Dynamic Geometric Mean Studies Using a Single Headed Rotating Gamma Camera

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A technique for acquiring dynamic geometric mean studies utilizing a single-headed rotating gamma camera has been developed. The camera head is repeatedly rotated between opposed views under computer control. A single data set results, from which a dynamic sequence of geometric mean images can be produced. Software has been developed to accomplish data acquisition and the reformatting required. The accuracy of the geometric mean data formed using this technique has been studied experimentally, and compared with results obtained from anterior and posterior sequences. In a simple clearance experiment of a 1-l volume with a known clearance of 20 ml·min^{-1}, the geometric mean data resulted in estimates of volume remaining in the container with a mean error or +2.0 ml (s.d. = 5.7 ml, range −4.5 ±15.3 ml), while the anterior and posterior images yielded volume estimates with mean errors of −10.1 ml (s.d. = 16.6 ml, range −47.4 ±10.5 ml) and +35.5 ml (s.d. = 22.6 ml, range −3.2 ±51.6, ml), respectively. The technique is easy to implement and does not require modification of existing hardware. An application of the technique to a clinical study of gastric emptying is also included.

J Nucl Med 30:1865–1869, 1989

Many nuclear medicine investigations require a quantitative assessment of radioactivity in vivo that is independent of source geometry and position, and attenuation by the body. The method of using geometric mean (GM) images is particularly applicable for this purpose because of the depth-independent characteristics of the technique (*1*). A geometric mean image is formed by calculating

$$G_{gm}(i,j) = (G_{\theta}(i,j)*G_{\theta+180}(i,j))^{1/2},$$

where G(i,j) is the value of the image for each pixel (i,j), G_{θ} & $G_{\theta+180}$ are diametrically opposed views of the object distribution, and the subscript gm indicates the geometric mean.

Numerous reports have been published describing the use of GM images in the measurement of in vivo radioactivity (*2–5*). This method has decided advantages in dynamic measurements of, for example, gastric emptying, where the source distribution and depth in the abdomen change markedly as the radionuclide moves through the stomach (*6*). Without the use of GM data, or attempting to make a spatially variant depth correction on a single view dataset, the measurement of radioactivity leaving the stomach can be in error because of, in general, the posterior-anterior transit of the meal as it moves from proximal to distal stomach. Quantitative measures of radioactivity in the thorax can be achieved by combining the GM image with a transmission scan and result in activity estimates accurate to ~5% (*7*). However, dynamic GM studies, such as measurement of gastric emptying, have previously only been accomplished with a dual-headed gamma camera, or using two separate cameras, one of which is usually mobile. Both solutions have disadvantages; the first is an expensive option, while the second places a high demand on resources, with two cameras being required to record one study. Other problems relating to field size and sensitivity also ensue.

A method developed in our department is reported here where a single headed rotating gamma camera has been used to record dynamic GM studies by sequentially rotating between opposing views under computer control. Subsequent reformatting allows serial GM images to be formed.

Received Apr. 29, 1988; revision accepted July 18, 1989.

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MATERIALS AND METHODS

The method has been implemented on two different gamma cameras in this department (Diagnost Tomo Philips, Hamburg, FDR & GE400AT General Electric Medical Systems, Milwaukee, WI). Both are large field-of-view (LFOV) gamma cameras normally used for routine planar and single photon emission tomography (SPECT) imaging. All camera movements are controlled by an on-line computer (PDP-11 Digital Equipment Corporation (DEC), Maynard, MA) which also acquires the radionuclide image data. The hardware, which is used for controlling the gantry rotation during SPECT acquisitions, has not required any modifications for the current work. The Philips camera is controlled by a serial interface (DLV-11/J DEC, Maynard, MA) and the General Electric camera by a parallel interface (DR-11/C DEC, Maynard, MA). The computer operating system is a foreground/background environment (RT-11FB DEC, Maynard, MA), permitting two concurrent jobs to run. Software written in RATFOR (*8*) and MACRO-11 (DEC, Maynard, MA) has been developed which operates in the background mode to control this gantry rotation and the amount of time spent stationary, while dynamic image acquisition is performed by the foreground job using the normal software package (GAMMA-11 DEC, Maynard, MA).

Acquisition strategy. With the subject positioned on a cantilevered scanning couch, both foreground and background jobs are started simultaneously. After the acquisition of the first (anterior) image the background program rotates the camera while the foreground program continues acquiring into the next frame of the dynamic. When the camera is in the new (posterior) position a software clock in the background program waits for the present ("rotation") frame to finish collecting and then the camera remains stationary for the length of time equivalent to the next frame in the dynamic study. At the end of this period the background program rotates the camera back to the original (anterior) position and waits to commence acquiring the next frame, and so on. The frame time is chosen so as to be always slightly greater than the camera's rotation time so that the camera waits a short time before the next dynamic frame starts acquiring to ensure synchrony. The result at the end of the study is a single dataset which contains alternate anterior and posterior views interspersed with superfluous frames acquired during the gantry rotation. In this department, most of the acquisitions are over 30–60 min. Reformatted frame times are usually in the range 30–90 sec/frame.

Reformatting is performed after the completion of the study. The software developed makes use of an array processor (AP400 Analogic Corporation, Wakefield, MA) to minimise computation time. For each frame (apart from the first and last), the program firstly forms a *temporal* GM interpolated image of the $(n-1)^{th}$ and the $(n+1)^{th}$ image, which corresponds to the opposing view at the time of the n^{th} image, ignoring the "rotational" images. One of the views (usually the posterior) is then mirrored, and both the temporal mean and n^{th} images are corrected for center-of-rotation (COR) offset, as for a SPECT study, before reforming the GM image (see Fig. 1). This procedure is next carried out on the n^{th}, $(n+1)^{th}$, and $(n+2)^{th}$ images in the same way, and so on. Correction for radionuclide decay is also performed. An-

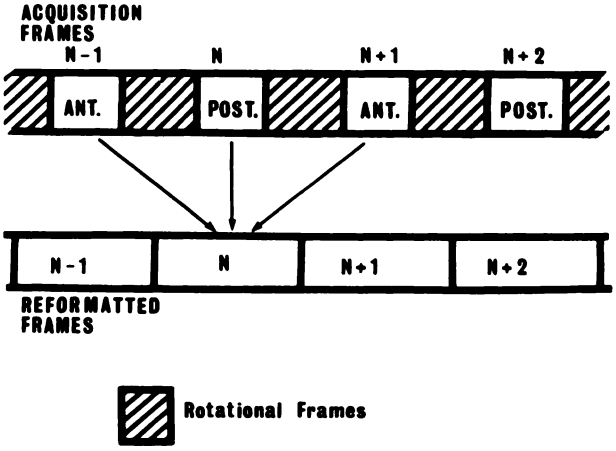

FIGURE 1
The relationship between the frames acquired in the dynamic series (including rotational frames) and the reformatted GM images is shown. Any reformatted frame N is the GM of the acquisition frame N with the GM of frames N − 1 and N + 1. This is repeated for every acquisition frame. The rotational frames may contain more than one single frame interspersed between anterior and posterior views, and the time to rotate is always slightly less than a multiple of the acquisition frame rate.

other option in a dual radionuclide study, such as in simultaneous liquid-solid gastric emptying with ^{111}In and ^{99m}Tc, is to remove scatter in the lower energy window from the higher energy radionuclide using a previously described convolution-subtraction method (*9,10*). The GM advantage of relative depth-independence is equally desirable in this operation. Further information about the acquisition and reformatting programs and source code are available upon request.

It can be seen that the reformatted data exhibits two features that distinguish it from a "normal" dynamic dataset: first, the data is sampled for a certain period of time within a larger time interval and is therefore noncontinuous, and second, the data has an inherent geometric 1-2-1 smooth built into it by virtue of combining with the temporal GM image. Neither of these features is felt to present a problem as long as the reformatted rate is sufficient to adequately sample the rate of change under consideration in the study.

Experimental Validation

A simple clearance experiment was conducted to test the technique. A one litre soft plastic infusion ("drip") package containing saline had approximately 200 MBq (5.4 mCi) of ^{99m}Tc in 0.3 ml added and was subsequently well mixed. The pack was then connected to an infusion set so that flow out of the pack could be regulated. The pack was placed in a tank (dimensions 30 cm × 20 cm × 20 cm) and the tank filled with water. The pack was supported at an inclined angle by a piece of sponge rubber and a piece of perspex, to offer some non-homogeneous attenuation. A dynamic GM study was acquired while the infusion set was regulated to flow out of the pack at ~20 $ml \cdot min^{-1}$. The liquid leaving the pack was collected and the total amount removed was recorded each minute. The acquisition was over a 30-min period. In this way, the volume and flow determined from the GM data could be compared with the liquid measured, as well as the anterior and posterior

images. The total volume of the pack was determined at the end of the study.

RESULTS

Experimental Validation

Figure 2 shows the calculated volume remaining in the pack during the acquisition from the measured volume, GM counts, the anterior, and posterior counts. All counts are decay corrected. No corrections for attenuation have been made. Compared with the measured volume, the GM volume shows an average error for the entire study of +2.0 ml (s.d. = 5.7 ml, range −4.5 - +15.3 ml), the anterior mean error is −10.1 ml (s.d. = 16.6 ml, range −47.4 - +10.5 ml), and the posterior mean error is +35.5 ml (s.d. = 22.6 ml, range −3.2 - +51.6 ml). As the pack emptied it collapsed towards the bottom surface of the tank, which, because of changes in depth and hence attenuation, may explain the general overestimation of the posterior counts and the underestimation of the anterior counts relative to the GM. The GM showed high accuracy, even taking these positional variations into account.

Clinical Example

An example taken from a clinical study is included to illustrate the differences that may be observed with different acquisition strategies. A solid phase gastric emptying study utilizing the rotating GM method was acquired and subsequently reformatted as (1) GM data, and (2) anterior and (3) posterior only data by selecting out those frames from the acquisition data. This is shown in Figure 3. It is clear that the GM and anterior data show similar emptying rates, while the posterior, in this example, is different. As there was no correlation

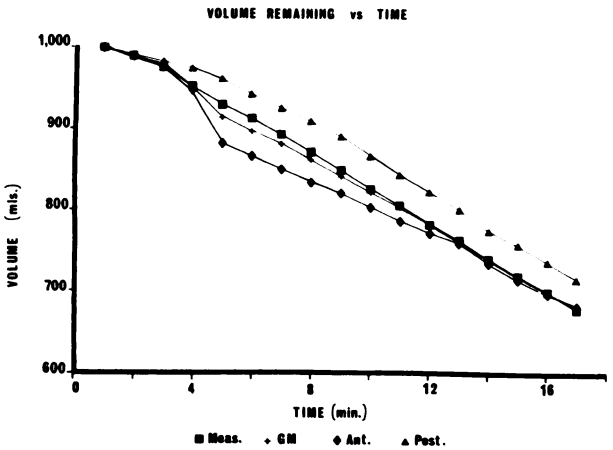

FIGURE 2
Volume remaining is shown with respect to time for the measured volume (meas.), the GM, and anterior, and posterior views. The GM exhibits a mean error of +2.0 ml in estimated volume over the whole study, compared with −10.1 ml for the anterior and +35.5 ml for the posterior.

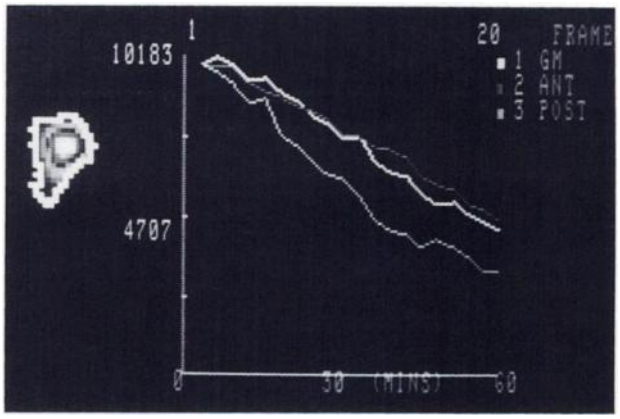

FIGURE 3
Solid phase gastric emptying is shown for (1) geometric mean, (2) anterior, and (3) posterior data for the same acquisition. In this example the GM and anterior data result in the same emptying rates while the posterior is different. This situation would not necessarily apply to another individual.

of this patient's gastric emptying with a gold standard technique for validation, this example only serves to illustrate that differences may be observed depending on the view acquired. In this example the GM and anterior data would have resulted in the same emptying values, but this may not be true for a different individual.

DISCUSSION

Dynamic GM studies are well accepted as offering considerable advantages in studies involving radiotracers which move through an organ or compartment. In gastric emptying studies, the dynamic GM is accepted as the "gold standard". Compared with this, other single view methods require modifications for attenuation correction using lateral views and are less accurate (*6*). In this department we have employed the method described in dual radionuclide liquid-solid gastric emptying studies and measurements of radioaerosol elimination from the lungs via mucociliary clearance (*11*). In the latter application, a transmission scan is recorded beforehand to allow activity changes to be calculated with time. This is a step closer to better quantitation: to be able to measure the time course of absolute activities in vivo.

As can be seen from Figure 1, the reformatted frame time is equivalent to twice the acquisition frame time, when frame time is approximately equivalent to the rotation time. In general, the reformatted frame time will be given by

$$F = \frac{A}{R}$$

where F = reformatted frame time, A = acquisition frame time, and R = the "live" time ratio, that is the ratio of "live" acquisition time to the total time for one sequence (i.e., live frame plus rotational frames up to the next live frame).

On the Philips camera, it takes ~17–18 sec to rotate the 180° from anterior to posterior. In an implementation with 20 sec per acquisition frame this leads to an equivalent reformatted frame time of 40 sec. The General Electric camera takes slightly <60 sec to rotate through 180°. The acquisition frame time normally employed here is 30 sec, giving one live frame followed by two rotational frames. This results in a live time ratio of 0.33 and consequently a reformatted frame time of 90 sec. Of course, faster or slower reformatted frame times can be employed even given the limitations of a fixed rotation time. For example, the General Electric camera implementation could be made to be 60 sec per acquisition frame, leading to a reformatted frame time of 120 sec. Alternately, the Philips camera's reformatted frame time could be reduced to 30 sec by using an acquisition frame time of 10 sec. It must be remembered, though, that the shorter the frame time the lower the live time ratio. It is usually desirable for statistical considerations to have the highest live time ratio acceptable.

Some points related to the implementation here are worth commenting on. First, it would be more satisfactory to integrate the rotation control into the data acquisition program, as is done in SPECT acquisition. This would result in two major advantages: there would be no "rotational" frames which would need to be deleted during reformatting, and synchrony between rotation control and image acquisition would be assured. However, this would require either modification of the software manufacturer's source code which, in general, is not available, or developing in-house data acquisition programs. Both of these options require a good deal more programming effort than in our implementation. As the same hardware clock is used for both foreground and background programs it is unlikely that the respective programs will get "out-of-step". Also, a reformatting program will still be required to correct for COR offset, radionuclide decay, and forming the GM images. Therefore, this simple implementation in-house seems to be satisfactory. Reformatting time using an array processor is <0.5 sec per reformatted frame, including COR offset, decay correction and subtraction of previously estimated scatter. If an array processor is not available, the reformatting can be carried out by the same program that controls the gantry rotation in the spare time it spends waiting for the current frame to acquire, by operating on the previous frames. This would result in the reformatted dataset being available shortly after the final frame has finished acquiring.

Second, the temporal mean image formed is a simple geometric interpolation of frames (n − 1) and (n + 1). Whether the clearance under consideration is linear or exponential, the interpolation error introduced by using a geometric mean will be minimal. Use of an arithmetic interpolation would lead to greater errors for a nonlinear change in countrates than would the geometric interpolation. Both cases are in fact present in normal gastric emptying; liquid emptying following an exponential function while solid emptying follows a linear function (*12*).

The implementation of this software into a nuclear medicine department would require the development of a program that allowed the user to control the camera gantry. While this is not sophisticated in itself, the camera manufacturer must be willing to provide the information about the gantry control instructions necessary to accomplish the task. The reformatting program is straightforward and should be simple to implement on any nuclear medicine computer system.

The advantages of this method are considerable. A dual-headed gamma camera is an expensive option outside the justifiable expenditure of most departments. Even here though, there may be differences in sensitivity and uniformity between the two detectors. This option does, however, have the advantages of a twofold increase in sensitivity and monitoring is continuous, thereby enabling fast sampling frame rates to be achieved. The use of two separate cameras has disadvantages of a high demand on resources (two cameras required for one study), and usually two computers would be required to acquire the data. Even after both cameras' data are on the same analysis computer, considerable manipulation of the data is needed to adjust for differences in frame size, sensitivity, and image position in the matrix. Conversely, most departments have at least one single headed SPECT-capable camera to which this method may be applied, without any hardware modifications. The main disadvantage would be that monitoring is non-continuous. However, for studies where measurements are made over long periods of time (e.g., 10 min to 1 hr) this method is adequate. Examples of such studies include gastric emptying and mucociliary clearance.

Another attractive feature of this method is that it provides GM *images* of the activity distribution, rather than simply curves. This allows the activity changes to be visualized (as GM images) in, for example, a cine mode, which gives a global overview of the activity changes and may allow better definition of regions of interest.

The simple experimental example cited serves to illustrate the variations in clearance measurements that can be obtained when the activity distribution under examination changes in position during the course of the study. It would be possible in the example given to perform a lateral image correction for attenuation, how-

ever, this is not regarded as being as accurate as GM data (*6*).

SUMMARY

Software has been developed to control the rotation of single-headed SPECT LFOV gamma cameras to allow the acquisition of dynamic GM studies. The method provides GM images of a changing activity distribution for minimal software development. This could be implemented in any department with a rotating gamma camera. Reformatting is rapid and may incorporate corrections for radionuclide decay, COR offset, and scatter subtraction while the GM image is formed. The method has application in dynamic studies recorded over a time period of minutes to hours, and especially where the radiotracer may move anterioposteriorly during the measurement period. Without the use of GM images, this would result in inaccuracies in clearance measurements.

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