular study using this system was 15-20 minutes.

Radionuclide Angiography

Resting equilibrium radionuclide angiography was performed in the 45° LAO position with a 10° caudal tilt after i.v. injection of 20 mCi of technetium-99m-labeled human serum albumin. A 37 photomultiplier tube gamma scintillation camera equipped with a low-energy, all-purpose, parallel-hole collimator was used for image acquisition. The pulse-height analyzer was centered at 140 keV with a 20% window. Image acquisition occurred under electrocardiographic control such that count information in consecutive corresponding 40-msec segments of each cardiac cycle was summed and stored as images in the computer core memory (Medical Data Systems) until each frame contained at least 300,000 counts. Nine-point spatial smoothing was then performed on each image of the composite cycle. A semiautomated computer program (MDS MUGE) then defined a left ventricular region of interest for each image, determined the activity in each region of interest during the cycle, and generated a time-activity curve from these regions of interest after background subtraction was defined from an end-systolic paraventricular region. Operator intervention to modify edge detection was permitted, and a left ventricular time-activity curve and end-diastolic and end-systolic counts were obtained. EF was calculated by subtracting end-systolic from end-diastolic counts and dividing by the diastolic counts.

Data Analysis

All three techniques were analyzed independently by different investigators without knowledge of the results of the other two techniques. In addition, 10 randomly selected cross-sectional echocardiograms were analyzed by one of the authors on two different occasions and the same 10 echocardiograms were analyzed independently by another investigator. Intra- and interobserver variability were then assessed; intra-
and interobserver variability in the radionuclide angiographic EF measurements were evaluated in a similar manner. Paired t tests were used to compare the mean cross-sectional echocardiographic and angiographic volume and EF data. To test for differences between the mean EF values obtained by all three techniques, an analysis of variance with covariance and a Newman-Keuls mean comparison test were used. Linear regression analyses were performed by the least-squares method, and 95% confidence intervals for the data and standard errors of the estimate were obtained in the standard manner. Also, a Z-transformation was used to test for differences between correlation coefficients. A p value < 0.05 was considered significant for all statistical methods. Left ventricular EF data for the 25 patients who had cross-sectional echocardiography, radionuclide angiography and biplane cineangiography were further analyzed to assess the predictive value and overall accuracy of each noninvasive method for estimating normal and abnormal left ventricular cineangiographic performance. A normal angiographic EF was considered to be greater than 52%, and an abnormal EF, less than 51%.

Results

Cross-Sectional Echocardiographic and Cineangiographic Comparison

The cross-sectional echocardiographic left ventricular EDV in all 70 patients averaged 158 ± 56 ml (± sd) and was significantly less than the mean single-plane (30° RAO) cineangiographic EDV of 176 ± 68 ml (p < 0.001, r = 0.80) (fig. 2A). The average cross-sectional echocardiographic end-systolic volume (ESV) of 78 ± 57 ml was not different from the mean angiographic ESV of 84 ± 70 ml (r = 0.88) (fig. 2B). The cross-sectional echocardiographic left ventricular EF averaged 55 ± 16% and was not different from the mean single-plane angiographic EF of 57 ± 19% (r = 0.90) (fig. 2C).

Thirty of the 70 patients (43%) underwent biplane cineangiography for identification of possible wall motion abnormalities due to coronary artery disease. In these patients, the average cross-sectional echo-
cardiographic EDV of 166 ± 62 ml was significantly less than the mean biplane angiographic EDV of 217 ± 75 ml \( (p < 0.001, r = 0.81) \) (fig. 3A). In addition, the cross-sectional echocardiographic ESV averaged 89 ± 69 ml and was significantly less than the mean biplane angiographic ESV of 114 ± 89 ml \( (p < 0.001, r = 0.92) \) (fig. 3B). The average cross-sectional echocardiographic left ventricular EF of 52 ± 19% was not different from the mean biplane angiographic EF of 52 ± 17% \( (r = 0.87) \) (fig. 3C).

Reproducibility Data

The intraobserver variability in cross-sectional echocardiographic EDV, ESV and EF was negligible \( (r = 0.97, 0.98 \) and 0.96, respectively). The average intraobserver differences in left ventricular EDV, ESV and EF were 10%, 12.4% and 5.1%, respectively. The interobserver variability was larger for these measurements \( (r = 0.85, 0.98, \) and 0.90, respectively). The average interobserver differences in left ventricular EDV, ESV and EF were 26%, 22%, and 8.1%, respectively. The intra- and interobserver variability in radionuclide EF measures was similar to that of the corresponding cross-sectional echocardiographic comparisons \( (r = 0.94 \) and 0.95, respectively).

**Comparative Ejection Fraction Analysis**

The left ventricular EF data were initially analyzed for the 60 patients who underwent both radionuclide and single-plane (30° RAO) contrast angiography. The mean cross-sectional echocardiographic left ventricular EF estimate of 54 ± 17% was not different from the average single-plane angiographic EF of 56 ± 20% \( (r = 0.91) \) (fig. 4A). However, the mean equilibrium radionuclide angiographic EF of 50 ± 18% was significantly less than the single-plane angiographic EF \( (p < 0.01, r = 0.81) \) (fig. 4B). The mean radionuclide angiographic EF value was also significantly less than the average cross-sectional echocardiographic EF measurement \( (p < 0.01, r = 0.81) \) (fig. 4C). Moreover, the correlation coefficient for the
radionuclide and single-plane angiographic left ventricular EF comparison was significantly lower than that of the cross-sectional echocardiographic and angiographic EF comparison ($p < 0.05$).

The left ventricular ejection fraction data were then compared in the 25 patients who underwent biplane cineangiography. The cross-sectional echocardiographic EF in these patients averaged $51 \pm 20\%$ and was not different from the mean biplane angiographic EF of $50 \pm 17\%$ ($r = 0.90$) (fig. 5A). The equilibrium radionuclide angiographic EF averaged $46 \pm 18\%$ and was significantly less than the mean biplane angiographic EF ($p < 0.05, r = 0.93$) (fig. 5B). The average radionuclide angiographic EF value was significantly less than the mean cross-sectional echocardiographic

left ventricular EF estimate ($p < 0.01, r = 0.88$) (fig. 5C).

Both the biplane cineangiographic and cross-sectional echocardiographic EF estimates were normal in 12 patients and abnormal in nine. Four estimations were discordant (fig. 6A). Therefore, the predictive value of cross-sectional echocardiography for a normal cineangiographic EF was $86\%$ (12 of 14 patients correctly predicted) and the predictive value for an abnormal angiographic EF was $82\%$ (nine of 11). Therefore, the overall accuracy of the echocardiographic method for the angiographic EF measures was $84\%$ (21 of 25). Similarly, both the cineangiographic and equilibrium radionuclide angiographic EF estimates were normal in 10 patients and abnormal in 10. However, five estimations were discordant (fig. 6B). The predictive value for a normal and abnormal left ventricular angiographic EF by equilibrium radionuclide angiography was $90\%$ (10 of 11) and $72\%$ (10 of 14), respectively, and the overall accuracy of the radionuclide method for the angiographic EF was $80\%$ (20 of 25).

**Discussion**

Our data indicate that cross-sectional echocardiog-
raphy underestimates single-plane and biplane left ventricular cineangiographic EDV and ESV. However, the correlations between the cross-sectional echocardiographic and cineangiographic EDV and ESV estimates were linear. Our data also show that cross-sectional echocardiographic measurements of left ventricular EF are similar to and correlate with both the single-plane and biplane cineangiographic EF values.

Carr and co-workers\(^5\) initially reported a correlation of 0.46 between cross-sectional echocardiographic and cineangiographic EDV indexes. Technical problems with this early work may explain their relatively low correlation. First, they traced the left ventricular images from a video screen, which may have introduced a parallax error. Second, the small sector angle they used required overlapping tracings in some views to create composite images of the left ventricle. Further, multiple combinations of views were used to calculate volume, depending on which views were technically adequate in each patient. Schiller and co-workers,\(^7\) using a different technique, reported that cross-sectional echocardiography substantially underestimated angiographic EDV and ESV by 30% and 33%, respectively, but correlated with the biplane cineangiographic measurements. However, these authors also used images traced from a video screen, and because the conditions for using a modified Simpson’s rule algorithm were not met by the anatomic views obtained, they introduced a correction factor to adjust the calculated cross-sectional echocardiographic and angiographic volumes. Parisi and co-workers\(^7\) reported that cross-sectional echocardiographic volume calculations obtained using a geometric model of the left ventricle based on a modification of Simpson’s rule correlated with single-plane (30° RAO) angiographic EDV and ESV, but the echocardiographic technique again markedly underpredicted the volumes. Their volume estimates were particularly poor in left ventricles whose actual shape might have

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**FIGURE 5.** (A) The cross-sectional echocardiographic (CSE) left ventricular ejection fraction (EF) estimates are plotted against the biplane cineangiographic (CINE) values for patients who underwent biplane ventriculography and all three studies. The format is similar to that in figure 2. (B) The radionuclide angiographic (RNA) EF estimates are plotted against the CINE values for patients who underwent biplane ventriculography and all three studies. (C) The CSE left ventricular EF estimates are plotted against RNA values for patients who underwent biplane ventriculography and all three studies.
formance in patients with coronary artery disease and potential wall motion abnormalities by single-plane (30° RAO) cineangiography alone may be misleading.\textsuperscript{16} Therefore, we compared the cross-sectional echocardiographic data with the single-plane and biplane cineangiographic volume and performance measurements. However, Wynne and co-authors\textsuperscript{17} have shown that the biplane oblique volume calculations we used regularly exceed true volume measurements. They attributed this to variation in patient rotation in the LAO projection, which foreshortens the LAO long axis and increases the calculated volume. Even though we sought a constant and reproducible 60° left anterior obliquity, this may not have been obtained exactly in all patients. Moreover, differences in cardiac position would also tend to vary the LAO long-axis measurement. To compensate for these factors, we used the regression equation developed by Wynne et al. to correct the calculated left ventricular volumes to true volumes. Sequential contrast injections may also have affected our volume calculations. Hamby et al.\textsuperscript{24} reported that both normal subjects and patients with varying degrees of coronary artery disease increase their left ventricular EDVs after sequential contrast injections. However, Hamby et al. demonstrated no significant effect on global left ventricular function. Therefore, the biplane angiographic technique we used might have overestimated actual left ventricular volumes, but it should have provided a reasonable estimate of global left ventricular function. Finally, the disparate left ventricular volume measurements by cross-sectional echocardiography and angiography in our study may have been caused by the inherent differences in left ventricular chamber border display by each technique.

The accuracy of volume measurements using the microprocessor-controlled light-pen system has been shown by Eaton and associates in vitro.\textsuperscript{24} We found a close correlation between measurements made by the same observer and by a different observer for left ventricular volumes and EF using the same light-pen system. This reproducibility in measurements of left ventricular volumes and EF is similar to that reported by Schiller et al., who used a different processing method.\textsuperscript{4} Therefore, the microprocessor-controlled light-pen system appears to be an accurate and reproducible method of processing cross-sectional echocardiographic images.

Our data further indicate that the cross-sectional echocardiographic and the gated equilibrium radionuclide angiographic EF estimates correlate with both the single-plane and biplane cineangiographic left ventricular EF measurements. However, the correlation coefficient between the cross-sectional echocardiographic and single-plane angiographic values was significantly higher than that between the radionuclide and single-plane angiographic EF estimates. As shown in figure 4, this difference may be explained by the broader variability in normal EF estimates obtained by the equilibrium radionuclide technique, as observed by other investigators.\textsuperscript{14} Also, the gated

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FIGURE 6. Two-by-two analyses of the ability of cross-sectional echocardiography (CSE) (A) and radionuclide angiography (RNA) (B) to estimate normal (NL) and abnormal (ABNL) biplane cineangiographic (CINE\textsubscript{B}) left ventricular ejection fraction (EF) accurately.

differed from their geometric model. In addition, their use of only single-plane ventriculograms in patients with coronary artery disease and a high probability of wall motion abnormalities has potential problems relative to left ventricular volume calculations.\textsuperscript{16}

We eliminated some of the technical problems described above by using a wide-angle, phased-array ultrasonograph and a single apical transducer position to obtain two mutually perpendicular views of the entire left ventricle with common long axes to fulfill the requirements for the Simpson's rule algorithm. Therefore, we did not need composite images, geometric assumptions or correction factors. Also, processing the images with the microprocessor-controlled video light-pen system eliminated parallax problems. The average underestimation of the single-plane angiographic volumes by our echocardiographic technique was only 7–10%, whereas the underestimation of the biplane volumes, which were performed primarily in patients with coronary artery disease or wall motion abnormalities (26 of 30 patients), was 28%.

We do not know the reason for the systematic underestimation of left ventricular volumes by cross-sectional echocardiography in our study. First, even though we carefully positioned the echocardiographic transducer over the point of maximal apical pulsation, the exact apex of the left ventricle may not have been visualized adequately in all patients. Second, we measured the left ventricular long axis from the apex to midpoint of the mitral valve plane in both cross-sectional echocardiographic views, rather than from the apex to the aortic valve, as has been done by angiographic methods.\textsuperscript{14, 16, 22} For both of these reasons, the left ventricular long axis may have been foreshortened. The Simpson's rule algorithm requires a similar left ventricular long-axis measurement in two mutually perpendicular planes from which volumes are calculated based on the average value for the two long-axis measurements obtained. Therefore, the potential foreshortening of the left ventricular long-axis measurement and difficulty identifying the entire left ventricular apex could have introduced underestimations in the calculated left ventricular volumes.

The evaluation of left ventricular volumes and per-
equilibrium radionuclide technique significantly underestimated both the average single-plane (30° RAO) and biplane angiographic left ventricular EF measurements. However, the cross-sectional echocardiographic and angiographic EF estimates were not different. Nevertheless, these noninvasive techniques for assessing normal and abnormal biplane cineangiographic left ventricular EF were equally accurate. Also, the correlations between the equilibrium radionuclide and single-plane and biplane cineangiographic left ventricular EF values in this study were similar to results reported by several groups who have documented independently the accuracy of the gated equilibrium radionuclide technique for estimating cineangiographic EF.11-14

Radionuclide methods are relatively independent of geometry, and therefore are more accurate than standard M-mode echocardiography for assessing left ventricular performance in patients with cardiac disorders that affect wall motion.25 The early cross-sectional echocardiographic studies also showed that this echocardiographic method was superior to standard M-mode echocardiography for assessing left ventricular performance, primarily in patients with wall motion abnormalities.5, 6 In one study, the cross-sectional echocardiographic and first-pass radionuclide estimates of left ventricular EF compared equally well with cineangiographic EF values.26 One limitation of the cross-sectional echocardiographic method compared with radionuclide methods is the inability to obtain adequate echocardiograms in all patients; we obtained technically adequate studies in 80–90% of all patients evaluated, whereas radionuclide studies can be obtained in almost everyone. However, our data, comparing cross-sectional echocardiography with equilibrium radionuclide angiography, and the data of Folland and co-workers28 clearly demonstrate the ability of cross-sectional echocardiography to provide similar information about left ventricular performance in many patients without exposure to potentially harmful radiation.

Recently, the gated equilibrium radionuclide technique has been shown to provide valuable information about left ventricular performance during exercise in patients with valvular regurgitation27, 28 and coronary artery disease29-32 and sequentially after drug administration.33, 34 Our data indicating the comparatively similar assessment of left ventricular performance by both cross-sectional echocardiography and gated equilibrium radionuclide angiography suggest that cross-sectional echocardiography may also provide valuable information about left ventricular size and performance in patients during exercise or after drug administration. In an initial report by Wann et al.,36 cross-sectional echocardiography during exercise in patients with coronary artery disease provided evidence for myocardial ischemia by detecting the development of new wall motion abnormalities. However, more studies are needed to confirm this initial impression and to document the usefulness of this valuable noninvasive approach in other cardiac disorders.

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M R Starling, M H Crawford, S G Sorensen, B Levi, K L Richards and R A O'Rourke

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