The Effect of Energy Window on Cardiac Ejection Fraction

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ECG gated gamma-ray energy spectra from the left ventricle were created each 50 msec during the cardiac cycle. Nine of ten subjects were studied with a nonimaging NaI probe, and the tenth with a high-resolution Germanium detector. Placing multiple energy windows over the energy spectra, EF was found to vary with the energy window selected. Moving a 20% window across the photopeak produced a roughly linear increase in EF with energy (2.3 EF units per 10 keV increase in energy) in eight of the ten subjects. Dividing the photopeak into a low (126–140 keV) and high-energy (140–154 keV) portion gave significantly different EFs (high energy exceeding low energy by 17%). Increasing the width of a narrow window centered about the photopeak produced negligible change in EF. Examining the energy spectra showed that the small-angle scattered radiation (126–139 keV) was proportionately greater at end systole than at end diastole, after normalizing the spectra to the same photopeak area.

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Changes in the volume and shape of the cardiac chambers may significantly alter the energy distribution of photons emitted by the heart during a gated equilibrium cardiac study. In addition, the presence of scattered radiation from adjacent structures also affects this energy distribution. These alterations in energy distribution could cause quantitative data derived from a gated cardiac study to be a function of the gamma camera energy window used for the acquisition (*1–3*). Such effects might be important in assessing the applicability of asymmetric energy windows to gated cardiac studies. In particular, variations in energy window might result in variability of quantitative data such as ejection fraction (EF). This supposition was investigated by creating ECG gated gamma-ray energy spectra of radiation emitted by the heart at each 50 msec interval of time during the cardiac cycle, from end diastole to end systole. From this series of energy spectra, LV time activity curves (TACs) could be created using any portion of the energy spectrum. Thus, the effects of altering the width or the position of the energy window could be assessed.

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METHODS

Nine consecutive subjects were studied at rest. Each subject's red blood cells were labeled (in vivo) with 20 mCi technetium-99m, preparatory to a standard ECG gated equilibrium cardiac study. A single 3-in.-diameter NaI crystal ("probe"), equipped with a parallel hole collimator (similar to that used in a high-sensitivity gamma camera collimator) was positioned over the subject's left ventricle (LV) in a modified (15° caudad) left anterior oblique (LAO) position. It was necessary to ensure that the probe was placed properly over the LV. This was accomplished by first placing a gamma camera over the subject's chest in the modified LAO position, and positioning a lead annulus, 3-in. inner diameter, to overlay the LV as best possible as determined by observing the real-time cine display. This insured there was no overlapping of the right ventricle or atria. The position of the lead annulus was marked and the probe positioned accordingly at the same LAO position. In this manner, by using the visual cine display, the probe could be accurately (if not easily) positioned to encompass the LV. Because of the circular field of view, some noncardiac activity (on the lateral free wall side) was included in this fixed probe region of interest (ROI). Once the probe was positioned over the LV, ECG gated energy spectra (256 channels each) were accumulated at every 50 msec interval of the cardiac cycle for at least 300 beats. These gated energy spectra were obtained in exactly the same manner as would be the gated image sequence of a cardiac study, except energy spectra, rather than images, were recorded. Care was taken to eliminate spectral changes due to count rate effects. Figure 1A illustrates two spectra (one at ED and one at ES) from the LV

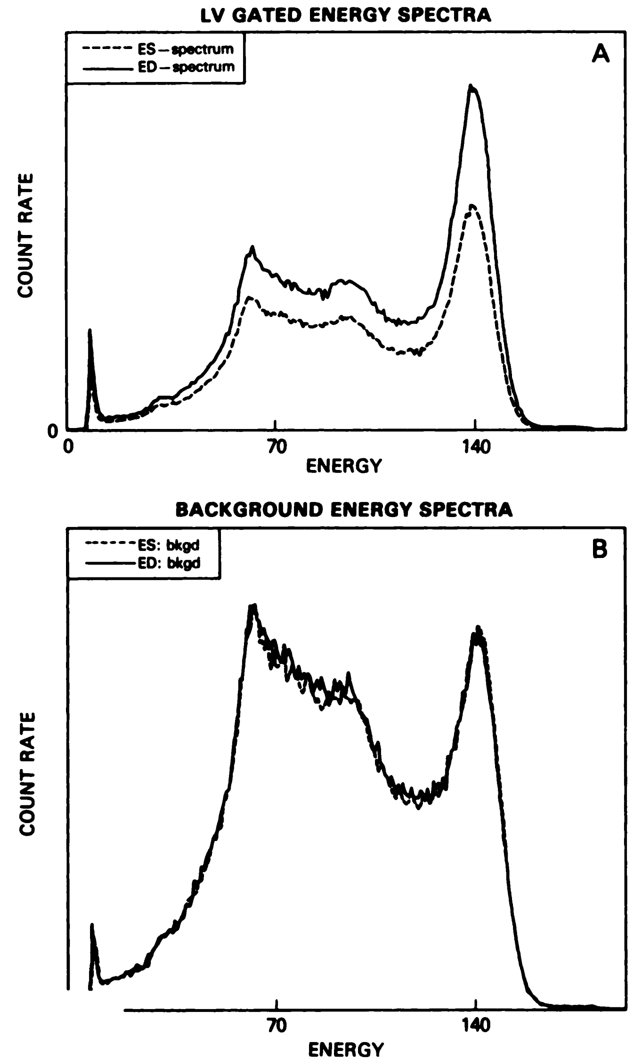

FIGURE 1
A: Energy spectra (counts versus energy) over the left ventricle at ED and ES. B: Energy spectra over background ROI at ED and ES.

of a typical subject. Following acquisition of the LV spectra, gated spectra from a background ROI were collected. The probe was again located using the gamma camera, this time over a region adjacent to the lower lateral free wall of the LV (avoiding spleen activity), in much the same location (but using a larger number of pixels) as would be used for a background ROI in a conventional gated imaging study. Figure 1B illustrates typical ED and ES background spectra. After the gated spectra were acquired, a conventional gamma camera gated imaging study (LAO-modified 15° caudad) was performed.

Time-activity curves were created from the gated spectra by placing a window on the energy spectrum and plotting the number of counts within the window versus time. In this manner, TACs could be made from any portion of the energy spectrum. Background correction (when performed) was accomplished by putting the same energy window on the background spectra, creating background TACs, and subtracting them from the corresponding LV TACs.

In order to gain a better understanding of the energy spectrum of photons emitted by the LV, one additional subject was studied with a high-resolution, liquid nitrogen cooled, planar Germanium detector (2000 mm^2 active area). This detector had an energy resolution of about 0.75 keV. It was fitted with a parallel hole collimator and was otherwise employed in a manner identical to that used with the NaI detector.

RESULTS

One of the most commonly used energy windows is a 20% (i.e., 126 keV to 154 keV) window located symmetrically about the technetium-99m (^{99m}Tc) photopeak. A background corrected TAC was created for each subject with this energy window. The window was then shifted to the right (i.e., higher energy) by 0.74 keV keeping the width the same, and another TAC created. This process was repeated 20 times until the window was located at ~140 keV to 164 keV. Each subject then had 20 TACs, one for each successively increasing energy window. After background correction, ejection fraction was calculated for each of these TACs. EF increased with increasing energy in seven of the nine subjects. In two subjects, EF was observed to decrease very slightly with increasing energy. One of these two subjects (Subject 5) was found to have a background TAC which was not flat with time, but rather was LV shaped, decreasing by 15% from ED to ES with a symmetrically placed window. All other subjects had the expected flat background TAC. Misplacement of the background ROI was suspected as the cause of the anomalous behavior in Subject 5. Indeed, when LV TACs without background correction were created, every subject produced an EF (unbackground corrected) which increased with energy. Figure 2 shows a typical variation of EF with energy. Although there was no theoretical reason to expect a linear increase in EF with energy, for descriptive purposes, a straight line was fit to each subject's plot of EF versus energy. Table 1 summarizes these results by giving the slope of this straight line for each subject. In addition, Table 1 shows the probe and gamma camera determined (symmetric 20% window) EFs for each subject. Seven of the nine subjects had quite similar increases in EF with energy (average slope 3.2 EF units/10 keV for these seven subjects, standard deviation = 1.1). The remaining two subjects (Subjects 2 and 5 in Table 1) had EF versus energy slopes which were nearly flat, with a slight negative slope (−0.4 EF units/10 keV and −1 EF units/10 keV, respectively). As mentioned above, one of these two subjects (Subject 5) had a background TAC which varied in a similar manner to the LV TAC, suggesting mispositioning. It should be noted that the gamma camera and single crystal EFs correlated quite well (r = 0.97), although the probe EF values were consistently lower.

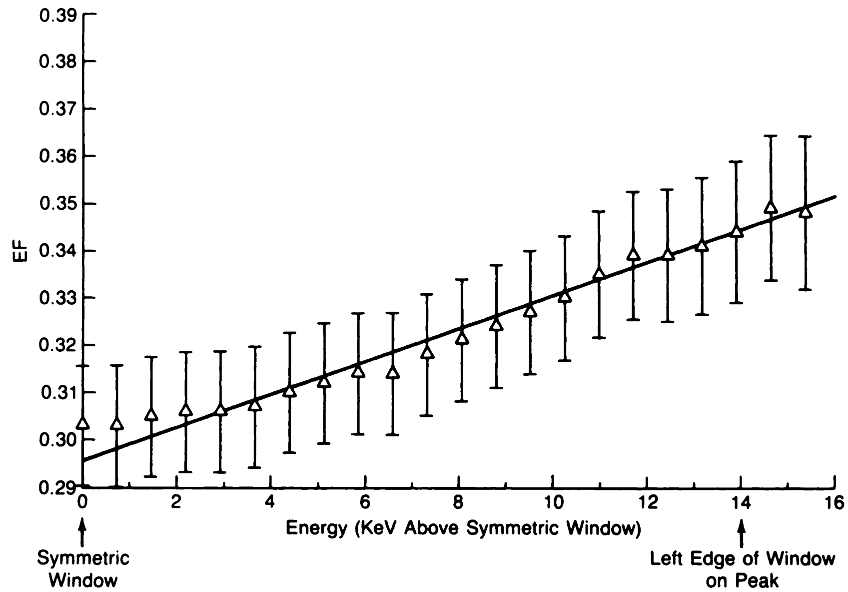

FIGURE 2
Ejection fraction as a function of location of energy window. Zero on abscissa corresponds to a symmetrically placed 20% window.

To determine the effect that background correction had on the above results, the data were re-analyzed with no background correction (Table 1, column 3). The EF values with no background correction (EFNOB) behaved in exactly the same manner as did the background corrected EFs, except the average EFNOB versus energy slope was higher (2.9 versus 2.3 EF units/10 keV). The slopes of EF versus energy without background correction were positive for all nine subjects.

In addition, the background TACs were studied to determine if there were any alterations in the value of background from ED to ES. Excluding the one subject (Subject 5) discussed above, the following results were obtained. Over the whole photopeak (126–140 keV), background at ES was 0.5% lower on average than at ED. Over the upper half of the photopeak (140–154 keV) background was 0.17% lower at ES than at ED. Over the low energy side of the photopeak (126–140 keV) background at ES was 1.1% lower than at ED. Hence, in the entire energy range of the NaI photopeak, background changed very little from ED to ES. Measurements made at much lower energies (in the scattered portion of the energy spectrum—a window of 90–120 keV) showed a decrease in background from ED to ES, averaging 3% for the eight subjects (excluding Subject 5). As mentioned previously, the background (symmetric window) of Subject 5 decreased by 15% from ED to ES.

TABLE 1
Slope of EF Versus Position of Energy Window, and Value of EF for Each Subject

Subject	Slope (EF units/10 keV)	Slope no—BKGD (EF units/10 keV)	EF (probe)	EF (camera)
1	4.0	3.5	33	45
2	−0.42	0.9	15	14
3	2.5	4.4	44	58
4	3.5	4.1	48	68
5*	−0.97†	2.5	54†	61
6	3.2	3.1	30	42
7	1.0	0.8	08	10
8	3.6	4.1	44	52
9	4.5	3.0	34	43
	⟨2.3⟩ (All subjects)	⟨2.9⟩ (All subjects)	EFcam = (EFprobe)•1.27 −0.2 (r = 0.97; S.E.E. = 5.2)	

* Units of slope are in EF units (ranging from 0–100) per 10 keV, for a 20% window.
† Subject whose background TAC was not flat, but had an LV shape.

Because asymmetric energy windows have been considered to be of possible clinical value, the influence of such windows on EF was investigated. For each subject, EF was calculated using a low-energy (126–140 keV), high-energy (140–154 keV) and symmetric (126–154 keV) window. Figure 3 shows these data for each subject. On average, the high-energy window EF values were 17% higher than the low energy values (22% of Subject 5 is excluded) and 9% higher than the symmetric window values (11% higher if Subject 5 is excluded). These results are consistent with other previously reported preliminary results (*2,3*).

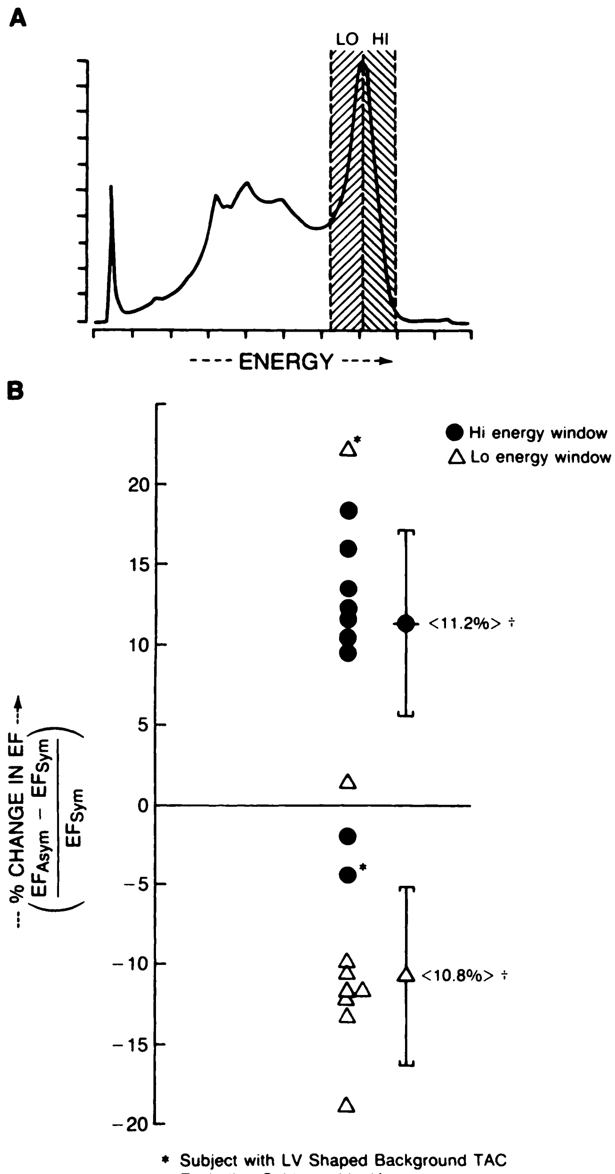

FIGURE 3
A: Illustration of high, low and symmetrically (low and high) placed windows. B: EF for each subject. Ordinate is percentage change in EF from a symmetric window. Subject 5 is shown with an asterisk.

The effect of window width on a symmetrically placed window was investigated. A 20% window was placed symmetrically about the photopeak, and the width of the window was gradually decreased in a symmetrical fashion. EF was measured as a function of window width. EF did not change significantly with increasingly narrow, symmetrically placed, energy windows.

To observe the change in shape of the energy spectrum from ED to ES, the ED and ES spectra of Figure 1A were normalized to the same maximum photopeak peak counts (Fig. 4B), and to the same total photopeak counts (Fig. 4A). Ignoring background, this latter normalization scheme is equivalent to the two energy spectra which would be obtained if one were able to fill the LV at the end diastole with a certain amount of activity and measure its spectrum and then fill the LV at end systole with the *same* amount of activity and measure its spectrum again. Note that the scatter portion of the spectrum is higher at ES than at ED when either normalization is performed. Figure 4C shows the energy spectra obtained at ED and ES (normalized to the same photopeak area) using the germanium detector. Again note the normalized ED and ES spectra show a larger scatter contribution at ES than at ED. The low-energy region, just below the Tc photopeak in the Ge detector spectrum, would normally be included in an NaI 20% window, and is shown expanded on the Germanium spectrum of Figure 4C.

From Figures 2 and 3, and Table 1, it is clear that variations in energy window settings can cause significant variations in ejection fraction. A 10 keV shift in energy results in a 2.3 EF units change in ejection fraction, on average. Use of very asymmetric energy windows may therefore result in a small but significant alteration in the ejection fraction—probably towards a more "correct" value, less contaminated with scatter. A window placed on the upper half of the photopeak resulted in EFs which were 11% higher than would be obtained from a symmetrically placed energy window. In clinical practice, due to the loss in counts, one might not move the energy window this high and would hence obtain a much smaller change in EF. The slopes in Table 1 can be used to estimate what the effect on EF might be for a given shift in energy window. It should be pointed out that use of an asymmetric energy window would presumably also improve image quality.

The shape of the ED spectrum was different from that of the ES spectrum. Examining Figure 1A, no single multiplicative or additive factor will cause the ES spectrum to overlay the ED spectrum. This is confirmed in Figure 4C with the Germanium detector. It is not surprising then, that EF will increase as more and more of these excess scattered counts at ES are eliminated by moving the energy window to higher values. Presumably, the scattered radiation is not adequately reflected in the background measurements.

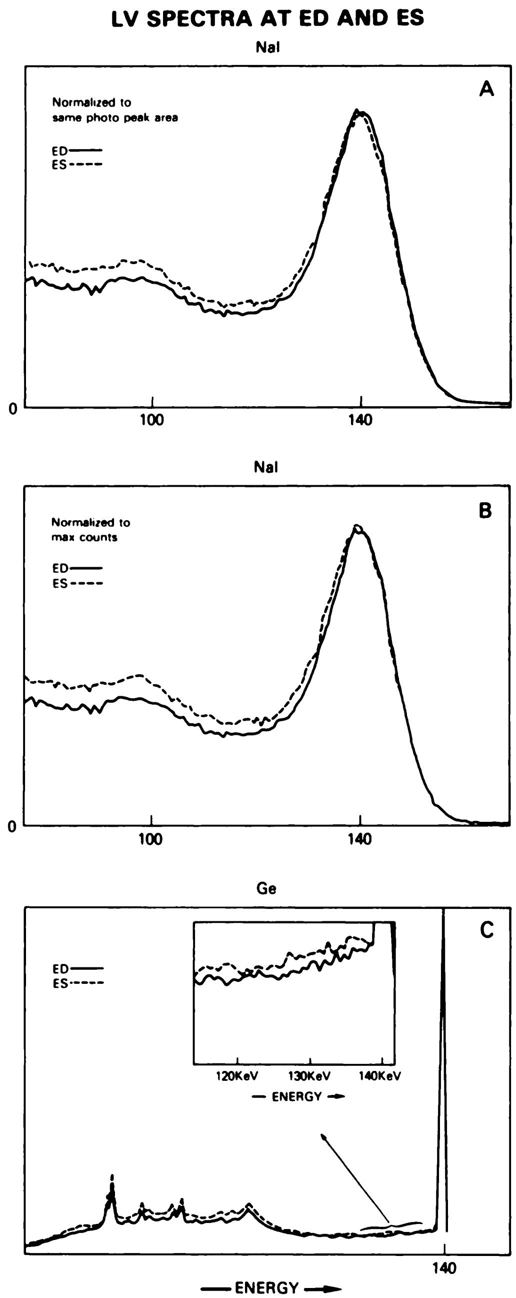

FIGURE 4
A: ED and ES energy spectra over the LV normalized to the same photopeak area. B: As in A but normalized to same peak counts. C: ED and ES energy spectra obtained with high-resolution germanium detector, normalized to same photopeak area.

DISCUSSION

One may speculate upon the physical bases for these observations. The radiation seen by the (collimated) detector when it is placed over the LV may be divided into three principal components. First, there is direct, unscattered radiation, emanating primarily from the LV, as well as from structures in front of and behind the LV. Second, there is self-scattered radiation which originates from the detector field of view (the LV and structures in front of and behind it) and which has scattered from mass within the same field of view, but is still within the acceptance energy window. Finally, there is external scattered radiation emanating from outside the LV which scatters from mass within the field of view of the detector, into the detector collimator acceptance angle.

The poor energy resolution of the NaI detector prevents one from distinguishing direct radiation from much of the scattered radiation. A 20% window symmetrically placed around the photopeak accepts ^{99m}Tc photons which have been scattered by more than 50°, so obviously much of the detected radiation may have had previous scatter interactions. As the energy window is shifted to higher energies, each of the above three components of detected radiation will be affected differently. In addition, as mentioned above, Figure 4 makes it clear that the ES spectrum has a larger (fractionally) scatter component (both self and external) than does the ED spectrum. The portion of the spectrum below the photopeak is higher at normalized ES than at ED. Hence, the effects of moving the energy window to higher energies will be different at ED than at ES. Because the energy resolution of NaI is so poor, much of the relatively small angle (<50°) scatter is contained in the photopeak—primarily in its left-hand edge. This is obvious from observing the elevated left edge of the photopeak in Figure 4A and B, and is why normalizing to both peak and total counts was employed (although neither normalization method is perfect, either is adequate to demonstrate the effect). The ED and ES spectra from the germanium detector shown in Figure 4C (normalized to the same area under the photopeak) also clearly show that even at energies very close to the photopeak, normalized ES counts exceed ED counts in the scatter portion of the spectrum. Because of the excellent energy resolution obtained with the Ge detector, both of the two normalization schemes (to peak counts or to total photopeak area) gave identical results, with the normalized ES spectrum exceeding the normalized ED spectrum as seen in Figure 4C (inset). From the Germanium spectra, it is clear that as one moves a broad-energy window (126–154 keV) upward in energy, ES counts will be reduced fractionally more than ED counts, thus explaining the observed increase in EF with window energy. Since the background energy spectra differed so very little in either shape or magnitude from ED to ES, this effect will not be compensated for by background correction. This explanation for the observed increase in EF with increasing energy also affords a plausible (but unproven) explanation as to why Subjects 2 and 7 (Table 1) had a slope which differed so markedly from the subjects with higher EFs. Presumably, these subjects, who had such very depressed EFs, had very little change in cardiac size and shape from ED to ES and hence these subjects'

ES energy spectra would be nearly the same shape as their ED spectrum. If the ED and ES spectra are identical in shape (but not necessarily magnitude), one would not expect EF to change with energy window.

It should be noted that the background TAC was flat (for all but Subject 5) providing that the window was placed symmetrically about the photopeak. The background TAC remained flat when the window was raised to higher energies. Thus, the increase in EF with increasing energy (above a symmetric window) could not be explained on the basis of some deviation from *flatness* of the background TAC. Also, since the background uncorrected ejection fraction, EFNOB, also increased with increasing energy, the observed effect could not be explained solely on the basis of a change in the *magnitude* of the background correction with energy.

The change in shape of the energy spectrum appears to explain why EF increases with increasing energy of the window. The explanation as to what causes the ED and ES spectra shapes to differ is not completely clear. A partial explanation is that it is caused by the effects of background. It is obvious from Figure 1B that the background spectrum has a very low photopeak/scatter ratio compared to the LV spectra. The total LV spectrum is a sum of the true LV spectrum and its underlying and overlying tissue spectrum. As the LV contracts, the LV contribution to the total spectrum goes down while the more background dominated overlying and underlying tissue spectra presumably remain constant. If this effect were the only cause for the ED/ES spectrum difference, it could be eliminated by proper background correction. In fact, however, the increase in EF with increasing energy is observed when no background correction is employed, and persists when background correction is performed. One might ask whether or not the background measurements could be scaled so as to eliminate the observed effect. The answer is no. It was previously stated that the 126–140 keV background value averaged 1.1% lower at ES than at ED, while the 140–154 keV window background value was 0.17% greater at ED than at ES. The observed LV EF difference between these two portions of the spectra was about 20%. Thus, the background value could be increased by a large factor and still not eliminate the observed increase in EF with energy. Background correction then, is not likely to be the source of the observed result. It is possible, however, that a background ROI adjacent to the LV, as was employed here (and in conventional gated cardiac studies), does not give a true estimate of the actual energy spectrum of the true LV background. It is also possible that use of a smaller background ROI closer to the LV would reflect more of the LV scatter component. In addition, it is uncertain what the effect of a variable ROI would be on the measurements.

From the above discussion, two plausible observations may be made concerning the shape of the observed energy spectra. First, the LV spectra at ED and ES may differ due to the different shape and size of the LV and its relative location to other structures (independent of any background effects). Second, it is possible that the measured background energy spectrum from the region adjacent to the LV does not reflect the shape of the "true" (but unmeasurable) background from the underlying and overlying tissue. Whether either or both of these observations is true cannot be known from the present study, nor does their validity influence the clinical implications of the observed effect.

An important caveat must be pointed out to the reader. The data in this paper were obtained with a nonimaging, single-crystal probe. When asymmetric windows are employed on gamma cameras, the situation becomes much more complex, as significant spatial nonuniformities in the camera's response may occur. Such effects may be severe unless the camera's energy correction circuits can be re-adjusted for the particular asymmetric energy window being employed. Several modern gamma camera designs permit such re-adjustment, and hence the use of asymmetric windows, with its attendant potential for improved image quality, may be important.

CONCLUSION

Ejection fraction was observed to change measurably with alterations in the placement of the energy window. For the usual, small, asymmetric windows which are used in practice, the shift in ejection fraction may be of little clinical importance. For very large shifts in window position, the effects may be of greater significance. At least part of this change was due to variations in the relative shape of the energy spectrum from ED to ES. Since a nonimaging detector was used to perform the measurements, the observed effect could not be attributed to gamma camera dependent phenomena such as field nonuniformity. In any case, these data have been used in an attempt to shed some further light on the effects which the shape of the energy spectrum may have on clinical measurements such as calculation of EF. Many uncertainties still exist as to the detailed nature of the effects of scatter on gated blood-pool studies. It is hoped that this work may be of some use in designing future studies of the problems of photon scatter on gamma camera quantitation.

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