Ann Nucl Med (2015) 29:384–390
DOI 10.1007/s12149-015-0949-7

TECHNICAL NOTE

Effects of filtration on right ventricular function by the gated blood pool SPECT

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Received: 5 August 2014 / Accepted: 14 January 2015 / Published online: 31 January 2015

Abstract
Objective Gated blood pool single photon emission computed tomography (GBPS) offers the possibility of obtaining additional functional information from blood pool studies, including evaluation of left and right ventricular function simultaneously. The calculation of ventricular volumes based on the identification of the endocardial surface would be influenced by the spatial resolution in the reconstructed images. This study was performed to evaluate the effect of different filters on the right ventricular function.
Methods The normal four-dimensional (4-D) NURBS-based cardiac-torso (NCAT) phantom with known right ventricular volume and ejection fraction was generated. The SIMIND Monte Carlo program was used to create projections. The studies were reconstructed by FBP and post-processing filtration such as Butterworth, Hanning, Shepp-Logan, Metz and Wiener in different statuses (cutoff and order). Using the Cedars–Sinai QBS (quantitative blood pool SPECT) package, the ventricular functional parameters were computed. The calculated values were analyzed and compared with the normal NCAT results.
Results The results implied that the calculated right ventricular end diastolic volume (RVEDV) by Butterworth filtration (cutoff frequency = 0.3) agreed more with the NCAT Phantom characteristics [relative difference percentage (RDP) = 1.2 %], while the maximum accordance in the calculation of the RV ejection fraction (EF) (RDP = 3 %) was observed by Metz filter (FWHM 20 pixel). Also, the results of this study demonstrate that the Butterworth filter provided the most stable values (cutoff frequency = 0.4–0.5) in the estimation of RVEDV (RDP = 7.5 %). The Hanning and Shepp-Logan filters produced a much larger RDP, particularly in low frequency (41.1 and 21.5 %, respectively) compared to other filters.
Conclusions This study demonstrated that the operation of different filters has a severe effect in computing right ventricular volume. The resolution recovery and Butterworth filters tend to give more comparable ventricular volumes with the actual normal NCAT value. Further evaluation using a large clinical database is underway to evaluate the optimum protocol in a clinical setting.

Keywords GBPS · NCAT · Ventricular function · Filtration

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Introduction

Right ventricular (RV) function is known as an important diagnostic factor for many chronic diseases such as congestive heart failure, cardiomyopathy, pulmonary arterial hypertension, chronic obstructive pulmonary disease and valvular heart disease. Because of the complex structure, irregular shape and position of the RV in the chest, it may be impossible to assess it by the conventional approaches which are based on geometric assumptions [1–3].

Gated blood pool single photon emission computed (GBPS) method is count based and makes it possible to image the blood pool of the ventricles without any overlap from other heart structures, lending itself well to the assessment of improper RV as well as left ventricular function [4, 5]. Whereas the GBPS calculates the ventricular volumes and the ejection fraction (EF) based on a semiautomatic endocardium determination, its outputs may suffer from inauthentic raw data processing.

The determination of ventricular function is based on the specification of the blood pool volumes and the detection of the endocardial surface at end diastole and end systole. The EF is calculated subtracting the end systolic volume (ESV) from the end diastolic volume (EDV) using endocardial contours. Also, the quality of the tomographic image and quantitative accuracy of the SPECT images are degraded by several factors such as technical problems with the instrumentation, the quandary of attenuation correction, scatter of gamma ray photons, insufficient detection efficiency and spatial resolution [6–8]. The reconstruction and the filtrations substantially affect the volume edges resulting in a reduced accuracy of quantitative parameters.

Smoothing filters or low-pass filters are used to lessen or eliminate statistical noise in the SPECT images. These filters maintain the lower frequencies and eliminate the higher one. The low-pass filters are determined by the "cutoff frequency" and "order" parameters. The order value qualifies the slope of the filter operation and the high order leads to a sharp fall. The cutoff frequency specifies the effect of the filter on the image resolution and noise. The spatial resolution is improved by the use of a higher cutoff frequency, but includes more noise [7]. The use of a lower cutoff frequency will smooth the image more, reducing noise with the loss of resolution. A low-pass filter can potentially smooth an image too much, leading to contrast loss. The resolution recovery filters including Metz and Wiener filters enhance selected frequencies to compensate for their attenuation during acquisition. These filters simultaneously recover the resolution and reduce noise [7, 9].

There have been several studies on the effect of the different filtration methods and the selection of proper filter and cutoff frequencies in myocardial SPECT imaging [9–16]. Whereas there are a few quantitative investigation about the effect of reconstruction algorithms in GBPS, achieving appropriate filter and reconstruction procedure in quantification of data is one of the major problems in clinics and selection of proper protocol is valuable [17–20]. In this work, we seek to quantify the effects of the post-processing filtration performed using the Butterworth, Hanning, Shepp-Logan, Metz and Wiener filters in the assessment of RV function using GBPS.

Materials and methods

Phantom design

The four-dimensional (4-D) NURBS-based cardiac-torso (NCAT) phantom provides a realistic model of the normal human anatomy and cardiac and respiratory motions. It is widely used in medical imaging research to evaluate and improve imaging devices and techniques [21, 22]. In this study, the phantom was used to generate 16 different time frames to represent the motion of the heart during the cardiac cycle. The NCAT phantom was set to model the radioactive distribution of technetium-99m-labeled red blood cell (Tc-99m- RBC) with the activity of 25 mCi or 925 MBq/ml, to simulate a gated blood pool SPECT study. Figure 1 shows trans-axial images of an NCAT blood pool phantom patient. The RVEDV and RVEF in the simulated NCAT phantom were equal to 158 ml and 42.39 %, respectively.

Data simulation

Projections of the NCAT phantom were simulated using the SIMIND Monte Carlo software. The protocol for SIMIND simulation was designed based on a commercial imaging system and GBPS imaging using a low-energy high-resolution (LEHR) collimator. The projections were simulated to obtain 16 frames per cardiac cycle. For each frame, 64 views were obtained at about 180° with a start angle of 135° in counterclockwise (CCW) mode. The radius of rotation was constantly 25 cm. The matrix size for each projection was 64 × 64 (0.3 cm pixel size). The energy window was set to 20 %.

Reconstruction and quantification

The projections in the 64 views were imported to a dedicated computer (Symbia T2-Series, Siemens Medical Co.

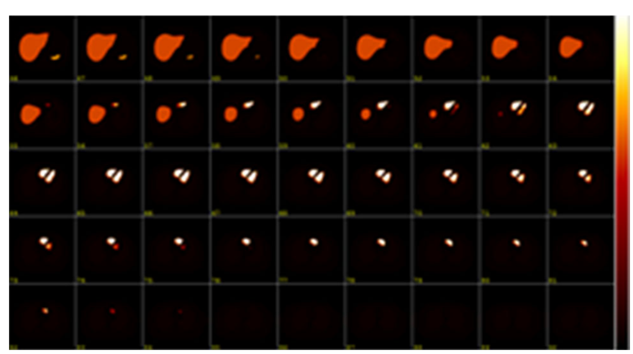

Fig. 1 Trans-axial images of an NCAT blood pool phantom

USA) with MATLAB program. The raw data were reconstructed with the FBP algorithm without applying post-processing filtration; Fig. 2. After reconstruction, five post-processing filters, Butterworth, Shepp-Logan, Hanning, Wiener and Metz, with different conditions were investigated.

The reconstructed phantom images, processed by the different filters, were quantified by the QBS 2009 version processing software. This algorithm developed at the Cedars-Sinai Medical Center (Los Angeles, California) is an interactive standalone application for the automatic segmentation and quantification of gated short-axis blood pool SPECT data. The RVEDV and RVEF were calculated with the surface-based algorithm. In the surface-based calculations, the ventricular end diastolic and end systolic volumes were computed from the 3D surfaces and the EF was calculated from the volumes [23]. In this algorithm, the ventricular segmentation was performed in multiple steps. First, a ventricular mask was generated to eliminate activity from the atria and extra-cardiac structures. Next, a biventricular surface was determined to cover both ventricles. Finally, a septal surface was determined to separate the ventricles. For the RV, another stage was used to specify the place of the pulmonary artery [23, 24].

Statistical analysis was performed with the measurement of 'relative difference percentage', RDP, as follows: $(A1 - A2)/A1 \times 100$, where $A1$ and $A2$ are the known NCAT phantom values and acquired QBS data, respectively.

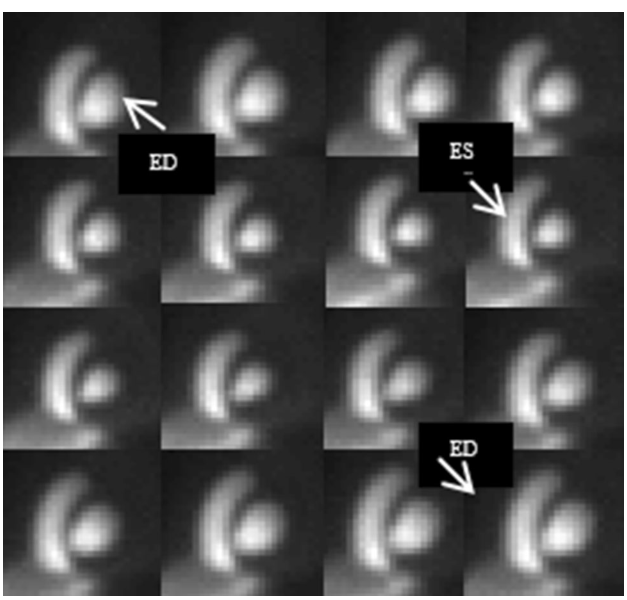

Fig. 2 Reconstructed short-axis images of a gated blood pool NCAT phantom; the images consist of 16 time frames from one slice during the cardiac cycle

Results

Figure 3 shows the effect of the different filters on the determination of the RVEDV and RVEF. Figure 3a illustrates how the ventricular quantitative parameters change by applying the Butterworth filter. We selected the cutoff frequency of this filter to range from 0.3 to 0.5 with steps equal to 0.05. The order value in smoothing and Metz filters was chosen to be fixed because it has been previously demonstrated that this parameter does not have considerable influence on the RVEDV and RVEF [25]. The RVEDV was stable at 0.4–0.5 Nq. According to our results, the cutoff frequency of 0.3 Nq provided the optimum value of the RVEDV as compared to the known value in the NCAT phantom (158 ml).

Figure 3b shows the effect of the Hanning filter on the estimation of the RVEDV and RVEF values. For this filter, the cutoff frequencies were selected from 0.2 to 0.8 Nq with 0.1 steps. Considering this figure, the cutoff frequencies of 0.7–0.8 Nq provided the best correlation with the NCAT phantom parameters. At 0.2 Nq, the Cedars-Sinai QBS could not quantify the NCAT output.

The Shepp-Logan effect results can be seen from Fig. 3c. We ranged the cutoff frequency from 0.2 to 0.5 Nq in steps of 0.1 Nq. The RVEDV was found to decrease when the frequency was increased.

Figure 3d shows the effect of the Metz filter on the estimation of the RV parameters. The FWHM was set to a range of 6–20 for comparison. Figure 3e, f displays the performance of the Wiener filter with the FWHM ranging from 6 to 20 and the SNR set to 1 and 5, respectively. As shown, the changing of SNR has a significant impact on the parameters. The comparison of the reconstructed images using different filters by the FBP method created more consistent results qualitatively for the evaluation of volumes. Figures 4 and 5 show the effect of smoothing and resolution recovery filtrations, respectively.

Table 1 summarizes the percent differences found for the RVEDV and RVEF (as compared to the known NCAT values) by implementing the FBP reconstruction method and utilizing the different filters. Since the main feature of GBPS is to measure LV as well as RV at the same time, this table also shows the left ventricle function such as left ventricle end diastole volume, LVEDV, and left ventricle ejection fraction, LVEF. The results indicate that the closest RVEDV and LVEDV calculated by QBS to the NCAT output (1.2 and 1.4 % relative difference) was obtained with Butterworth filtration (cutoff freq. = 0.3 Nq). Also, the closest RVEF and LVEF value (3 % relative difference) was provided with the Metz filter (FWHM = 20).

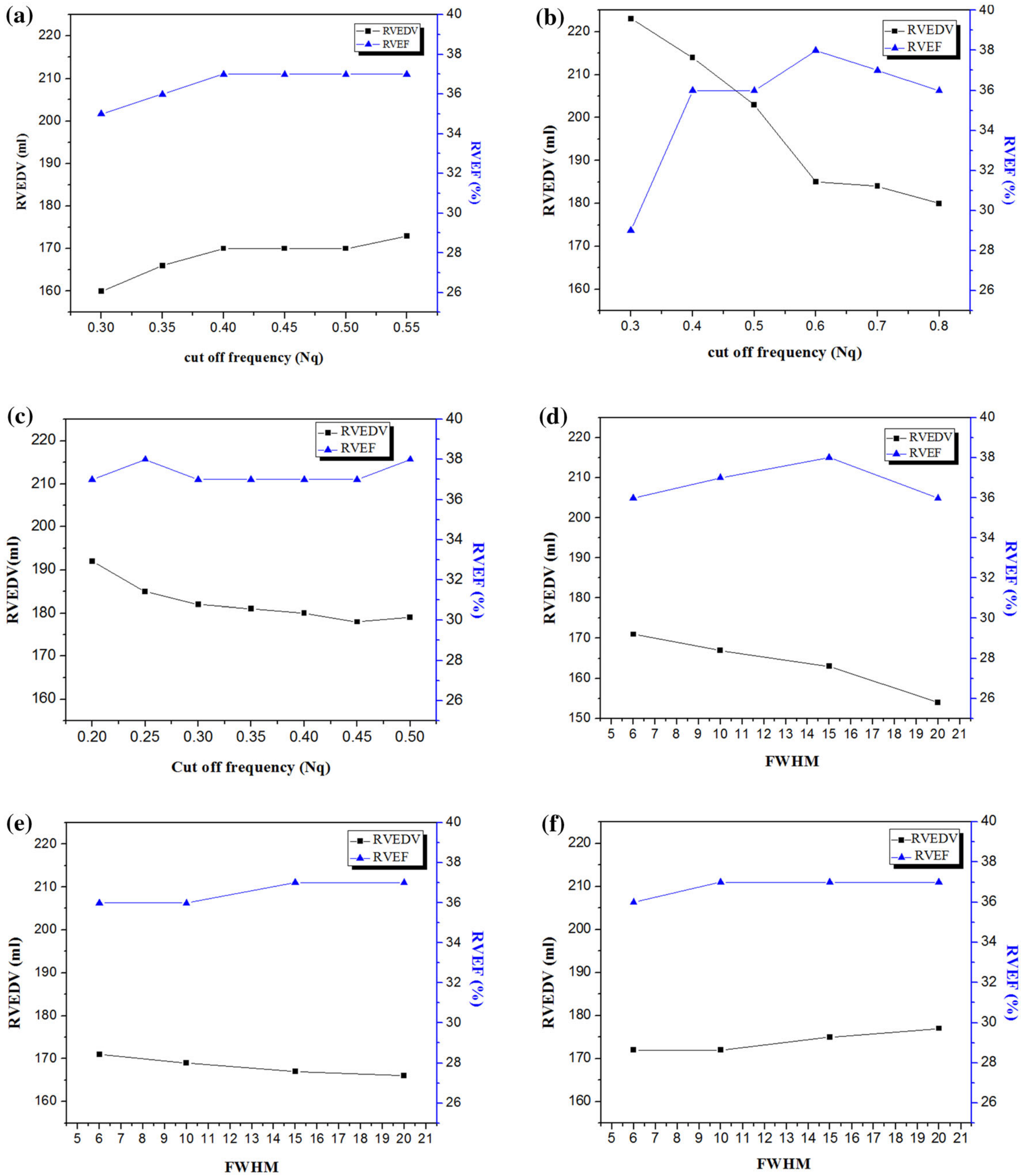

Fig. 3 The effects of **a** Butterworth, **b** Hanning, **c** Shepp-Logan, **d** Metz, **e** Wiener (SNR = 5) and **f** Wiener (SNR = 1) filters on RVEDV and RVEF quantitatively

Discussion

In this study, we investigated the effect of different processing filtrations on the calculation of the RV functional parameters from the GBPS using the QBS algorithm and simulated images of the NCAT phantom which have a known truth. This study demonstrates that different post-processing filtrations have dissimilar effects on the determination of parameters indicative of RV function. Parameters, such as the RVEF which has been shown to be a prognosticator of patient survival, need to be determined accurately to be used in the diagnosis and risk stratification of RV dysfunctions [26].

We examined the Butterworth, Hanning, Shepp-Logan low-pass or smoothing filters, and also the Metz and Wiener as typical restoration or resolution recovery filters. The smoothing filters have different effects on quantitative values depending on their profiles. The cutoff frequency

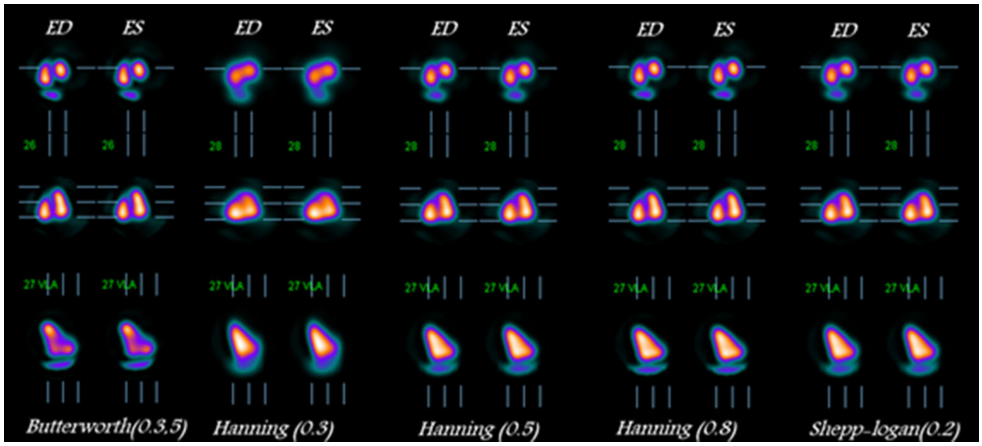

Fig. 4 Qualitative assessment of the effect of the smoothing filters on EDV and ESV with short-axis (SA) sections in the *top*, horizontal long axis (HLA) sections in the *middle* and vertical long-axis (VLA) sections in the *bottom*

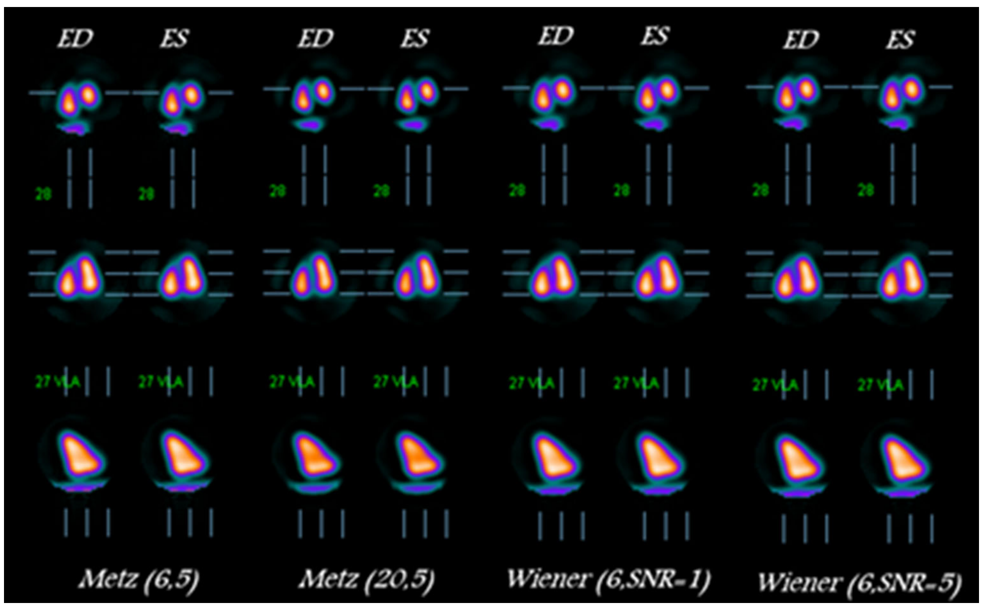

Fig. 5 Qualitative assessment of the effect of resolution recovery filtering on EDV and ESV with SA sections in the *top*, HLA sections in the *middle* and VLA sections in the *bottom*

determines the point at which the filter produces remarkable high-frequency prevention [27]. Because the edge has a high frequency, decreasing the cutoff frequency alters edge detection.

In the Butterworth filter, our investigation showed that the minimum relative difference of RVEDV with the NCAT data could be obtained using the cutoff frequency of 0.3 Nq. RVEF demonstrated as much as 17 % RDP at 0.3 Nq frequency.

Since the Hanning filter reaches zero quickly, it is very effective in noise reduction, but does not preserve image edges [7]. Using this filter, it was observed that the estimated ventricular volumes were severely reduced. At lower frequencies, the estimated volumes and EF varied abruptly.

The count-dependent nature of the Wiener and Metz filtering techniques and the difference with smoothing filters can be seen in Fig. 3. As shown, the low-pass filters have strong impact on the calculated RV volume, while both Metz and Wiener filters have no significant effect on the calculated EDV.

As explicit from the results, since the EF value is derived from the ratio of the volumes at the end of diastole and systole, the impact of the filters has been negligible on

Table 1 Comparison between actual RVEDV, RVEF, LVEDV and LVEF and Butterworth, Hanning, Shepp-Logan, Metz and Wiener post-processing filters for the NCAT phantom

Filter	RVEDV (RDP %)	RVEF (RDP %)	LVEDV (RDP %)	LVEF (RDP %)
Butterworth (cutoff, order)				
(0.3, 5)	1.2	17	1.4	22.8
(0.35, 5)	5.06	14	6.8	17.9
(0.4, 5)	7.5	12.5	9.6	16.3
(0.45, 5)	7.5	12.5	10.55	16.3
(0.5, 5)	7.5	12.5	10.55	14.6
(0.55, 5)	9.4	12.5	10.55	14.6
Hanning (cutoff)				
(0.2)	–	–	–	–
(0.3)	41.1	31.4	23.4	13.02
(0.4)	35.4	14	24.3	14.6
(0.5)	28.4	14	24.3	14.6
(0.6)	17	10	13.32	14.6
(0.7)	16.4	12	10.5	14.6
(0.8)	13.9	14	11.4	16.3
Shepp-Logan (cutoff)				
(0.2)	21.5	12	15.1	19.5
(0.25)	17	12	13.3	14.6
(0.3)	15.1	12	11.4	16.3
(0.35)	14.5	12	11.4	16.3
(0.4)	13.9	12	10.5	16.3
(0.45)	12.6	12	10.5	16.3
(0.5)	13	12	11.4	16.3
Metz (psf FWHM, order)				
(6, 5)	8	12.8	11.4	14.6
(10, 5)	5.6	12.5	9.6	13.02
(15, 5)	3.1	10	5.9	13.02
(20, 5)	−2.5	3	−8.3	16.3
Wiener (FWHM, SNR)				
(6, 1)	8.8	14	10.5	14.6
(10, 1)	8.8	14	8.7	16.3
(15, 1)	10	14	9.6	16.3
(20, 1)	12	14	8.7	13.02
Wiener (FWHM, SNR)				
(6, 5)	8.2	14	10.5	14.6
(10, 5)	6.9	14	10.5	14.6
(15, 5)	5.6	12	8.7	13.02
(20, 5)	5	12	8.7	13.02

The relative difference percentage (RDP %) for each method is also shown

RDP relative difference percentage

this quantity. The behavior of the Metz and Wiener filters was relatively constant compared to the other filters.

Regarding the intensive impact of the Hanning and, Shepp-Logan filters, the Butterworth and resolution recovery filters can be appropriate options in GBPS images.

The results of the quantitative comparison of the filters in terms of their effect upon the calculation of the RVEDV and RVEF values are given in Table 1. For RVEDV, the Butterworth (0.3), Metz (20) and Wiener (20, SNR = 5) filters with percent differences 1.2, 2.5 and 5 %, respectively, show the minimum relative difference in comparison with the known RV parameters from the NCAT phantom.

Conclusions

This study shows that the application of different filters has a significant effect in computing the right ventricular function parameters such as the RV end diastolic volume and the EF. As a result, accuracy is highly dependent on the selection of the reconstruction method and filtration. Since the number of counts in each organ is seriously influenced by the choice of filters and count level is different in patients, this study was conducted on one fixed input phantom, which can enhance the delicacy of calculations. Future work will involve the use of several anatomically variable phantoms. Since Butterworth and resolution recovery filters were constant approximately with changing filter parameters, these filters are suitable in GBPS imaging.

Acknowledgments The authors wish to express their sincere gratitude to Dr. Paul Segars for his helpful comments. We specially thank the partner and staff at the Cardiovascular Interventional Research Center, Department of Nuclear Medicine, Medical and Research Center, Rajaei Cardio-vascular Hospital for their assistance.

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