Two Optimal Prefilter Cutoff Frequencies Needed for SPECT Images of Myocadial Perfusion in a One-Day Protocol

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Objective: The purpose of this study was to determine if cutoff frequencies of two-dimensional Butterworth filters need to be changed, depending upon the amount of radiopharmaceutical administered in one-day protocols for reconstructing SPECT images of myocardial perfusion.
Methods: A scintilation camera and a phantom were used with 2.2 MBq and 10.6 MBq ^{99m}Tc. These activities corresponded to the approximate amounts used in our one-day myocardial perfusion imaging protocol. The projection data were collected in 30 positions spread over 180°. Thirty- and 150-sec acquisitions per position were performed to obtain the study and the high-quality reference images. Thirteen cutoff frequencies of the filter were used to reconstruct the SPECT images. Optimal cutoff frequencies were determined by visual assessment and by calculating the normalized mean square error (n.m.s.e.). These results were then compared. The same protocol was used to image three volumteers with no heart disease and the images were evaluated visually.
Results: In the phantom study, the optimal cutoff frequencies were 0.225 cycles/pixel for 2.2 MBq, and 0.275 cycles/pixel and 0.25 cycles/pixel for 10.6 MBq by visual inspection, and were 0.225 cycles/pixel and 0.275 cycles/pixel by calculating the n.m.s.e., respectively. In the patient study, the lower cutoff frequency of 0.20 cycles/pixel was optimal for the exercise study (low dose), while the higher cutoff frequency of 0.275 cycles/pixel was optimal for the resting study (high dose).
Conclusion: The optimal cutoff frequencies differed for the two activity levels. Cutoff frequencies should be changed according to the amounts of radiopharmaceuticals used for the first and the second examinations in one-day protocols.
Key Words: SPECT; cutoff frequency; normalized mean square error; myocardial perfusion imaging

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Myocardial perfusion has long been evaluated with ^{201}Tl (*1*). Recently several ^{99m}Tc-based myocardial perfusion agents have been developed to assess coronary arterial disorders (*2–4*). Technetium compounds have many advantages in diagnostic imaging over ^{201}Tl (*5–7*). Technetium has less absorption and scattering of its gamma ray due to the higher energy, and its shorter half-life allows the administration of larger amounts of radioactivity leading to higher image quality. In addition, as these ^{99m}Tc agents have no redistribution as seen in the delayed ^{201}Tl image, the resting and exercise myocardial perfusion examinations can be performed on the same day (*8–12*). With this physical superiority and clinical convenience, one-day protocols with ^{99m}Tc compounds are now favored over ^{201}Tl.

The quality of SPECT images is known to be affected by several factors such as the amount of radionuclide administered, the filter processing and the resolution of the collimators (*13–14*). Among these factors, the amount of radiopharmaceutical administered has dramatic impact on the quality of the images (*15*). Although different amounts of ^{99m}Tc-labeled compounds are administered for the resting and the exercise examinations in one-day protocols (about three times more radioactivity is given in the second examination than in the first), little attention has been paid to prefilter cutoff frequencies in reconstructing SPECT images of these two studies. Therefore, we investigated the optimal cutoff frequencies suitable for each examination.

MATERIALS AND METHODS

Phantom Study

Images were acquired with a rotating single-head scintilation camera equipped with a low-energy, high-resolution (LEHR) collimator with a FWHM of 5.7 mm. The phantom consisted of a cylindrical heart insert (10 cm diameter) of constant wall thickness (1 cm) that was inserted into an elliptical thorax (30 cm × 20 cm) that included the lungs (polystyrene/water mixture) and spine (acrylic). The heart insert had a myocardial space of 200 ml with one defect simulating myocardial infarction. The heart insert was filled with a ^{99m}Tc-saline solution of 2.2 MBq or 10.6 MBq for this study.

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The one-day protocol for myocardial perfusion imaging, including both rest and exercise and using ^{99m}Tc-1,2-bis[bis(2-ethoxyyethyl) phosphino] ethane (tetrofosmin), in our institution was followed (*16–17*). The exercise study is performed with 185 MBq (the first dose) of ^{99m}Tc-labeled agent and then the resting image is obtained about 3 hr later with the second administration of 740 MBq of the same agent. The calculated total-body activity was 880 MBq for the resting study. Since about 1.2% of the administered dose is estimated to accumulate in the myocardium (*18*), 2.2 MBq and 10.6 MBq were injected into the phantom.

Data Acquisition and Image Reconstruction. Projection images were obtained by rotating the scintilation camera with an acquisition matrix size of 64 × 64 and pixel size of 5.33 mm. The projection data were collected in 30 different positions equally spread over 180°. For the study images, a 30-sec acquisition was performed for each position. A high-quality image that was acquired to be used to calculate the normalized mean square error (n.m.s.e.). Counts were accumulated for 150 sec at each rotation angle, which was five times longer than that for the study images. Noise was relatively low in these images and these images served as the gold standard for comparison.

Transaxial SPECT images were reconstructed using a two-dimensional Butterworth prefilter (order 8) and ramp back-projection for the study images, whereas no prefilter was used for the high-quality images. Vertical long-axis SPECT images of the entire left ventricle were displayed from the reconstructed transaxial SPECT images by performing coordinate transformation reorientation with an appropriate interpolation. No attenuation or scatter correction was performed. Thirteen different filter cutoff frequencies, ranging from 0.1 cycles/pixel to 0.4 cycles/pixel, with increments of 0.025 cycles/pixel, were applied to reconstruct each of the SPECT images obtained with the two different ^{99m}Tc activities.

Image Assessment. Images were assessed using one frame of the vertical long-axis images that demonstrated the defect best. Optimal cutoff frequencies were determined by visual inspection and by calculating the n.m.s.e. (*19*).

SPECT images were reconstructed at the different cutoff levels for visual inspection. The vertical long-axis images were visually assessed by five experienced radiologists. The radiologists selected the most similar image among the study images, in comparison with the high-quality image, and optimal cutoff frequency was determined by visual inspection.

Image subtraction was performed between the study and the ideal image on a computer workstation to calculate the n.m.s.e. The values of n.m.s.e. were derived by the equation:

$$NMSE = \frac{\sum_{x=0}^{X}\sum_{y=0}^{Y}(g(x,y) - f(x,y))^2}{\sum_{x=0}^{X}\sum_{y=0}^{Y}f(x,y)^2},$$

where f (x, y) and g (x, y) indicate the location of a pixel on the x-y axes of the high-quality and the study images, respectively. The cutoff frequency that minimized n.m.s.e. was considered the optimal cutoff frequency determined with this method.

Subject Study

Three volunteers with no heart disease had myocardial perfusion imaging using the one-day protocol to evaluate if the same cutoff frequencies can be used for both high- and low-activity levels. Images of high cutoff frequencies were compared with those of low cutoff frequencies. The same acquisition parameters were used as for the phantom study. An acquisition time of 30 sec was used. Technetium-99m-tetrofosmin (185 MBq) was injected for the exercise study and 740 MBq were injected for the resting study. SPECT imaging was performed 30 min after injection for both studies. As in the phantom study, the same 13 different cutoff frequencies were used for image reconstruction and the images were compared visually.

RESULTS

Phantom Study

The SPECT images reconstructed using different cutoff frequencies at activities of 2.2 MBq and 10.6 MBq are shown in Figures 1 and 2. The images obtained with 10.6 MBq are much less noisy when compared with images of 2.2 MBq. When the study images were visually compared with the the high-quality image at 2.2 MBq, the radiologists considered the study images at a cutoff frequency of 0.225 cycles/pixel to have the highest quality. At 10.6 MBq, three of the five radiologists selected the study image at a cutoff frequency of 0.275 cycles/pixel and the remaining two radiologists selected a cutoff frequency of 0.25 cycles/pixel.

The cutoff frequencies that minimized the n.m.s.e. values at activities of 2.2 MBq and 10.6 MBq are shown in Figure 3. Cutoff frequencies of 0.225 cycles/pixel and 0.275 cycles/pixel minimized the values of n.m.s.e. at 2.2 MBq and 10.6 MBq, respectively.

Subject Study

Vertical long- and short-axis images at lower and higher activity levels of one of the three volunteers are shown in Figure 4. At 2.2 MBq, compared with the image of 0.20 cycles/pixel (Fig. 4A, C), the image of 0.275 cycles/pixel (Fig. 4B, D) shows an irregular margin of the heart wall with artifact-like defects that were misdiagnosed as myocardial infarction. At 10.6 MBq, the image of 0.20 cycles/pixel (Fig. 4E, G) shows a relatively smooth heart wall compared with that of 0.275 cycles/pixel (Fig. 4F, H).

DISCUSSION

Our phantom study shows how SPECT images vary depending on cutoff frequencies and amounts of radioactivity. In general, SPECT image quality depends on the reconstruction parameters such as matrix size, counts per pixel, radius of the camera rotation, and so on. The quality of SPECT images is known to be highly dependent on the cutoff frequencies of preprocessing filters and count density (*20–22*). Currently, the

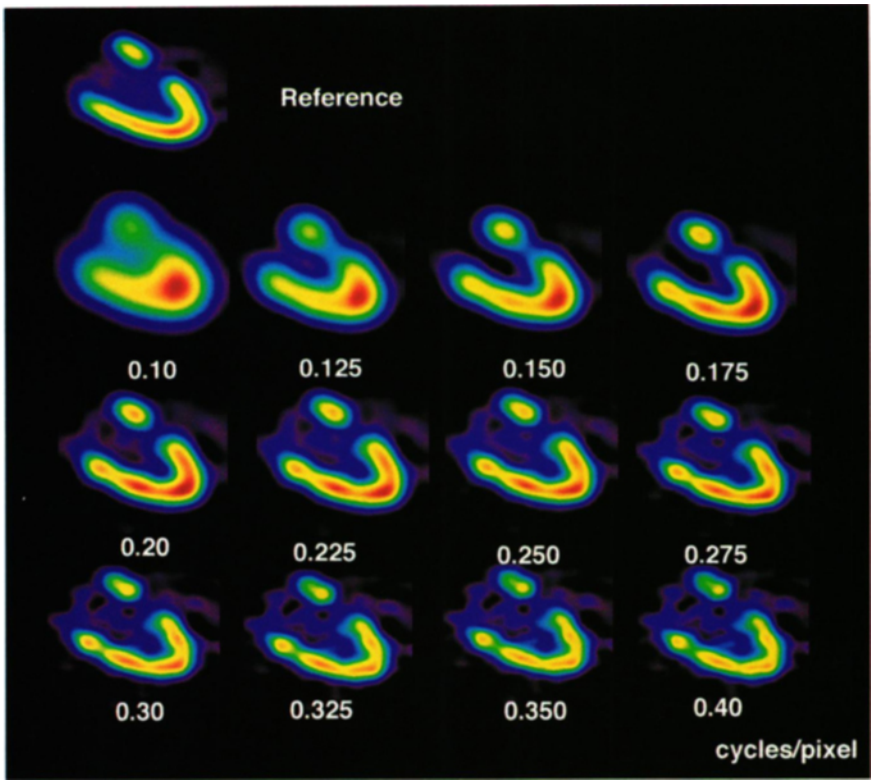

FIGURE 1. SPECT phantom images obtained with 2.2 MBq ^{99m}Tc saline solution. The top is the high-quality reference image, and the remainder are study images. The cutoff frequency for each study image is shown below the image.

two-dimensional Butterworth filter, low-pass filter is widely used as a prefilter before image reconstruction to reduce the high-frequency random noise that degrades image quality.

It is important to determine the optimal cutoff frequencies of the prefilter in reconstructing the SPECT images for one-day protocols. Garcia et al. (*23*) evaluated the optimal cutoff frequencies in relation to the ratio of maximum-to-minimum counts in regions of interest selected from one reconstructed image. In our clinical practice, however, SPECT images are visually evaluated. Clinicians observe not only local defects on

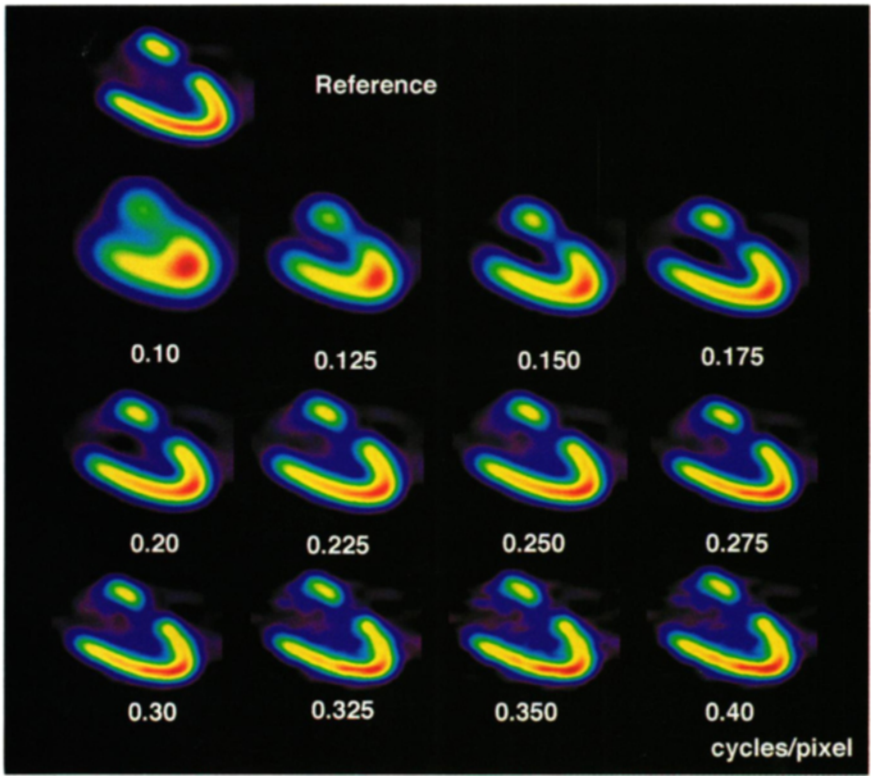

FIGURE 2. SPECT phantom images obtained with 10.6 MBq ^{99m}Tc saline solution. The top is the high-quality reference image, and the remainder are study images. The cutoff frequency for each study image is shown below the image.

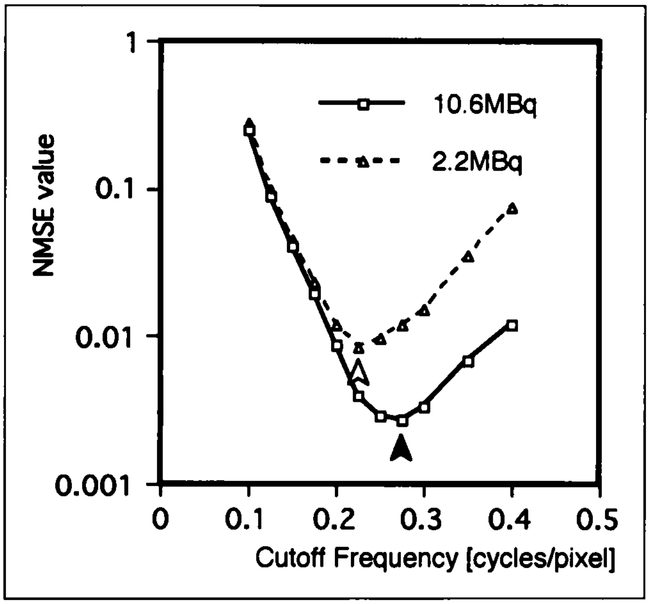

FIGURE 3. Relationships between cutoff frequencies and n.m.s.e. at the two activity levels. The solid and dotted lines are activities of 10.6 MBq and 2.2 MBq, respectively. The cutoff frequencies of 0.225 cycles/pixel and 0.275 cycles/pixel that minimize the values of n.m.s.e. at activities of 2.2 MBq and 10.6 MBq are indicated by opened and closed arrow heads, respectively.

the SPECT images but also the global shape of the images. Therefore, we evaluated optimal cutoff frequencies using visual inspection as well as n.m.s.e. In comparing the two sets of images at different activity levels, we observed that the lower activity images were of poorer quality. One reason is that reconstructed noise is enhanced in the reconstructed images. For lower activity levels, therefore, optimal cutoff frequencies need to be shifted to a lower frequency. However, when the cutoff levels are shifted to the low range, the images get blurred, as shown in Figure 1. When cutoff frequency level is shifted to higher frequencies, small perfusion defects, which may be fatal artifacts for clinical diagnosis, may appear (Fig. 1).

Our n.m.s.e. study reveals that the cutoff frequency of 0.225 cycles/pixel was optimal for low activity (2.2 MBq) images. This frequency was deemed appropriate from visual inspection of the images.

For the high activity (10.6 MBq) image, the optimal cutoff frequency assessed by visual inspection was slightly different among the radiologists. This inconsistency may be attributable to less noisy study images. When assessed by n.m.s.e., the optimal cutoff frequency was 0.275 cycles/pixel, which was close to that determined by visual inspection.

As shown in this study, the optimal cutoff frequencies evaluated by n.m.s.e. differed at the two activity levels. The radiologists also selected different optimal cutoff frequencies for the high and low activities. This result indicates that cutoff frequencies need to be changed depending on the amount of radiopharmaceutical administered. If the optimal cutoff frequency for the first examination (185 MBq) is fixed during the examination, this frequency would be too low for the second examination (880 MBq in total), and the images from the second examination would be sub-optimal. Likewise, if a cutoff frequency is optimized for the second examination, the images of the first examination may produce artifacts that might lead to misdiagnosis.

The subject study confirmed this concept, in that an artifact was observed at the higher cutoff frequency of 0.275 cycles/pixel at the lower activity level (185 MBq). The lower cutoff frequency of 0.20 cycles/pixel was optimal for the exercise study (lower activity), while the higher cutoff frequency of

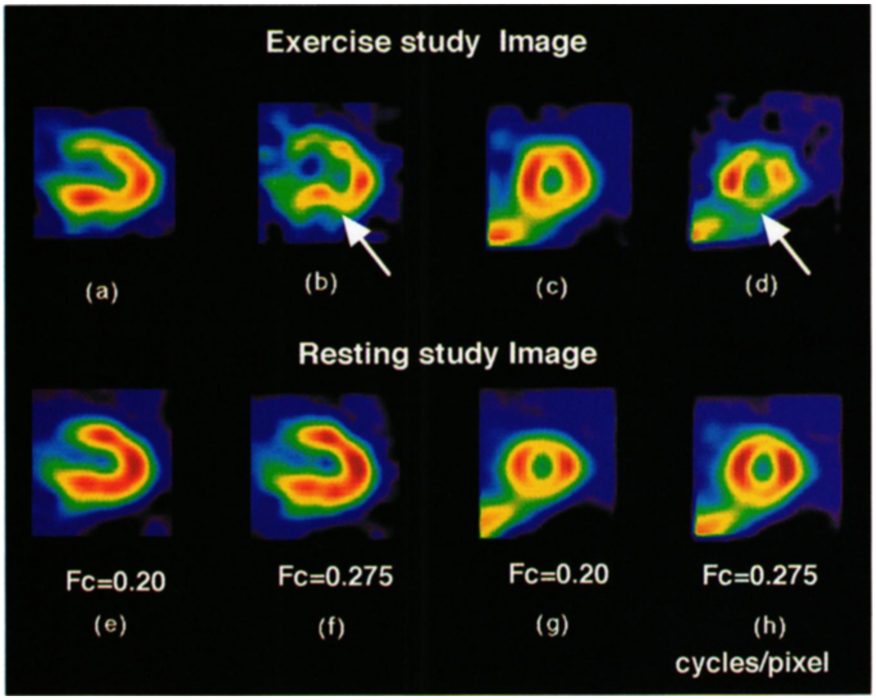

FIGURE 4. Vertical long- and short-axis images of the subject study at the two different cutoff frequencies. The upper and lower rows are at the lower and higher activities, respectively. (a, c, e, g) 0.2 cycles/pixel. (b, d, f, h) 0.275 cycles/pixel. The arrows indicate artifact-like defects at the inferior wall of the left ventricle images.

0.275 cycles/pixel was optimal for the resting study (higher activity). This trend would become more prominent in in vivo studies than in phantom studies because of heart motion, myocardial extraction fraction and other factors that can also affect image quality. Therefore, if only one cutoff frequency is used for both first and second examinations, neither of the images will be optimum for diagnosis.

CONCLUSION

Our study revealed that optimal cutoff frequencies are different depending on the amount of radionuclide administered to the patients. The cutoff frequencies should be adjusted to the optimal levels according to the amount of radionuclide used for the first and second examinations in a one-day protocol.

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