

Optimal Reconstruction Filter Parameters for Multi-Headed Brain SPECT: Dependence on Count Activity

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Objective: Reconstruction parameters must be optimized to approach the improved spatial resolution that is theoretically possible from modern SPECT imaging devices. One important reconstruction consideration is proper selection of the back-projection filter parameters. The aim of this study was to determine which Butterworth filter optimized image resolution for brain SPECT scans.

Methods: Ten normal subjects underwent brain SPECT following an intravenous injection of 15–20 mCi ^{99m}Tc -HMPAO (5 subjects) and 30–35 mCi ^{99m}Tc -HMPAO (5 subjects). Subjects were separated into two groups based on the counts per pixel in the anterior projection image: 5 subjects with low-count images (10.4–13.9 counts/pixel) and 5 subjects with high-count images (18.3–21.5 counts/pixel). All subject projection data were reconstructed at cutoff frequencies (F_c) ranging from 0.15–0.3 Nyquist, with orders ranging from 2–12 at each frequency cutoff. Optimal image selection was determined by blinded subjective assessment by three nuclear medicine faculty capable of evaluating brain SPECT image quality.

Results: Results demonstrated that for low-count images, optimum Butterworth filter reconstruction parameters were: $F_c = 0.20$, order 6. For high-count images, optimum parameters were: $F_c = 0.225$, order 7.

Conclusion: The proper selection of F_c is the most critical parameter for optimization of image reconstruction quality.

Key Words: SPECT; brain; image reconstruction; back-projection filter; technetium-99m-HMPAO

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High spatial resolution SPECT imaging of the brain has been enhanced by development of multiple-head detector systems. However, the highest image quality is obtained only by optimizing all elements of image processing.

Proper image reconstruction depends on the ability of the technologist to select appropriate reconstruction parameters

which produce brain SPECT images that maximize the information from the acquired counts to obtain the greatest sensitivity and specificity for disease detection. These reconstruction filter parameters for a Butterworth filter include frequency cutoff (F_c) and order. Other considerations for optimization depend on the matrix size, counts per pixel, radius of camera rotation, pixel size and personal preference of the interpreter (1–4). The purpose of our study was to determine the optimum Butterworth filter parameters for the dual-head gamma camera operating at conditions near its maximum resolution for brain SPECT. This was achieved by using a 25.4-cm square field of view and a 128×128 matrix (1.98 mm/pixel) acquiring 128 projections (64 stops per head) at 30 sec per stop. This resulted in an extrinsic spatial resolution (FWHM) at the brain cortex of approximately 8.5 mm for high-count brain images.

Performing reconstruction from a 128×128 , matrix requires a greater degree of ability to correctly select the frequency cutoff and order (as compared to a 64×64 matrix) since small adjustments in frequency cutoff selection produce large variations in the image reconstruction quality. Images rapidly progress from an overly smooth appearance to an image that appears too noisy as F_c increases over a small range. The number of counts per pixel for a given pixel size is the greatest variable in selection of the appropriate reconstruction parameters. We performed studies on normal subjects that had significantly different cortical counts per pixel to determine which frequency cutoff and order produced optimal image reconstruction using the Butterworth filter. Figure 1 illustrates the mathematical characteristics of the Butterworth filter and shows how the filter function (in Fourier frequency space) is dependent on the product of the ramp function times the window function. Use of this product to define the event selection criteria results in a relatively small contribution from very high or low frequencies and larger contributions from intermediate frequencies. The optimum choice of frequency cutoff and order results in most contributions arising from intermediate frequencies, and the overall image quality depends on the counts per pixel and filter function.

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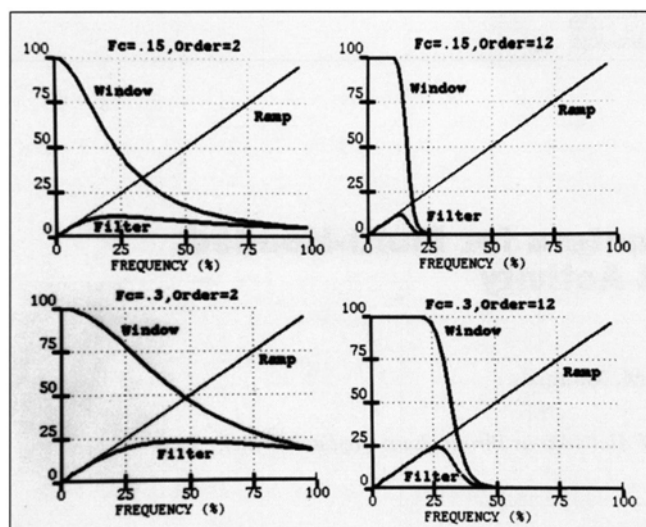


FIGURE 1. Butterworth filter function for representative frequency cutoffs (0.15–0.3) and orders (2–12) used in this analysis. The filter function is the product of the ramp times the window function (in this case, Butterworth). Larger values of F_c increase the point of maximum window acceptance for a fixed order, while increasing the order for a fixed frequency cutoff increases the steepness at which the window drops to its minimum value.

METHODS

Ten normal subjects were evaluated after the intravenous injection of a low dose (15–20 mCi) and higher dose (30–35 mCi) of ^{99m}Tc -HMPAO. Imaging was performed approximately 15 min post-injection. Imaging was performed using the dual-head Anger gamma camera (ADAC Dual-Head Genesis, ADAC Laboratories, Milpitas, CA), equipped with low-energy, high-resolution, parallel-hole collimators, obtaining 128 projection images over 360° rotation. The field of view was 25 cm. Image data was acquired and stored into a 128 × 128 matrix and filtered back projection reconstruction was performed using a Butterworth filter. The Chang attenuation correction algorithm was employed in all subjects (5). The attenuation correction coefficient value was 0.12 cm^{-1} for ^{99m}Tc . A reference system device used on all subjects ensured

that the oblique reorientation was standardized (6–8). Cortical counts were determined by averaging the counts per pixel from six equally spaced cortical regions (10 × 10 pixels) on the first (anterior) projection image. This method of count determination was used since the technologist can quickly perform this task to obtain cortical pixel count data. Five subjects had low (10.4–13.9) counts per pixel while the other 5 had high (18.3 to 21.5) counts per pixel, as shown in Table 1. Each subject's data was reconstructed at frequency cut-offs ranging from 0.15–0.3 Nyquist (at 0.025 intervals) and orders ranging from 2–12 (2, 3, 4, 5, 6, 7, 8, 10, 12). In all cases a section positioned at approximately canthomeatal (CM) + 5.5 cm (section through the basal ganglia) (9) was evaluated for image quality at all frequency cutoffs and orders. This provided 63 images per subject for analysis.

Images were subjectively rated on a five-integer scale (–2, –1, 0, +1 or +2) where the numerical score of 0 was assigned to the best image, defined by the image demonstrating the greatest detail without introduction of reconstruction artifacts or noise. The score +1 indicated a too-smooth image, defined by loss of image structure due to pixel blurring, and –1 indicated a noisy image, defined by introduction of pixel densities that could be misinterpreted as actual structure. Images receiving a +1 or –1 score, however, were considered acceptable to render diagnostic information. Overly smooth or overly noisy images were scored as +2 and –2, respectively. Thus an image having a score of +2 or –2 was considered of unacceptable quality. The 63 images for each subject were subjectively scored by three independent observers familiar with the qualitative appearance of good brain SPECT images.

RESULTS

Figure 2 illustrates sections from a typical subject (Subject 1, Table 1) in the low cortical counts per pixel group. It is noted that optimal image quality is produced at the lower frequency cutoff values for a given order. Figure 3 illustrates sections from another subject (Subject 10, Table 1) in the high cortical counts per pixel group. Optimal image quality is obtained at a higher frequency cut-off for the same order as compared to the

TABLE 1
SPECT Acquisition Information

Subject	Amount of ^{99m}Tc HMPAO	Average Cts/Pixel (Anterior projection)	Total Counts $\times 10^6$ (Entire acquisition)	Radius of rotation (cm)	Sec/Stop	Matrix size
1	15–20 mCi	10.4	4.22	14.2	30	128 × 128
2	15–20 mCi	12.6	4.68	13.0	30	128 × 128
3	15–20 mCi	13.5	4.73	14.7	30	128 × 128
4	15–20 mCi	13.5	4.91	14.3	30	128 × 128
5	15–20 mCi	13.9	5.32	13.4	30	128 × 128
6	30–35 mCi	18.3	6.17	14.1	30	128 × 128
7	30–35 mCi	18.7	6.22	14.3	30	128 × 128
8	30–35 mCi	20.5	6.41	14.0	30	128 × 128
9	30–35 mCi	20.5	7.22	13.6	30	128 × 128
10	30–35 mCi	21.5	9.05	14.7	30	128 × 128

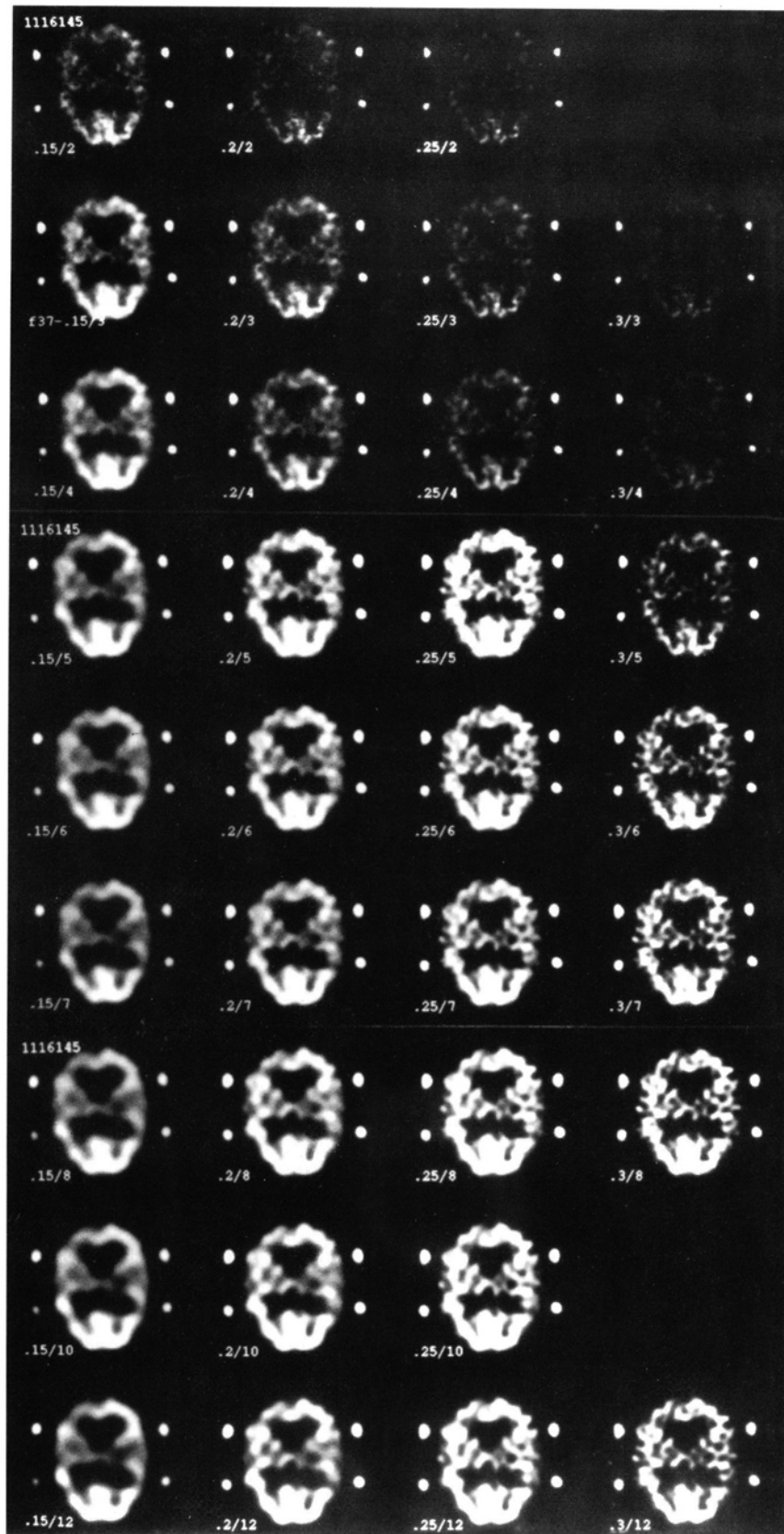


FIGURE 2. Thirty-six of the 63 reconstructed brain sections for Subject 1 (Table 1) in the low-count category. In the lower left corner of each image, the cutoffs and orders (Fc, O) used for image reconstruction are shown. The general pattern of progression is from images which are too smooth to those which are too noisy.

TABLE 2
Low-Count Images*

Order (n)	Frequency Cutoff (Nyquist)						
	0.150	0.175	0.200	0.225	0.250	0.275	0.300
2.00	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00
3.00	-1.27	-1.57	-1.87	-1.93	-2.00	-2.00	-2.00
4.00	0.60	-0.27	-1.13	-1.43	-1.73	-1.87	-2.00
5.00	1.40	0.57	-0.27	-0.77	-1.27	-1.63	-2.00
6.00	1.53	0.80	0.07	-0.53	-1.13	-1.53	-1.93
7.00	1.87	1.20	0.53	-0.30	-1.13	-1.50	-1.87
8.00	1.93	1.53	1.13	0.20	-0.73	-1.30	-1.87
10.00	1.93	1.67	1.40	0.33	-0.73	-1.30	-1.87
12.00	1.93	1.73	1.53	0.40	-0.73	-1.30	-1.87

*Average numerical scores from the three observers for subjects in the low-count group quantifying image quality as a function of Fc and order for the average of the 5 subjects (15 total values for each Fc and order).

low counts images. To subjectively quantify the image quality for different frequency cutoffs and orders for the two groups, score results from the three evaluations for the 5 subjects in each category were averaged and analyzed. Table 2 shows the average numerical scores for subjects in the low-count group. The values shown are the average of the three evaluations for the 5 subjects, (the sum of all scores divided by 15). The optimal Fc and order were found to be 0.2 and 6, respectively. Table 3 shows the average numerical scores for subjects in the high-count group. The values shown were calculated in the same manner as described for the low-count group. The optimal Fc and order were found to be 0.225 and 7, respectively. The better image quality at the higher cutoff frequency can be seen by comparing Figure 3 with Figure 2.

Figures 4 and 5 show three-dimensional plots of the inverse of the absolute value using the distant weighted least squares method (10). Therefore the coordinates (Fc, O) of the image having the better quality are represented as peaks whereas the poor image quality coordinates are near the value of 0.5. Figures 4 and 5 show a color contour map of the image quality for the low-count and high-count images, respectively. The highest image quality is illustrated at the frequency cutoff 0.20, order 6 for low-count images. The three-dimensional contour plot and surface projection illustrates that for high-count images the better image quality is positioned at higher frequency cutoffs (0.225, order 7). These plots also show a characteristic trend of the manner in which image quality changes with increasing counts as a function of frequency cutoff and order. Figure 5, as compared with Figure 4, shows a broader range over which the frequency cutoffs and orders produce adequate images, as evidenced by a wider peak and higher counts of the contour plot showing the best image qualities. In addition, there is an extension of acceptable image qualities (light green) to higher frequency cutoffs (0.22 to 0.28) and higher orders (both orders 12 and 13).

Both Figures 4 and 5 illustrate the general trend between this association of image quality, frequency cutoff and order. These contour plots may be of value when determining which frequency

cutoff and order are most appropriate for the count statistics of an image. If an unsatisfactory reconstruction result is obtained, the contour of the three-dimensional surface plot can assist the technologist on the next selection of Fc and O to obtain maximum image quality by moving the next selection of order and frequency cutoff parameters in the direction of the three-dimensional peak image quality as indicated in Figures 4 and 5.

DISCUSSION

Determination of the optimum reconstruction parameters for brain SPECT images by the operator can be more rationally achieved by a basic understanding of the filtered back-projection process, and the experimental data presented here. The first step to achieve good image quality is a good acquisition. The production of best image in high-resolution brain SPECT is critically dependent on pixel size, frequency cutoff and order, especially when using a 128×128 or higher matrix size. The acquisition should contain at least 128 projections (11).

The filter choice should reflect both the frequency context of the noise and the frequency context of the organ in the image (11). The cutoff frequency is entered as a percentage of the Nyquist frequency. Therefore, the cutoff frequency can range from 0.0 to 1.0 (in this study, range from 0.15–0.3). A cutoff frequency of 0.5 represents 50% of the Nyquist frequency (Fig. 1). The filter order specifies the steepness of the cutoff necessary to eliminate structures that may overlap in frequency. For example, if there is high-frequency data and high-frequency noise, a sharp cutoff will help isolate the data (12). Otherwise, a gradual cutoff is more suitable.

In this study, images reconstructed using the cutoff frequencies between 0.20 and 0.225 cycles per pixel were determined as the best images to show suitable smoothing of the cortical accumulation and clear visualization of the caudate and the thalamus. Figure 3 shows that in higher count images there is slightly less sensitivity in the selection of reconstruction parameters to produce optimal image quality. High-quality images created from high-count projections had a high image quality

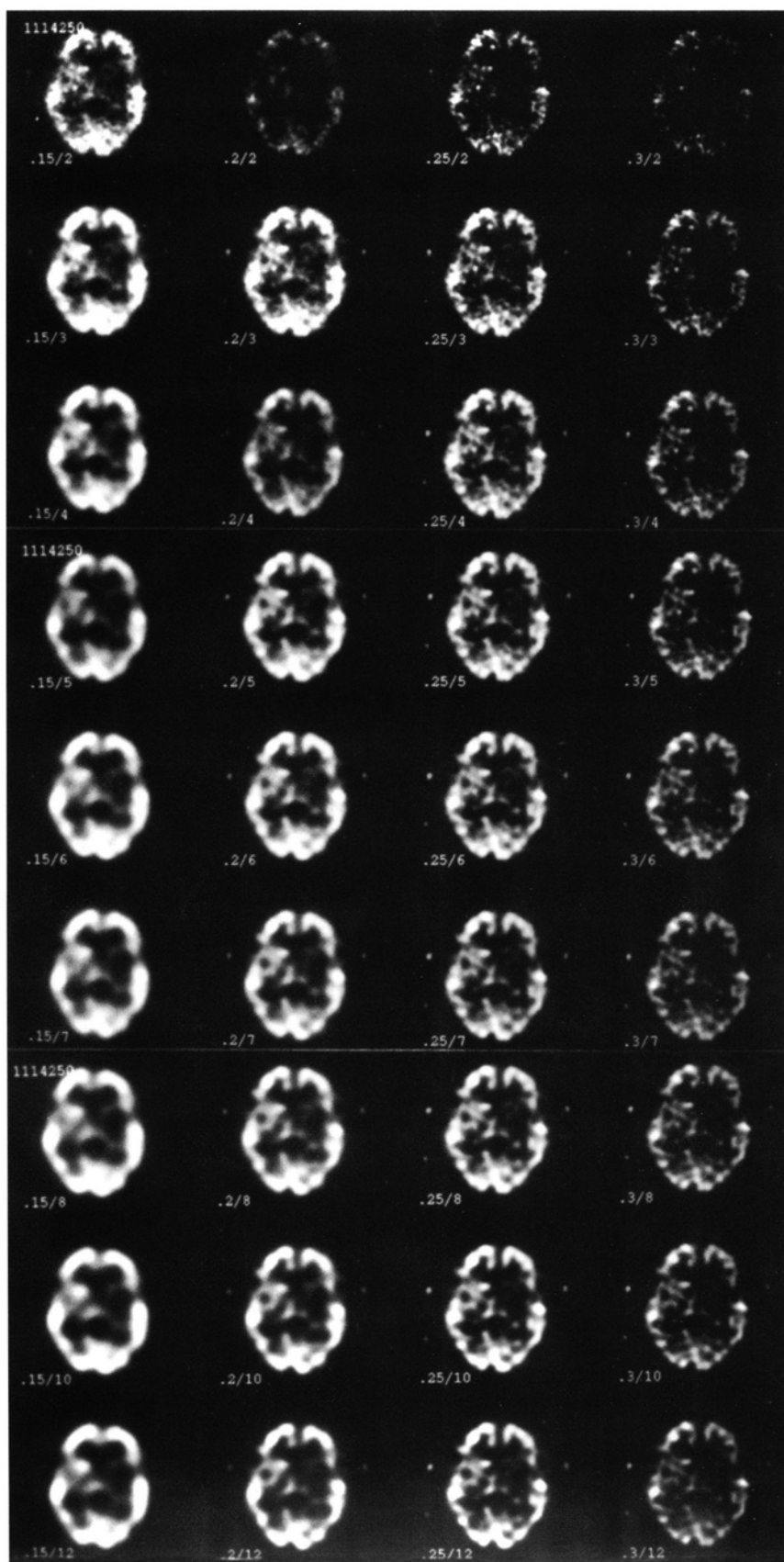


FIGURE 3. Thirty-six of the 63 reconstructed brain sections for Subject 10 (Table 1) in the high-count category. In the lower left corner of each image, the cutoffs and orders (Fc, O) used for image reconstruction are shown. The general pattern of progression is from images which are too smooth to those which are too noisy. Compared to the low-count images (Fig. 2), there is a greater range of reconstruction parameters producing acceptable images.

TABLE 3
High-Count Images*

Order	Frequency Cutoff (Nyquist)						
	0.150	0.175	0.200	0.225	0.250	0.275	0.300
2.00	-1.87	-1.93	-2.00	-2.00	-2.00	-2.00	-2.00
3.00	-1.07	-1.23	-1.40	-1.70	-2.00	-2.00	-2.00
4.00	1.13	0.23	-0.67	-1.07	-1.47	-1.73	-2.00
5.00	1.53	0.87	0.20	-0.40	-1.00	-1.50	-2.00
6.00	1.73	1.10	0.47	-0.20	-0.87	-1.33	-1.80
7.00	1.93	1.30	0.67	-0.07	-0.80	-1.30	-1.80
8.00	2.00	1.67	1.33	0.40	-0.53	-1.17	-1.80
10.00	2.00	1.67	1.33	0.47	-0.40	-1.10	-1.80
12.00	2.00	1.73	1.47	0.53	-0.40	-1.13	-1.87

*Average numerical scores from the three observers for subjects in the high-count group quantifying image quality as a function of Fc and order for the average of the 5 subjects (15 total values for each Fc and order).

with a wide range of cutoff frequencies of the Butterworth filter. These considerations are well illustrated in our results. On the other hand, Figure 2 shows that low-count images require optimal selection of reconstruction parameters over a narrow range.

The results of this paper can be applied directly to routinely encountered clinical situations. The importance of the correct selection of reconstruction parameters is evident in everyday work, since too low a cutoff value produces over-smoothed images, possibly obscuring a lesion. Too high a cutoff value produces noisy images which appear patchy, and may suggest the presence of a false lesion. We emphasize that improper filtering may mask lesions and may lead to an inaccurate diagnosis of a study.

Our data suggest that an optimal frequency cutoff and order can be chosen by evaluating the counts per pixel per stop of the

cerebral cortex and choosing the frequency cutoff and order that produce the best image for low- and high-count brain SPECT acquisitions. If the image is still of undesirable quality after selection of the suggested frequency cutoff and order, (i.e., too smooth or too noisy) follow vectors perpendicularly inward along isocontour to the peaks on the three-dimensional surface contour plots to provide the next best estimate of a more appropriate frequency cutoff and order for optimal reconstruction of a brain image. Since our results were validated on a dual-head detector system and there are differences in the mathematical implementation of filters between vendors and sometimes even between software versions of a particular computer system, the results cannot be strictly applied to other multiheaded brain SPECT systems. However, the method for selection of optimal reconstruction parameters is not expected to significantly change between scanners and, therefore, our

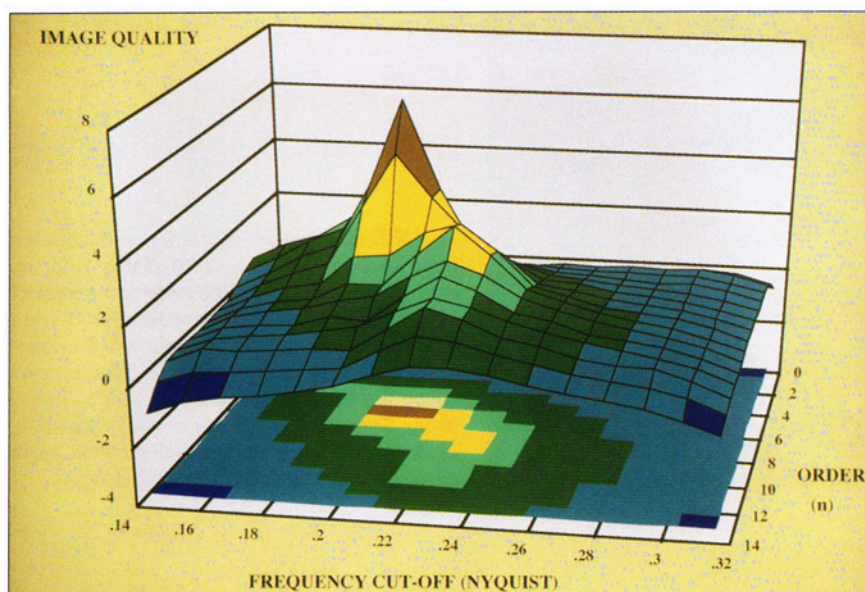
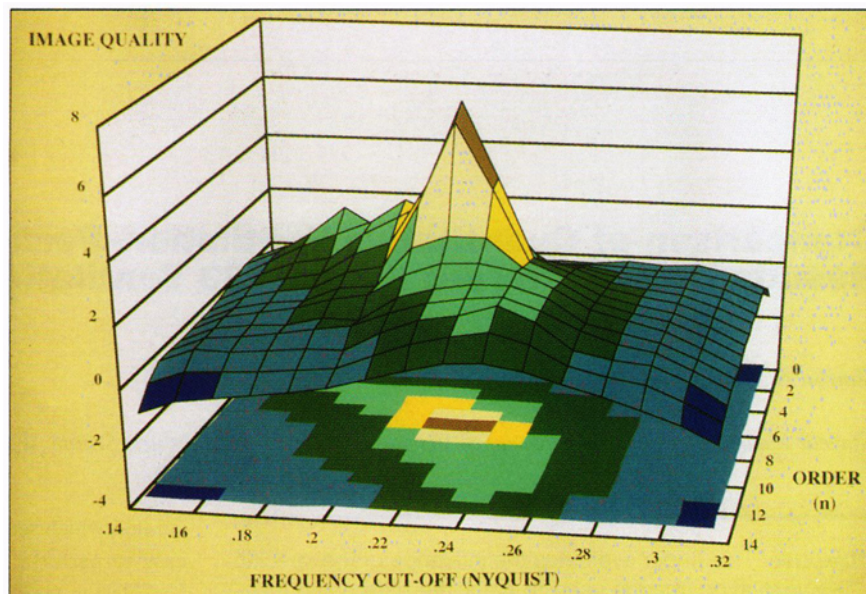


FIGURE 4. Image quality as defined by a three-dimensional surface contour plot for the average of the 5 subjects in the low-count category as evaluated by the three observers (15 total values for each frequency cutoff and order). Blue represents poor image quality while progressively higher color tones, which center at frequency cutoffs between 0.15 and 0.28 and orders between 3 and 12, show varying degrees of better image quality as depicted by the color scales. The best image quality is illustrated at the frequency cutoff 0.20, order 6.

FIGURE 5. Image quality as defined by a three-dimensional surface contour plot for the average of the 5 subjects in the high-count category as evaluated by the three observers (15 total values for each frequency cutoff and order). Blue represents poor image quality while progressively higher color tones, which center at frequency cutoffs between 0.15 and 0.28 and orders between 3 and 12, show varying degrees of better image quality as depicted by the color scales. The best image quality is illustrated at the frequency cutoff 0.225, order 7. Compared with Figure 4, there is a slightly broader range over which the frequency cutoffs and orders produce adequate images, as evidenced by a wider peak and higher counts of the contour plot showing the best image qualities.



results can provide general guidelines for image reconstruction of brain SPECT acquisitions from different imaging systems.

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