A Dual Collimator Design for Beat-to-Beat Measurement of Cardiac Performance with an Anger Camera

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A dual collimator was designed for an Anger camera to permit measurement of cardiac performance on a beat-to-beat basis. Special all-purpose (SAP) and special high-sensitivity (SHS) collimator sections can be interchanged without movement of the patient. Thus, left-ventricular regions of interest delineated on SAP multigated images can be transferred to SHS dynamic images to generate beat-to-beat volume curves. Preliminary balloon studies demonstrated an excellent correlation between ejection fractions calculated with the two collimators: \( r > 0.99 \), \( n = 17 \), \( p < 0.001 \). Varying the volume of an adjacent "right ventricle" balloon failed to alter significantly the count rate from the "left ventricle" balloon's region of interest. Preliminary results on 12 patients, comparing standard-camera ejection fractions with average beat-to-beat ejection fractions, showed that it is possible to measure cardiac function on a beat-to-beat basis with a single-crystal gamma camera. There was minimal difference between the ejection fractions calculated by the dual-collimator method and a standard gated technique (\( r = 0.98 \), \( n = 12 \), \( p < 0.001 \)).


A number of nuclear medicine methods are available for the evaluation of cardiac performance, but few are applicable to beat-to-beat studies. Multigated Anger-camera acquisition usually requires 2–7 min, limiting the temporal resolution of the measurement (1–3). Patients with atrial fibrillation or other cardiac arrhythmias present timing problems in developing an accurate composite cardiac cycle. First-transit techniques require multiple injections if information is to be obtained for more than 4–7 cardiac cycles or during a prolonged observation period. The high count rates required by the first-transit technique are obtainable only on the multicrystal or the new "digital" camera (2,4–8).

The nonimaging probe can record ejection fraction, relative cardiac output, and stroke volume every 30 sec and reportedly can monitor beat-to-beat changes (9–11). However, accurate identification of the left ventricle with a nonimaging system is difficult in many patients and motion artifacts may limit the accuracy of such a technique for beat-to-beat measurements.

We have devised a dual collimator that takes advantage of the resolution characteristics of an all-purpose collimator and the counting statistics of a high-sensitivity collimator to permit cardiac function analysis on a beat-to-beat basis with a gamma camera.

MATERIALS AND METHODS

The new collimator consists of a lead sheet, 3 mm thick, having a central, 14-cm circular hole. Two parallel-hole collimators are provided: a special high-sensitivity one (SHS) and a special all-purpose one (SAP); they are fused end to end so that they can slide in aluminum tracks, placing either one over the large hole (Fig. 1) without requiring movement of either the patient or the camera's detector. Thus, a region of interest drawn on an image made with the all-purpose collimator can be transferred directly to a high-count image made with the SHS collimator. Just outside the collimators is a pair of lead shutters with semicircular inner edges (Fig. 1); they also slide in aluminum tracks and serve to limit the camera's field of view to the left ventricle and a small part of surrounding background. The characteristics of these special collimators are shown in Table I. The SAP section provides sensitivity and resolution similar to those of a typical all-purpose collimator, while the SHS section has a sensitivity approximately seven times that of a typical high-sensitivity collimator.

Using the SHS collimator with a 10-cm aperture and a 25-mCi patient dose of Tc-99m-labeled RBCs, observed patient count
rates are on the order of 45–55,000 cps. For the camera used in the patient studies, a measured count rate of 50,000 cps produced a
dead-time loss (with 5 cm of Plexiglas for scatter) of about
23%.

Preliminary validation experiments used a balloon to simulate the
left ventricle. The balloon was immersed in an 8-l water
phantom so that the center of the balloon was 7 cm from the face
of the collimator. The balloon was filled to a volume of 80 ml with
a solution containing Tc-99m at 4.4 mCi/l and activity was added
to the surrounding water to achieve a balloon-to-background ratio
of approximately 3:1. These activity levels were selected so that
dead-time effects would be minimized, with count rates ranging
from 1000 to 15,000 cps, depending on collimator type. Com-
ercial units were used for data acquisition and processing. Images
were obtained in a 128 128 matrix with the balloon filled to 40,
60, 80, 100, 120, 140, and 160 ml. At each volume, images were
obtained with the SAP and SHS collimators, moving only the
collimators. Images from each volume were analyzed by drawing
manually a region of interest (ROI) around the balloon border on
the high-resolution (SAP) image. A background region of interest
was similarly created eight pixels away from the outer edge of the
balloon. These regions of interest were then superimposed on the
high-sensitivity image obtained with the SHS collimator. Thus for
each balloon volume two background-corrected count rates were
obtained, one for the SAP and one for the SHS image.

To simulate the effects of right-heart activity on the left ven-
tricle, a second (right) balloon was introduced beside the “left”
balloon, separated by a 12-mm Plexiglas sheet. While the volume
of the left balloon was kept constant at 100 ml, SAP and SHS
images were obtained with the right balloon filled with 50, 100,
and 150 ml of the same radioactive solution. Typical images pro-
duced by the two collimators are shown in Fig. 2. A left-balloon
region of interest was generated from the SAP image. This region
was then transferred to the SHS images to examine changes in the
left balloon’s count rate as a function of activity in the right bal-
loon.

Preliminary data have been obtained from 12 patients under-
going standard tests for resting ejection fraction and wall motion.
Following the routine patient study, the normal collimator was
replaced with the dual collimator. The patient was repositioned
for an LAO projection using the SAP section, and a multigated
study was performed. The sliding lead aperture was then adjusted
to include only the left ventricle and some adjacent background,
and the collimator was switched to the SHS section. Additional
images were then obtained at the rate of 20 frames per sec in 32
X 32 “zoom” mode. Left-ventricular regions of interest were drawn

![FIG. 1. Exploded view showing arrangement for sliding special
collimators in front of 14-cm hole in aluminum-backed lead frame.
Special all-purpose (SAP) section is to the left, special high-sen-
sitivity (SHS) section to the right. Overlying pair of lead shutters
can be adjusted to limit field of view to left ventricle and a small adjacent
background, minimizing dead-time effects.](image1)

![FIG. 2. Typical images obtained with special collimators. Left: SAP
section imaging two balloons, each 150 ml, separated by 12-mm
plexiglass septum. Only a part of right balloon is visible through
aperture. Right: same, using SHS section.](image2)

![FIG. 3. Comparison of ejection-fraction determinations with SAP
and SHS collimators using count rates for various combinations of
balloon volume.](image3)

| TABLE 1. DUAL-COLLIMATOR
<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>Hole shape</td>
</tr>
<tr>
<td>Septum thickness</td>
</tr>
<tr>
<td>Effective hole diameter</td>
</tr>
<tr>
<td>Collimator size*</td>
</tr>
<tr>
<td>Sensitivity</td>
</tr>
<tr>
<td>(30% window)</td>
</tr>
<tr>
<td>Resolution (FWHM)</td>
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<td></td>
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</table>

* Can be reduced with variable lead aperture.
The effect of varying the volume of a right-heart balloon on the measured left-balloon activity was examined as described in the previous section. No appreciable change in the left-balloon count rate was observed.

Beat-to-beat left-ventricular volume curves for a typical patient study are shown in Fig. 4. Data were acquired with the SHS collimator. Table 2 lists the values for the standard-camera ejection fraction and average beat-to-beat ejection fraction for 12 patients. Linear regression analysis confirms a highly significant correlation ($y = 1.02x - 3.2$, $r = 0.98$, $p < 0.001$).

**DISCUSSION**

The results of this study demonstrate that it is possible to monitor cardiac function accurately on a beat-to-beat basis with an Anger camera. Routine multigated blood-pool studies require about 4-10 million counts over the total field of view for adequate delineation of the end-diastolic and end-systolic left-ventricular borders. However, once the border has been outlined, volume changes can be monitored with substantially fewer counts per frame. Our approach uses a dual collimator to obtain the higher-resolution image necessary for proper heart-border delineation, followed by low-resolution images with the high count rate necessary for beat-to-beat statistics.

The SHS collimator was designed to permit statistically significant beat-to-beat measurements without incurring appreciable dead-time losses. This requires the use of the sliding lead aperture to eliminate counts from areas outside the left heart except for a small region of adjacent background. To achieve similar left-ventricular statistics with a traditional 25-cm collimator would necessitate accepting count rates of more than 200,000 cps. This is beyond the capability of all but the multicrystal camera or possibly one of the new "digital" cameras.

Although a significantly larger penumbral region is produced in the low-resolution image, the correctly sized region of interest from the higher-resolution image limits the high-sensitivity field of view to counts from within the true ventricular border. The increased count rate is almost entirely due to an increase in sensitivity within the region of interest, and only a small component will come from the background outside this area. The background region of interest serves to measure this increase in background counts when collimators are shifted, and is chosen far enough from the ventricular volume.

**FIG. 4.** Left-ventricular beat-to-beat volume curves from a patient study acquired with SHS collimator. Upper curve acquired from end-diastolic ROI; lower curve from end-systolic ROI. Ejection fractions are calculated from peaks of end-diastolic curve and troughs of end-systolic curve.

Using both the end-diastolic and end-systolic frames from the higher-resolution image, a background region was drawn on the end-diastolic frame. These three regions of interest were then transferred to the high-sensitivity images for beat-to-beat processing.

**RESULTS**

Using a region of interest drawn around the balloon border on the SAP image, linearity of balloon count rate versus balloon volume was confirmed for both the SAP and the SHS collimator sections ($r > 0.99$, $n = 7$, $p < 0.001$ for each collimator section).

Ejection fractions were calculated from count rates for all possible combinations of balloon volumes and are compared for the two special collimators in Fig. 3. The data show a correlation coefficient of $r > 0.99$, $n = 17$, $p < 0.001$.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Avg. EF</th>
<th>No. of beats</th>
<th>Std. dev. (EF units)</th>
<th>Standard EF (SAP collimator)</th>
<th>EF difference: standard—beat-to-beat</th>
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<tr>
<td>1</td>
<td>59.6</td>
<td>40</td>
<td>2.6</td>
<td>60.9</td>
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<td>2</td>
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<td>3</td>
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<tr>
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<td>42</td>
<td>1.6</td>
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<tr>
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<tr>
<td>9</td>
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<td>85</td>
<td>4.1</td>
<td>71.0</td>
<td>-1.5</td>
</tr>
</tbody>
</table>
tricular border to be outside the penumbral region of the ventricle.

As shown in Fig. 2, counts from a RV balloon overlap into the photon-deficient 12-mm septal region and spill into the LV balloon region to some extent. Note, however, that the increased septal activity is due to contributions from both balloons, and therefore any visual appearance of significant RV overlap into the septal area may be misleading. Comparison of counts from the high-sensitivity images of a 100-mL LV balloon (using the higher-resolution ROI) while the RV balloon simulated a 67% ejection fraction (50 to 150 ml) resulted in no appreciable change in the LV balloon count rate.

This method has advantages for beat-to-beat monitoring of cardiac function over techniques using a nonimaging probe. With such a probe the left ventricle must be localized in a blind manner making localization, as well as subsequent repositioning, uncertain and time-consuming procedures. In addition, artifacts from patient motion and the possible inclusion of right-heart activity must be considered potential problems. Thus, the Anger camera’s ability to locate the left ventricle represents a significant improvement for the monitoring of beat-to-beat phenomena.

Although this system does not permit visualization of wall motion in the beat-to-beat mode, that information is available from the initial multigated study. In the beat-to-beat mode, however, we can measure rapid changes in ejection fraction, stroke volume, relative end-diastolic and end-systolic volumes, and relative cardiac output, which were not previously obtainable on a beat-to-beat basis with a gamma camera. Possible applications of this technique include monitoring cardiovascular changes during arrhythmias and during drug interventions.

REFERENCES