Effect of Scintillation Camera Nonuniformity on Ejection Fraction Measurements

Ellinor Busemann-Sokole, Thomas J. Farrell, and Trevor D. Cradduck

Academic Medical Center, University of Amsterdam, Amsterdam, Netherlands; and Victoria Hospital Corporation, and University of Western Ontario, London, Ontario, Canada

A rotating cardiac phantom with three possible ejection fraction (EF) values was used in conjunction with a scintillation camera employing energy correction and count skim arithmetic for uniformity correction. Studies were collected with and without any correction, with the energy window of the analyzer set properly, and with the camera properly tuned. The uniformity was then degraded in one experiment by off-setting the analyzer window both high and low with respect to the primary photopeak and in another experiment by de-tuning a selected photomultiplier tube. In both experiments studies were taken with no correction enabled, and then with each of the correction options enabled. The results of both experiments show that ejection fraction values could be in error when the differential uniformity using National Electrical Manufacturers Association (NEMA) protocols exceeds 10%. If either energy correction alone, or energy correction combined with count skim correction is used, the ejection fraction values return to more acceptable values. Asymmetric windows, improper setting of the energy window or a badly tuned photomultiplier will likely result in poor analog images before the effect on ejection fraction measurements becomes evident. Uniformity correction devices do not adversely affect the numerical results obtained from these phantom studies, but should, nevertheless, be used with caution.

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Ejection fraction (EF) measurements from gated blood-pool studies have become a routine procedure in many institutions. Considerable reliance is placed upon the results of these tests but they can be affected by a number of factors such as data acquisition protocols, camera/computer operation, patient physiological conditions, and data analysis procedures. The effect of camera nonuniformity on ejection fraction measurements has not been fully documented.

Nonuniformity is a result of both variations in sensitivity across the scintillation camera face and spatial distortions (*1–3*). Nonuniformity can be introduced by operating the scintillation camera with the analyzer window centered off the photopeak or by one or more photomultiplier tubes being out-of-tune. Uniformity of a scintillation camera is a sensitive indicator of the camera performance and good uniformity is an essential requirement for imaging. Uniformity quality control checks are largely subjective. Even when numerical methods are applied in order to obtain objective criteria of nonuniformity, the level of nonuniformity beyond which clinical data become unreliable has, as yet, never been established.

This study was divided into two parts. The first part investigated the effect on ejection fraction values when scintillation camera uniformity was degraded due to improper analyzer window positioning. The second part of the study was to determine the effect on ejection fraction values of the "cold" photomultiplier tube. In both cases the particular objective was to determine the level at which the scintillation camera/computer system performance could be deemed unacceptable. In addition, the effect of the microprocessor camera correction devices was investigated. The NEMA protocol for uniformity quantitation was adopted and a cardiac phantom was used to provide simulated ejection fraction data.

MATERIALS AND METHODS

A cardiac phantom was used to provide standardized ejection fraction data that could be collected under various conditions of camera nonuniformity. A scintillation camera* that had the facility of acquiring data with and without its uniformity correction processor activated was used on line with a computer† for the data collection and analysis.

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For reprints contact: Ellinor Busemann-Sokole, MSc, Dept. of Nucl. Med. Academic Medical Center, Meibergdreef 9, 1105 AZ Amsterdam, Netherlands.

The cardiac phantom

Ejection fraction measurements were obtained with the Vanderbilt cardiac phantom‡ (4–6). This phantom consists of two hollow spheroids positioned orthogonally to each other so that, when rotated, the silhouette of a left ventricle and left atrium is simulated. A single metal attenuator attached adjacent to the major axis of the left ventricle spheroid rotates conjointly with the spheroid in order to simulate a stroke volume of specific ejection fraction. Three attenuators are supplied to mimic specific nominal ejection fractions of 25, 50, and 75%. A hollow background chamber imaged behind the spheroids provides a simulation of background activity with increased activity representing a fixed right ventricle, right atrium, and aorta. A TTL logic trigger pulse is produced once every full rotation of the spheroids, which results in an R-R interval encompassing two simulated heart beats. By attenuation of photons the metal attenuator produces a time-activity curve that simulates a stroke volume curve in the first half of the R-R interval only (6).

The spheroids and background chamber were filled with a homogeneous solution of technetium-99m (^{99m}Tc) in a concentration of ~ 25μCi/ml (1 MBq/ml). The cardiac phantom was then positioned in front of the scintillation camera fitted with a general purpose, low-energy collimator.

Ejection fraction data were collected under framing rate and count statistics conditions similar to those usually encountered in clinical studies. Acquisition parameters were set to collect 30 frames over the first half of a full rotation (corresponding to a complete R-R interval), and ~ 200,000 counts were collected per frame. The rotational speed of the spheroids was set to give a simulated heart rate of 80 beats per min (6,7).

The left ventricular ejection fraction was calculated from a single region of interest drawn using an automatic edge detection program (8). In order to obtain reproducible ejection fraction values which approximated the nominal values expected, a background region of constant size and shape (rectangular) was selected adjoining the left ventricular region. The value of background in the first frame, at end diastole, was chosen to correct for the background activity in the left ventricular region throughout the whole R-R interval. This algorithm was strictly adhered to in order to give a fixed methodology that was as independent of the operator as possible.

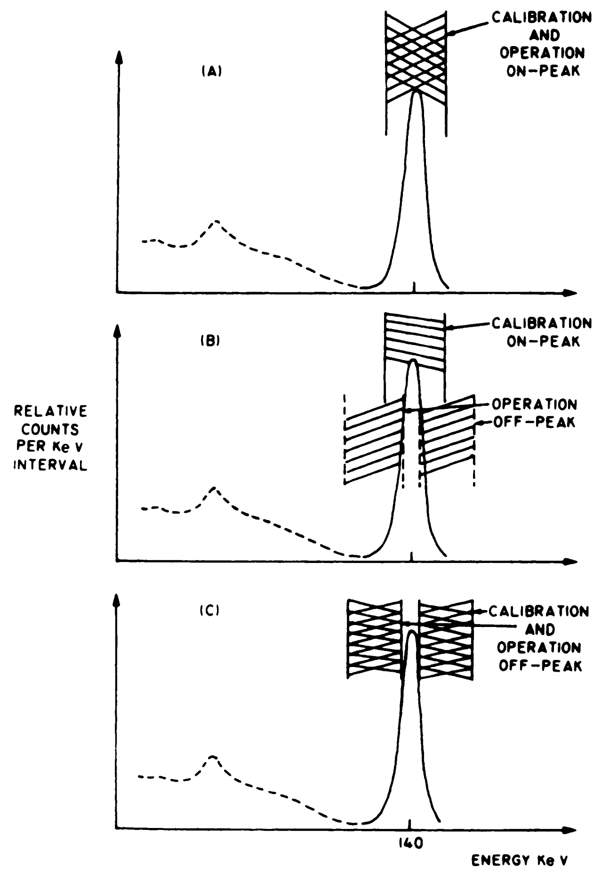

FIGURE 1
Different combinations of calibration window and operational window were used to create different differential uniformities. Camera was operated with window: (A) Centered over photopeak for both calibration and data acquisition; (B) Centered for calibration, but off-set on low side of photopeak and on high side of photopeak for data acquisition; (C) Offset on low side of photopeak and offset on high side of photopeak for both calibration and data acquisition. (Note that the analyzer windows and spectrum shown here are schematic only and are drawn only in order to illustrate directions of window shifts used-they are not drawn to scale

Uniformity quantitation

Integral and differential intrinsic uniformity parameters were calculated according to the NEMA standards protocol (9). The activity of the ^{99m}Tc point source used to obtain the uniformity flood image was chosen to give a count rate of less than 30,000 counts per sec in a 20% analyzer window centered over the 140 keV photopeak of ^{99m}Tc. A flood-field image of 40 million counts total in a 64 × 64 matrix was collected in order to obtain ~ 10,000 counts in the center pixel. The digital useful field-of-view (UFOV) was taken to be that of the collimated field-of-view and the central field of view (CFOV) was calculated to be 0.75 of the UFOV.

After a nine-point smooth of the flood-field data, integral and differential uniformity were calculated in the CFOV. Differential uniformity was obtained using a 6-pixel search range and was calculated to be the maximum ratio in either X or Y direction (9,10).

Experimental protocol–Asymmetric window

The scintillation camera was tuned to its best performance prior to the start of this study. This was judged by both visual inspection and application of the NEMA protocols for uniformity quantitation. Degradation of the scintillation camera uniformity was achieved by off-setting the position of a 20% analyzer energy window with respect to the photopeak of ^{99m}Tc. The scintillation camera had a uniformity correction processor that provided an energy correction as well as a combined energy and count skim correction. The uniformity correction processor could be switched to give acquired data under three conditions: without any correction, with only energy correction, or with both energy and count skim correction.

In order to represent conditions that would imply that the scintillation camera was used in its best uniformity condition as well as in conditions where uniformity was badly compromised, five different combinations of analyzer window positions were used for the uniformity correction processor calibration and data acquisition (Fig. 1). In three cases, (A) and (C), the calibration and operational windows were the same. In two cases, (B), the camera was operated at a window position different than that used for calibration.

For each of these window combinations, uniformity and ejection fraction for nominal values of 25, 50 and 75% were measured under each condition of operation of the uniformity correction processor. Measured ejection fractions were then plotted against the corresponding uncorrected differential uniformities within the CFOV.

Experimental protocol–De-tuned photomultiplier

Degradation of the camera uniformity for this portion of the study was achieved by adjusting the gain of a single photomultiplier tube near the center of the field-of-view. The photomultiplier tube was first tuned to optimum performance by peaking it with a small source of cobalt-57 (^{57}Co). Adjusting the gain to either side of this peak caused the photomultiplier tube to become progressively "colder" and the count rate from the whole camera face decreased. The reduced count rate, as a percentage of that obtained at optimum performance, was used as a measure of degradation (Fig. 2). Ejection fraction measurements were taken when the overall count rates were 80, 70, and 50% of the maximum (or optimum) count rate and were achieved by de-tuning the chosen photomultiplier both above and below the system photopeak. Following degradation of the gain of the photomultiplier tube the uniformity correction processor was re-calibrated to correct for the nonuniformity which had been introduced, so that the calibration and operational conditions were the same.

For each level of degradation of the photomultiplier tube gain ejection fraction measurements were taken with each of the three attenuators giving nominal ejection fraction values of 25, 50, and 75%, in each of the three modes of operation of the uniformity correction processor. The measured ejection fractions were plotted against the uncorrected differential uniformities at each level of de-tuning.

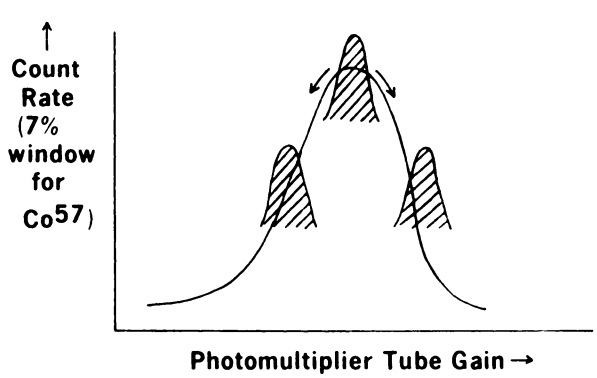

FIGURE 2
Experimental protocol. As gain of one photomultiplier is altered its photopeak moves out of coincidence with system photopeak and count rate decreases. Decreased counts were used as measure of performance degradation. Note that, as in Fig. 1, individual tube photopeaks and camera photopeak are not drawn to scale

RESULTS

The selected data acquisition parameters produced a 1 s.d. statistical error in the ejection fraction measurement of ~1% ejection fraction. The 40 million count flood-field image, giving a center-pixel count of about 10,000, produced a 1 s.d. statistical error of ~0.4% uniformity (*10*).

Asymmetric window

The optimum operational condition for this part of the study was considered to be when all photomultipliers were properly tuned and the analyzer window was centered carefully over the photopeak for both uniformity processor calibration and phantom measurements. Integral and differential uniformity obtained in this mode of operation were, respectively, 8.5 and 5.2% with the uniformity processor disabled, 8.1 and 6.0% with energy correction only, and 2.8 and 2.1% with both energy and count skim correction.

Off-setting the analyzer window for either or both the calibration and data acquisition represented incorrect analyzer window settings and produced generalized nonuniformity over the whole field-of-view. This gave uniformity values with the processor disabled in the range (31.3–41.4)% integral, and (16.1–22.7)% differential. Applying energy correction improved uniformity to between (8.7–11.5)% integral, and (5.9–7.5)% differential. When both energy and count corrections were applied, uniformity improved further to a range of (3.0–6.3)% integral, and (1.9–3.8)% differential.

In order to compare ejection fraction values obtained at different levels of nonuniformity, ejection fraction values were plotted against the corresponding uncorrected differential uniformities. These results are shown in Figs. 3 and 4 for each nominal ejection fraction. The results with no correction applied are shown in Fig. 3, while Fig. 4 demonstrates the effect of applying first energy correction and then both energy and count correction.

There appear to be no great variations in measured ejection fraction values for each nominal ejection fraction when the different conditions of offset window settings were used. At high levels of nonuniformity there is a slightly greater divergence of values from those obtained with the optimum operating conditions. The application of energy correction and additional count skim correction did not appreciably influence the ejection fraction values obtained.

De-tuned photomultiplier

The optimum operating condition for the scintillation camera was considered to be the situation when all of the photomultipliers were properly tuned to the photopeak of ^{57}Co using a small point source. Integral and differential uniformity obtained at the time of this experiment were, respectively, 9.6 and 6.5% with the uniformity processor disabled, 8.7 and 6.0% with energy correction only, and 3.3% and 2.0% with both energy and count skim correction.

De-tuning a photomultiplier produced a single cold area which gave rise to uniformity values with the processor disabled in the range (9.6–26.4)% integral, and (6.5–18.9)% differential. Applying the energy correction improved uniformity to between (8.7–14.1)% integral, and (6.0–8.6)% differential. When both energy and count skim corrections were applied,

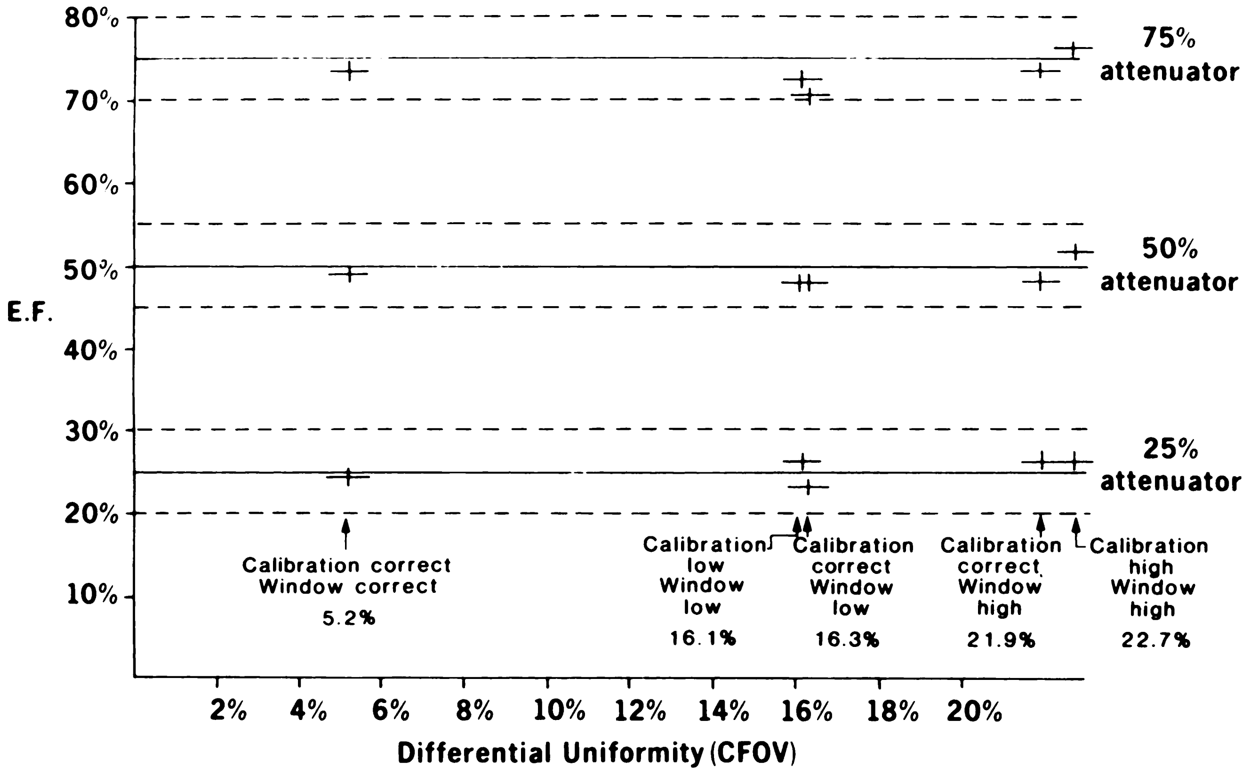

FIGURE 3
Plot of ejection fraction values versus differential uniformity caused by various improper operating conditions without application of any correction (asymmetric window, correction circuits off)

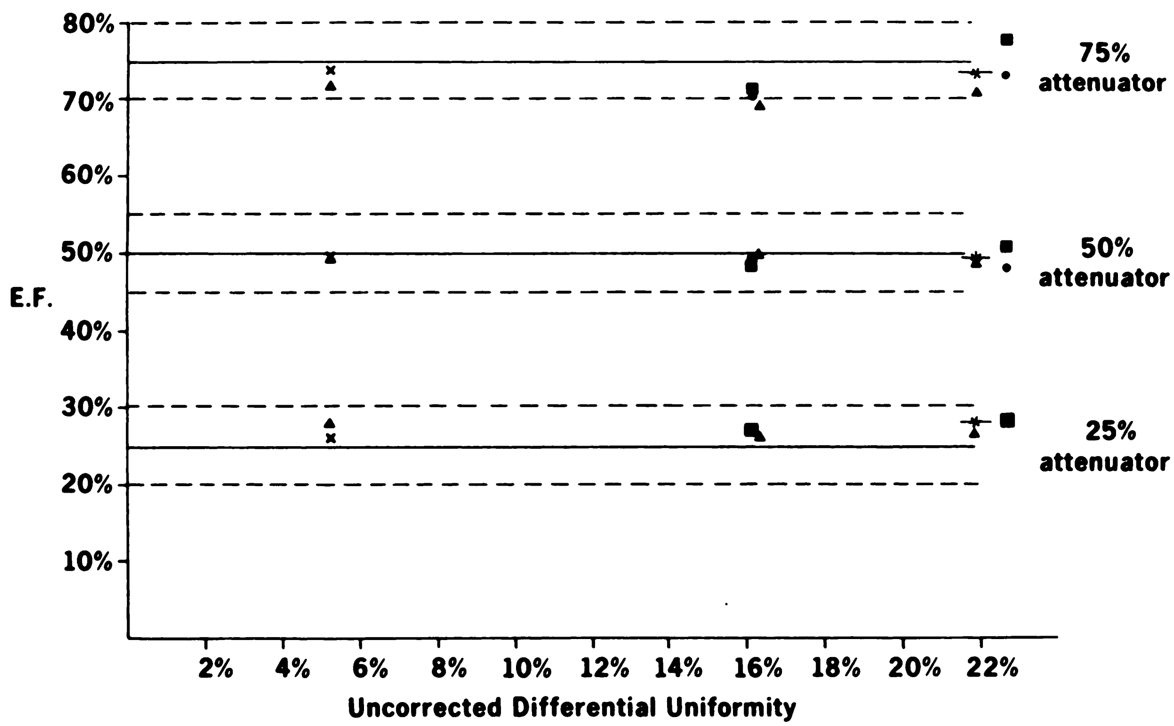

FIGURE 4
Plot of ejection fraction values versus uncorrected differential uniformity caused by various improper operating conditions with first energy correction alone and then both energy and count correction applied (asymmetric window). (X) Energy correction only, calibration correct, (●) Energy correction only, calibration off-peak, (▲) Both corrections on, calibration correct, (■) Both corrections on, calibration off-peak

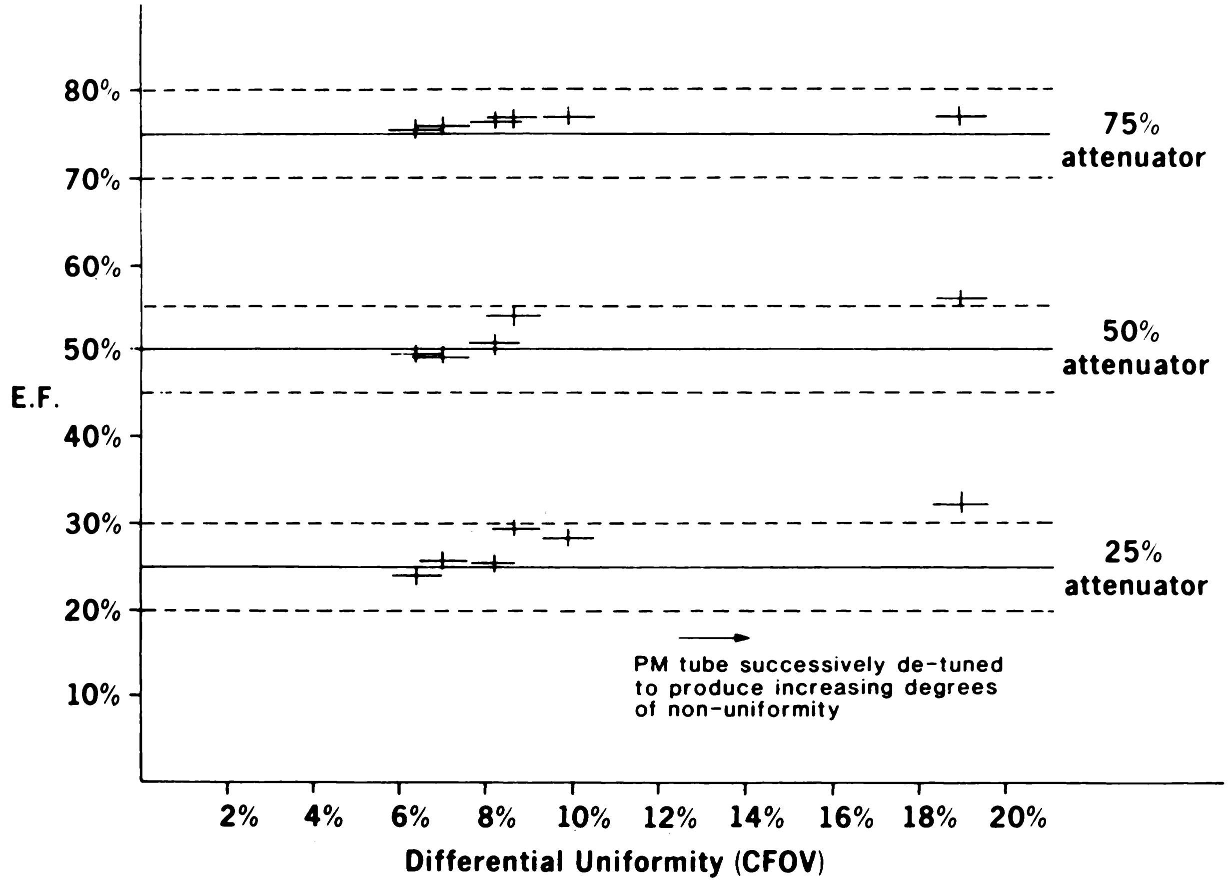

FIGURE 5
Plot of ejection fraction values versus differential uniformity for different levels of de-tuning without any correction circuits enabled (detuned pm, correction circuits off)

uniformity improved further to a range of (3.3–2.6)% integral, and (2.0–2.1)% differential.

The change in uniformity affected the ejection fractions for the three different attenuators to different degrees. The ejection fractions measured for each attenuator were plotted against uncorrected differential uniformity in order to compare the effect of the de-tuning (Fig. 5). As can be seen from the graph the ejection fraction for the 25% attenuator showed the greatest change while the ejection fraction of the 75% attenuator showed the least change. In all situations the ejection fraction rose as the photomultiplier tube was adjusted to become "colder". If a maximum deviation from the expected ejection fraction of 5% is chosen as an unacceptable deviation, i.e., an action level, one can see that this level is reached near 10% differential uniformity for both the 25 and 50% ejection fraction attenuators, whereas for the 75% ejection fraction attenuator this level is not reached, even up to 19% differential uniformity.

The ejection fractions measured with the correction devices enabled showed little difference from the expected values (Fig. 6). It is not obvious that there is a greater deviation from the expected ejection fractions for any one of the attenuators. Although the ejection fractions measured under these conditions seem to be reasonable, it was found that with the count skimming correction enabled the study took much longer to collect the required 6 million counts. This is an undesirable effect of the adjustment of the gain of the photomultiplier tube and is caused by the rejection of counts (count skimming) from areas of high count concentration.

DISCUSSION

Substantial reliance is placed on the numerical outcome of an ejection fraction measurement from a gated cardiac study, so that the reproducibility and reliability of this measurement are vital. Consistency in the method of data acquisition and analysis need to be carefully heeded. However, the effects of camera performance and camera operation are usually not taken into account. The purpose of these studies was to determine whether camera nonuniformity affected the outcome of ejection fraction measurements.

Camera nonuniformity is generally considered to be the result of changes in camera performance, usually gain shifts of the photomultiplier tubes. However, nonuniformity can also result from asymmetric positioning of the analyzer window with respect to the photopeak. For cameras which have uniformity correction processors that require regular calibration, correct window positioning for both the calibration procedure and subsequent clinical ac-

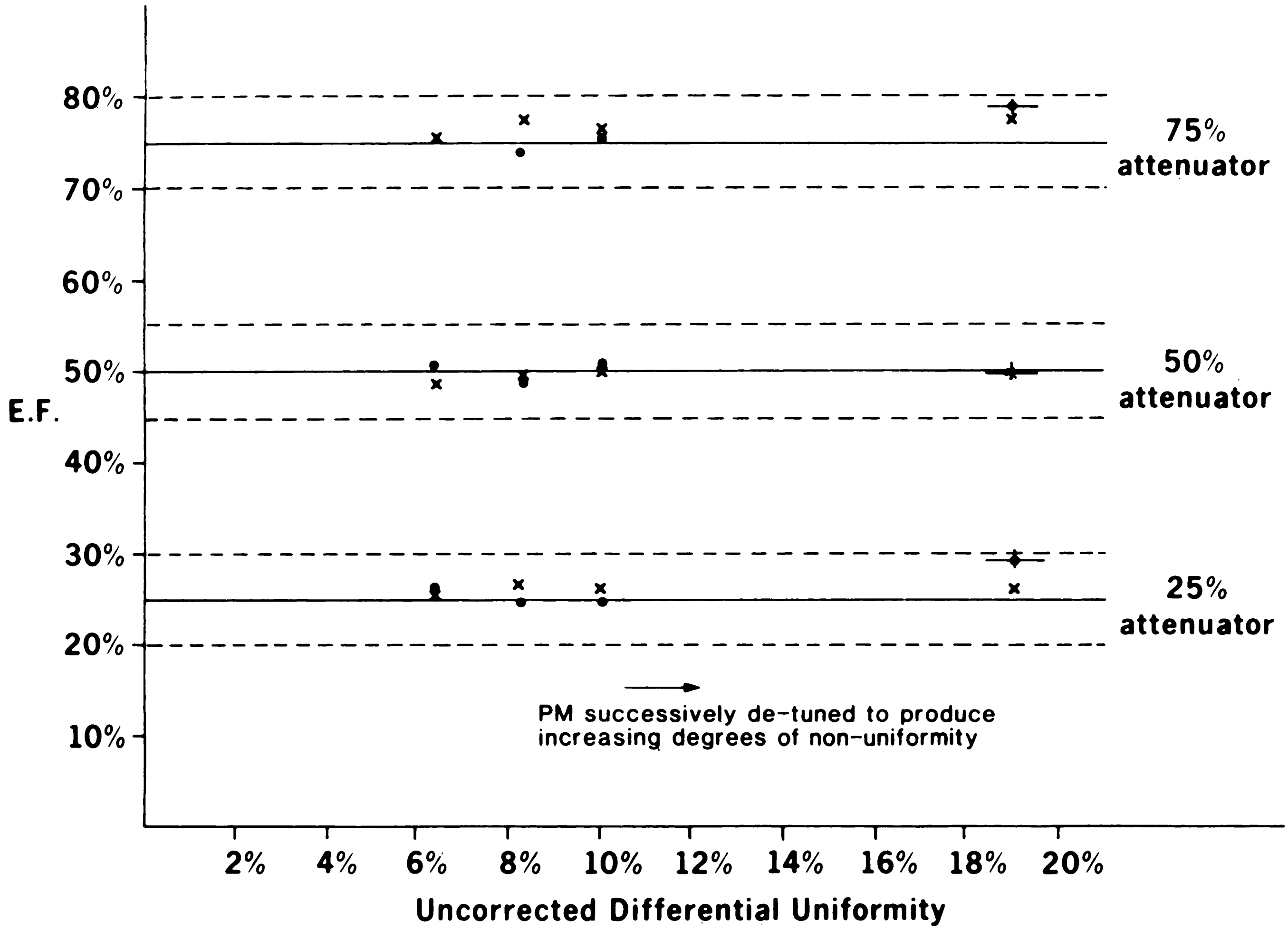

FIGURE 6
Plot of ejection fraction values versus uncorrected differential uniformity for different levels of de-tuning (detuned pm). The data have been collected with (a) energy correction and (b) both energy and count correction enabled. Differential uniformity is that which pertained under identical conditions of de-tuning without correction. (X) Energy correction only, (●) Both corrections on

quisition is essential. Improper camera operation may readily pass unnoticed, especially when quality control checks of uniformity are only carried out with the processor correction applied (*11*). For such cameras, it is always advisable to obtain uniformity checks with the processor disabled as well as enabled. A comparison of the resulting images will indicate the level of nonuniformity actually present and the amount of correction that is being applied.

Nonuniformity was achieved in these experiments in the first instance by offsetting the analyzer window position, which represented the situation of an improperly used camera and, in the second instance, by deliberately de-tuning a photomultiplier tube from its optimum setting. The nonuniformity thereby obtained in each of these cases was visually assessed and objectively analyzed by the application of the NEMA standards protocol in order to obtain parameters for the integral and differential uniformity present (*9*). These two parameters do not portray the overall pattern of nonuniformity nor do they necessarily give the nonuniformity that actually pertains to that portion of the detector used for the ejection fraction measurement. Indeed, in the case of asymmetric windows the nonuniformity achieved may be considered to be generalized over the camera surface, whereas, when a photomultiplier is de-tuned, the nonuniformity is localized to the area close to that tube. Nevertheless, such measurements are indicative of the worst nonuniformity present and the numerical values so obtained may then form the basis for an action threshold criteria.

When the analyzer window was considerably offset, exceedingly high integral and differential uniformity values were obtained without the uniformity processor applied. In this mode of operation, flood-field images appeared alarmingly nonuniform over the whole field-of-view and cardiac phantom images were grossly distorted. The clinical use of the camera with this level of nonuniformity would have been totally inadmissible. The application of the energy correction improved uniformity values so that the visual impression of the uniformity and phantom images appeared more tolerable. With the added count skim correction, uniformity values and the visual appearance of uniformity returned to "acceptable" levels. The combined correction therefore totally obscured the fact that an offset window was being used and that a considerable internal correction was being made by the uniformity correction processor. The only indication that such correction was taking place was the excessive increase in imaging time required to collect the same number of counts.

The ejection fractions corresponding to the different situations of analyzer window settings for both calibration and data acquisition showed only a small variation, although they appeared to have more divergence from those obtained with the optimum window setting at higher levels of nonuniformity (Fig. 3). No particular trend in results was evident, perhaps due to the different nonuniformity patterns produced by the different window settings. Application of energy and additional count skim correction did not adversely affect the ejection fraction results.

When a photomultiplier tube was de-tuned, the measured ejection fraction at low nominal values demonstrated a greater change than for the higher nominal ejection fraction values (Fig. 5). The effect of energy correction improved uniformity and brought ejection fraction values closer to those obtained under optimum conditions. The additional effect of a count skim uniformity correction further improved uniformity and did not appear to adversely affect the ejection fraction results.

The fact that the ejection fraction values did not change appreciably at low levels of degradation is not surprising. Intuitively one would expect that when the photomultiplier tube is de-tuned the counts in the region of the photomultiplier tube would decrease by a factor which depends upon the level of degradation. This decrease would be due to a decrease in sensitivity, as well as a change in linearity in the region, i.e., counts would be pulled to surrounding regions. Given the ejection fraction algorithm that was used, if there were no background subtraction this factor would not affect the ejection fraction. Since the ejection fraction is calculated as the ratio of the difference of counts at end-diastole and end-systole to the counts at end-diastole, the factor by which the counts are reduced will not enter into the calculation and the ejection fraction will be unchanged. When background subtraction is included in the calculation of the ejection fraction, this reduction factor becomes important. If the reduction factor, r, is defined as the ratio of counts per unit area inside the region occupied by the de-tuned photomultiplier tube to those counts per unit area in normal regions (which includes the background region of interest), the formula for ejection fraction can be written as

$$\mathrm{EF} = (\mathrm{ED}-\mathrm{ES})r/(\mathrm{ED}r-\mathrm{BG}) \qquad (1)$$

where EF is ejection fraction, ED is end-diastole counts, ES is end-systole counts, BG is background counts, and r is the reduction factor. This can alternatively be written as

$$\mathrm{EF} = (\mathrm{ED}-\mathrm{ES})/(\mathrm{ED}-\mathrm{BG}/r). \qquad (2)$$

For a given ejection fraction value the numerator (ED–ES) will remain constant. As the level of degradation increases the counts in the vicinity of the photomultiplier tube will decrease, and the reduction factor, r, will decrease. This will cause BG/r to increase and the denominator (ED–BG/r) to decrease, thereby causing the ejection fraction itself to increase. Since the numerator for lower ejection fractions is smaller, low ejection fractions will be affected to a greater extent than larger ejection fractions.

The purpose of the energy and uniformity correction devices is to eliminate the reduction factor, as defined above, for the counts in the region of the de-tuned photomultiplier. This should result in restoring the ejection fractions to the expected values.

Based on a very subjective assessment, one could consider a 10% differential uniformity for an uncorrected camera as a rule of thumb action threshold beyond which numerical results of ejection fraction become unreliable. The flood field and phantom images showed marked visual degradation even at 10% differential nonuniformity. For the de-tuned photomultiplier studies this degradation was less dramatic on the phantom images because the left ventricle, a hot source, was directly over the cold photomultiplier tube. Although application of energy and uniformity correction caused ejection fraction results to return towards their expected values, one should probably still exercise caution in using corrections which add or skim counts from the images.

The results of these experiments indicated that one can place a reasonable degree of confidence in results of ejection fraction measurements even when the camera nonuniformity is as much as 10%. One cannot, however, assume that the results can be extrapolated to the clinical environment with impunity. There are many other factors that are not present in a phantom study and which may play an important role in the clinical situation. Physiological variations in the R–R interval, patient movement and poor red blood cell labelling are examples of such factors.

It must be recognized that the studies reported here concentrated upon the effect of nonuniformity on only one region of interest (the left ventricle). The conclusions reached cannot be generalized to include studies where multiple regions of interest are compared one to another. The paramount question remains whether the nonuniformity action threshold of 10% suggested for ejection fraction measurements could be used for other quantitative studies, especially those such as renal studies or other similar studies which rely on comparison of several regions of interest located in different positions in the field of view.

FOOTNOTES

*Dyna-Mo, Picker International, Northford, CT.

†Gamma-11; Picker International, Northford, CT.

‡Vanderbilt Cardiac Phantom AP-201, Capintec Inc., Ramsey, NJ.

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