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Analysis of Peak Velocity and Mean Velocity According to Shimming Technique in 2D Phase Contrast : Comparison of 1.5 Tesla and 3.0 Tesla

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The purpose of this study was to compare the difference in peak velocity (PV) and average flow (AF) values between the shimming of the aortic arch (AA) and the left ventricle (LV) using the 2D phase contrast (PC) technique at 1.5 Tesla and 3.0 Tesla. The sino-tubular junction (S-T junction), the proximal AA, and the LV, an aortic valve, were examined using a 2D PC technique at 1.5 Tesla and 3.0 Tesla. At 1.5 Tesla and 3.0 Tesla, 2D PC technique was used to examine the proximal AA Sino-Tubular (S-T) junction and LV was examined at the aortic valve area. shim was not used (no_Shim) in 1.5 Tesla and 3.0 Tesla to compare differences in heart blood flow due to magnetic field strength. To assess the difference due to shimming, an auto_shim, target_shim was used and an all_shimthat used auto and target shim simultaneously was used. The average value between 1.5 Tesla and 3.0 Tesla as a result of inspection was different when AA_AF was no_shim and all_shim. In LV_AF, the difference in mean values was found in 1.5 Tesla and 3.0 Tesla when it was no_shim and all_shim. Other tests did not show any significant differences. Also, according to the shimming method in 1.5 Tesla, the mean value difference occurred in AA_AF and the mean value difference in LV_AF in 3.0 Tesla. In conclusion, it is necessary to improve uniformity of magnetic field through shimming for accurate blood flow evaluation in 1.5 Tesla and 3.0 Tesla. Therefore, this study is expected to be used as a basis for improving the uniformity of magnetic field.

Keywords : 2D Phase Contrast, cardiac blood flow, magnetic field inhomogeneity, magnet field shimming, VENC

1. Introduction

According to the statistics on the cause of death in Korea, heart and cerebrovascular diseases are the three major causes of death [1]. Cardiovascular disease is the most common complication in elderly patients, and is the leading cause of death after surgery, and postoperative complications can occur [2]. Therefore, functional evaluation of cardiovascular system before and after surgery is very important. However, since cardiovascular diseases are widely distributed in the human body and are often asymptomatic until symptoms are manifested, it is difficult to diagnose and early diagnose the disease [3]. In particular, an increase in cardiac blood flow may lead to excessive cardiac movement, which may be a risk factor for atrial fibrillation and cardiovascular disease [4, 5]. Therefore, quantitative evaluation of cardiac blood flow is very important for cardiovascular disease and patients before and after surgery. Doppler studies using echocardiography have been used to measure cardiac perfusion. Echocardiography can be used to measure cardiac perfusion and to observe blood flow velocity and anatomical defects. However, it is dependent on the operator and may cause aliasing due to Doppler shift, which is disadvantageous to the gradient of the probe [6, 7]. On the other hand, MRI can measure quantitative flow using phase shift. The phase contrast technique uses a phase shift phenomenon that occurs when a spin experiences an oblique magnetic field. When a bipolar gradient is

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applied, a fixed spin and a moving spin have different phase shifts. The phase contrast technique has already been validated for the accuracy of flow quantification in several studies [8]. In addition, studies on quantification of blood flow of carotid artery for cerebrovascular disease and blood flow quantification of cardiovascular using phase contrast technique are being studied [9, 10]. Quantitative evaluation of cardiovascular disease using phase contrast technique can be done simultaneously with cardiac function test because it can be done simultaneously with cardiac MRI. In this case, there is an advantage of confirming the status of the cardiovascular state of the patient even if the quantitative evaluation of the cardiac blood flow using ultrasound is not additionally performed. In recent years, cardiac MRI has been widely used in 3.0 Tesla due to improved device. Hinton [11] *et al*. reported that qualitative and quantitative improvement of bright blood and dark blood images during functional cardiac MRI was 3.0 Tesla compared to 1.5 Tesla. In other words, cardiac MRI can be tested in both 1.5 Tesla and 3.0 Tesla devices. Therefore, phase contrast test, which is a quantitative evaluation of cardiac blood flow, requires comparison between 1.5 Tesla and 3.0 Tesla. Therefore, in this study, we propose a method to identify the difference of quantitative evaluation of cardiac blood flow according to the magnetic field strength and to reduce the error according to the equipment.

2. Subjects and Methods

The blood flow of the cardiac aorta was measured by phase contrast MRI in 15 healthy volunteers. All genders were male and the mean age was 35.4 ± 4.10. The whole body MRI system (SignaHDxt, GE, USA) was used for both 1.5 Tesla and 3.0 Tesla. The surface coil was an 8 channel cardiac array coil. 2D phase contrast MRI imaging uses a phase shift phenomenon that occurs when a spin experiences a magnetic field. When a bipolar gradient is applied, the fixed spin and the moving spin have different phase shifts. In this case, phase image with velocity information of blood flow can be obtained by subtracting the velocity encoding image without flow compensation and the reference image using the flow compensation technique [12]. McRobbie [13] *et al*. defined the basic physics of phase contrast MRI as follows.

$$\omega_0 = \gamma B_0 \tag{1}$$

The phase of the spin is the integral of the time of the resonance frequency.

$$\Phi = \int \omega dt \tag{2}$$

The difference in phase of the spin in the gradient magnetic field G_x is as follows.

$$\Phi = \gamma \int (B_0 + G_x x) dt \tag{3}$$

The phase shift in the x direction in the moving spin with fixed velocity v is as follows.

$$\Phi = \gamma \int (B_0 + G_x(x + vt)) dt \tag{4}$$

Therefore, considering the single slope pulse of amplitude G and duration T, the phase difference will occur due to the following speed.

$$\Phi = \gamma \int_0^T Gvt \cdot dt = \left[\frac{1}{2}\gamma v G t^2\right]_0^T = \frac{1}{2}\gamma v G T^2 \tag{5}$$

The phase difference of spin in Eq. (5) varies with magnetic rotation rate (γ), blood flow velocity (v), gradient magnetic field strength (G) pulse duration (t) and pulse interval (T). The phase shift of a spin in a constant magnetic field follows the formula:

$$\Phi = \gamma \cdot G \cdot v \cdot t \cdot \mathrm{T} \tag{6}$$

Here, other influencing factors except for the magnetic field intensity (G) can't be artificially changed. γ is the magnetic rotation rate of the proton, and v, t and T are the blood flow rate and the duration and interval of the RF pulse, respectively. The protons that make up the nucleus have nuclear spins. The spin is the same as the electron and has a magnitude of angular momentum of $\frac{h}{2}$. This nucleus spin can be expressed as the sum of the angular momentum due to the inherent spin and orbital motion of the nucleus constituting the nucleus, and the self-rotation ratio is represented by this spin. In other words, the magnetic rotation ratio (γ), which tries to rotate when the spin is placed in the magnet field, is a constant of 2.68×10^6 rad s^{-1} T^{-1}. It can be expressed as 42.58 MHz/T when it is transformed into a linear frequency. v is the velocity of the blood flow in the blood vessel of the human body, t and T are the duration and interval of the RF pulse. This is an important factor that determines RF power and duration. The duration (t) and the interval (T) of the RF pulse are also excluded from the factors that cause the phase shift during image acquisition if the sequence type is determined. Therefore, other influence factors other than the intensity (G) of the oblique magnetic field among the factors involved in the phase shift cannot be artificially changed. Therefore, it is the intensity of the gradient magnetic field that influences the quantitative evaluation of blood flow during phase contrast MRI. However Lorenz [14] *et al.* reported that phase errors may occur due to eddy currents and local gradient field nonlinearities.

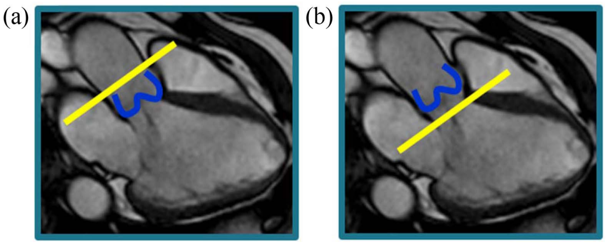

Fig. 1. (Color online) Measurement of ascending aorta (AA) at sino-tubular junction (a) Measured at the bottom of the aortic valve – labeled as left Ventricle (LV) (b).

Especially, the susceptibility difference between lung parenchyma and surrounding air is 9 ppm, which affects the collapse of T2* [15]. In addition, due to the characteristics of cardiac MRI using electro-cardiac gating (ECG), magneto-hydrodynamic MHD) effects and magnetic field interference occur [16]. Since this is all the cause of signal loss, it is necessary to plan the experiment considering the correction of these.

In this study, the parameters of the 2D phase contrast MRI were TR/TE 12.4/4.8 ms and the flip angle was 20°. The slice thickness/spacing was set to 5.0/0.0 mm, the field of view was 400 × 400 mm, matrix 256 × 128, NEX 1, and the bandwidth was set to 15.63 kHz. The pulse sequence is fast 2D phase contrast and the image option is flow compensation and sequential. The blood flow measurement position that the aortic arch (AA) was the sino-tubular junction and the left ventricle (LV) was the lower part of the aortic valve (Fig. 1). To compare the differences in cardiac blood flow due to the exact magnetic field strength, both 1.5 Tesla and 3.0 Tesla were tested without shimming (no_shim). In addition, auto shimming (auto_shim), target shimming (target_shim) and all shimming (all_shim) were performed to evaluate the difference in cardiac blood flow due to shimming (Fig. 2). The magnitude and velocity encoding images of the obtained 2D phase contrast MRI were quantitatively analyzed (Fig. 3). Electro-cardiac graphy (ECG) was used to evaluate the presence of arrhythmia and blood pressure was measured during phase contrast MRI to maintain the same heart rate in a stable state. To assess the presence or absence of valve disease, cine MRI was performed. The left ventricular outflow track (LVOT) and LVOT coronal images were used to evaluate the regurgitation of the aortic valve and the stenosis of the aortic valve. The

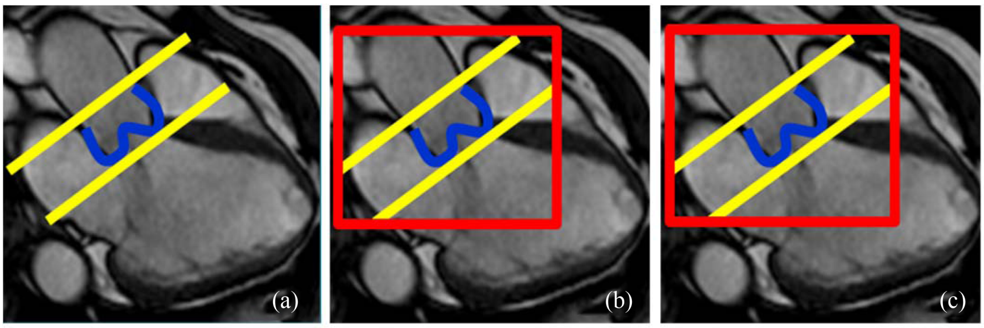

Fig. 2. (Color online) Examination with auto shimming (a) examination with local shimming (b) examination with auto shimming and local shimming (c).

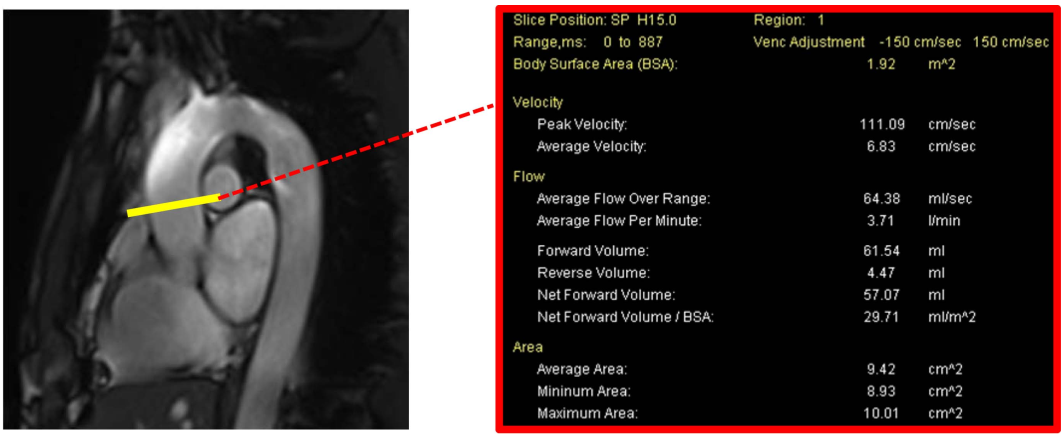

Fig. 3. (Color online) After plotting region of interest on magnitude and phase velocity images, flow rate is analyzed.

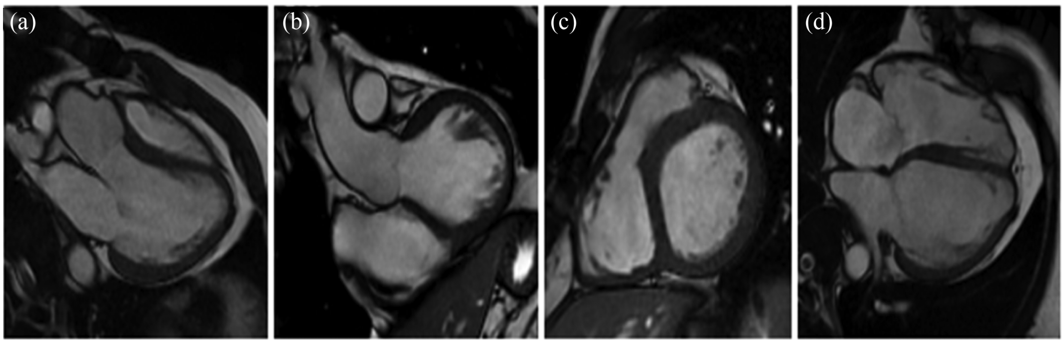

Fig. 4. Cine MRI imaging to evaluate the presence or absence of valve disease. LVOT (a) and LVOT-coronal (b) images were used to evaluate the regurgitation of aortic vasculature and the stenosis of aortic valves. Evaluation for regurgitation of mitral valve and stenosis of mitral valve via short axis (c) and 4 chamber view images.

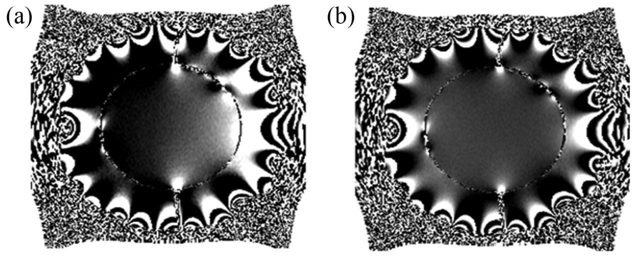

Fig. 5. In the 3.0 Tesla Magnetic field, before the correction of the inhomogeneous magnetic field (a) after the correction (b).

regurgitation of the mitral valve and the stenosis of the mitral valve were evaluated using short axis and 4 chamber view images. It was confirmed that there was no valve disease that could affect the cardiac blood flow evaluation (Fig. 4).

Other variables that may influence the cardiac blood flow due to magnetic field strength were identified. First, eddy current was measured and calibrated in MRI 1.5 Tesla and 3.0 Tesla. In addition, the gradient field nonlinearities were confirmed, and both 1.5 Tesla and 3.0 Tesla were in the normal range (Fig. 5).

Data were analyzed by means of SPSS (18.0, IBM, USA) independent t-test. The mean values of peak velocity and average flow of 1.5 Tesla and 3.0 Tesla were compared according to the shimming method. Also compared the mean peak velocity and average flow for no_shim, auto_shim, target_shim, and all_shim of 1.5 Tesla and 3.0 Tesla using the ANOVA test. At this time, it was judged statistically significant when p value was less than 0.05.

3. Results

The Table 1 shows the results of the difference between the average values of peak velocity and average flow of 1.5 Tesla and 3. 0Tesla of aortic arch and left ventricle. The actual image is shown in Fig. 6. In the no_shim method, the peak velocities in aortic arch and left ventricle were not different between 1.5 Tesla and 3.0 Tesla ($p > 0.05$). However, the average flow in aortic arch and left ventricle differed from 1.5 Tesla and 3.0 Tesla (p

Table 1. Average of peak velocity and average flow in aortic arch and left ventricle of 1.5 Tesla and 3.0 Tesla.

Shim	AA_PV	p	p*‡	AA_AF	p	p*‡	LV_PV	p	P*‡	LV_AF	p	p*‡
No_1.5T	99.0 ± 12.9	.522	.994*	96.7 ± 14.1	.000	.010*	89.5 ± 16.0	.135	.988*	76.1 ± 8.9	.000	.078*
No_3.0T	96.7 ± 14.1			80.4 ± 12.4			83.7 ± 13.6			63.8 ± 6.6		
Auto_1.5T	98.2 ± 12.0	.948		86.3 ± 17.8	.688		89.7 ± 13.9	.073		69.9 ± 13.5	.490	
Auto_3.0T	98.4 ± 18.3			84.8 ± 11.1			83.0 ± 14.1			67.8 ± 8.9		
Target_1.5T	98.9 ± 14.9	.355	.848‡	95.5 ± 13.3	.000	.561‡	90.7 ± 16.2	.245	.840‡	70.5 ± 13.2	.223	.048‡
Target_3.0T	95.5 ± 13.3			81.8 ± 13.4			86.0 ± 14.9			66.8 ± 10.2		
All_1.5T	98.9 ± 10.9	.264		84.9 ± 20.9	.709		89.5 ± 14.9	.186		75.0 ± 8.5	.034	
All_3.0T	95.5 ± 12.2			83.2 ± 12.2			85.0 ± 11.1			70.1 ± 8.9		

Note) p is 1.5 Tesla and 3.0 Tesla independent t-test, p*‡ is the average comparison between 1.5 Tesla and 3.0 Tesla shim method ANOVA test, *The sign after the probability of significance is the significance probability for the mean of each variable according to the shim method change (no_shim, auto_shim, target_shim, all_shim) at 1.5 Tesla, ‡The sign is the significance probability for the mean of each variable according to the change of shim method (no_shim, auto_shim, target_shim, all_shim) in 3.0 Tesla

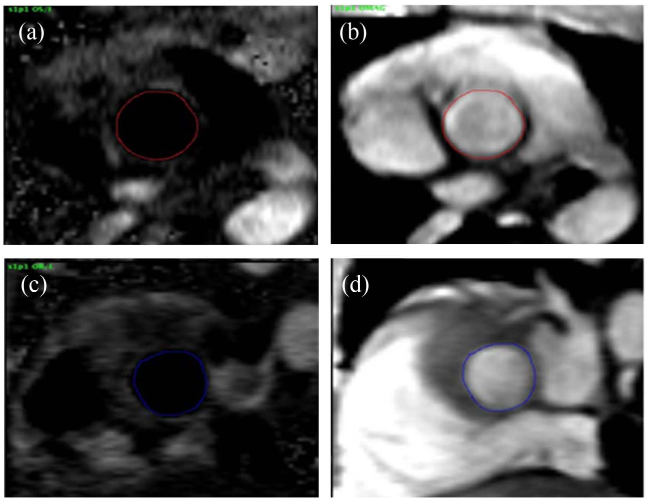

Fig. 6. (Color online) Quantitative analysis of 2 dimensional phase contrast image. Phase image (a) and Magnitude image (b) of aortic arch and phase image (c) and Magnitude image (d) of left ventricle.

< 0.05). In the auto_shim method, peak velocity and average flow in aortic arch and left ventricle were not different from mean values ($p > 0.05$). The peak velocity in the aortic arch and left ventricle in the target_shim method was not different between 1.5 Tesla and 3.0 Tesla, and there was no difference in average value in the left ventricle average flow ($p > 0.05$). However, in aortic arch, average flow was higher than that of 81.8 ± 13.4 of 3.0 Tesla with 95.5 ± 13.3 of 1.5 Tesla ($p < 0.05$). In all_shim method, peak velocity of aortic arch and left ventricle were not different from each other, and average flow of aortic arch was not different between 1.5 Tesla and 3.0 Tesla ($p > 0.05$). However, the average flow in the left ventricle was 1.5 Tesla 75.0 ± 8.5, which was higher than 70.1 ± 8.9 of 3.0 Tesla ($p < 0.05$).

According to the shim method, there was no difference in mean value between 1.5 Tesla according to peak velocity in aortic arch and left ventricle, and there was no difference in average value in average flow of left ventricle ($p > 0.05$). However, there was a difference in average value in the average flow of aortic arch. The no_shim method showed a highest mean value of 96.7 ± 14.1, and the lowest value of all_shim method was 84.9 ± 20.9 ($p < 0.05$). According to shim method, 3.0 Tesla showed no difference in peak velocity between aortic arch and left ventricle, and there was no difference in average flow in aortic arch average flow ($p > 0.05$). However, the average flow was different in left ventricle. The all_shim method showed a highest mean value of 70.1 ± 8.9, and the lowest value of no_shim method was 63.8 ± 6.6 ($p < 0.05$).

4. Discussion

Ultrasonographic evaluation of cardiac blood flow is widely used as a standard test, but there is a large difference in the skill of the practitioner and low reproducibility. 2D phase contrast MRI, on the other hand, provides morphological information for visualization of lesions such as valvular disease, which have a high reproducibility in the evaluation of cardiac blood flow and also affect blood flow changes. However, in the evaluation of cardiac blood flow measurement that may occur as the magnetic field increases. Therefore, in this study, we tried to analyze how the changes of magnetic field strength affect the quantitative measurement of cardiac blood flow.

In this study, we obtained some characteristic results. First, the heart blood flow measurements without using shimming in 1.5 Tesla and 3.0 Tesla showed no difference in peak velocity between aortic arch and left ventricle, but showed difference in average flow. Hani [17] *et al.* reported a peak velocity range of 72 to 120 cm/s in the aorta. In this study, the peak velocity of the aortic arch was 99.0 ± 12.9 at 1.5 Tesla and 96.7 ± 14.1 at 3.0 Tesla. Therefore, both tests were within the normal range of the values presented in the previously study, which means that the results of this study were not wrong. In this study, the mean difference of average flow measured at 3.0 Tesla and 1.5 Tesla aortic arch was 13.3 ± 1.7, which was 1.5 Tesla higher. And the mean difference in left ventricle was 2.3 ± 2.3, which was 1.5 Tesla higher. S. Muzzarelli [18] *et al.* reported that blood flow measurement may be inaccurate due to location of phase-offset error due to complicated flow phenomenon because aortic arch is ejected from left ventricular blood. Therefore, in this study, it is considered that the average flow difference occurred between 1.5 Tesla and 3.0 Tesla.

Secondly, the differences according to the sim method in 1.5 Tesla differ only in the average flow of aortic arch in no_shim, auto_shim, target_shim, and all_shim. The anatomical characteristics of the aortic arch seem to be magnetic susceptibility to magnetic field inhomogeneity in the surrounding lung [19]. Xiang [20] *et al.* reported that phase contrast depends on the structure of cellular and subcellular levels, and that the tissue structure has proteins, non-heme iron, lipid and deoxyhemoglobin that affect the susceptibility. Therefore, it is necessary to understand the characteristics of anatomy composed of various factors that cause magnetic inhomogeneity such as air, protein and lipid of lung, and to use the shimming which can increase homogeneity of magnetic field. In particular, the 3.0 Tesla showed a maximum difference of

6.3 ± 2.3 in the mean value of average flow when shimming was used and when it was no_shim method. Therefore, shimming is necessary for quantitative evaluation of blood flow in 3.0 Tesla.

5. Conclusion

In this study, we provide to identify the difference of quantitative evaluation of cardiac blood flow according to the magnetic field strength and to suggest a method to reduce the error according to the equipment. In addition, it was confirmed that quantitative measurement of cardiac blood flow was possible even in the high field test of 1.5 Tesla and 3.0 Tesla. However, it was confirmed that improvement of magnetic field inhomogeneity is required when using 1.5 Tesla and 3.0 Tesla phase contrast techniques. As a result, we confirmed the necessity of the shimming technique which is a method to enable the homogeneity of the magnetic field. Therefore, it is necessary to study the quantitative data of the phantom that can be used to evaluate the actual velocity of the peak velocity and average flow of the cardiac blood flow through MRI. This study is expected to provide basic data in the future.

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Joo-Wan Hong and Yeong-Cheol Heo equally contributed to this work; they are co-corresponding authors.

References

[1] S. K. Yoou and J. E. Lee, Korean J. Emerg. Med. Ser. **21**, 1 (2017).

[2] Y. C. Woo and D. C. Ha, Korean J. Anesthesiol. **39**, 4 (2016).

[3] Y. B. Lee, B. M. Choi, H. S. Hwang, H. S. Park, S. C. Park, and Y. O. Kim, Korean J. Med. **92**, 3 (2017).

[4] O. D. Divitiis, S. Fazio, M. Petitto, G. Maddalena, F. Contaldo, and M. Mancini, Circulation **64**, 3 (1981).

[5] J. K. Sung and J. Y. Kim, Korean Circ. J. **40**, 2 (2010).

[6] E. I. Bluth, A. T. Stavros, K. W. Marich, S. M. Wetzner, D. Aufrichtig, and J. D. Baker, Radiographics **8**, 3 (1988).

[7] P. Hennequin, C. Honore, J. M. Chareau, R. Sabot, A. Truc, A. Quemeneur, and N. Lemoine, Rev. Sci. Instrum. **75**, 10 (2004).

[8] S. O. Oktar, C. Yucei, D. Karaosmanoglu, K. Akkan, H. Ozdemir, N. Tokgoz, and T. Tali, Am J. Neuroradiol. **27**, 2 (2006).

[9] J. Lotz, C. Meier, A. Leppert, and M. Galanski, Radiographics **22**, 3 (2002).

[10] R. L. Vanninen, H. I. Manninen, P. L. Partanen, P. A. Vainio, and S. Soimakallio, Radiology **194**, 2 (1995).

[11] D. P. Hinton, L. L. Wald, J. RTR. Pitts, and F. Schmitt, Invest. Radiol. **38**, 7 (2003).

[12] N. J. Pelc, R. J. Herfkens, A. Schimakawa, and D. R. Enzmann, Magn. Reson. Quart. **7**, 4 (1991).

[13] D. W. McRobbie, E. A. Moore, M. J. Graves, and M. R. Prince, MRI from picture to proton-2nd edition, Cambridge university press, New York, USA, 2007, 269-70.

[14] R. Lorenz, J. Bock, J. Snyder, J. G. Korvink, B. A. Jung, and M. Markl, Magn. Reson. Med. **72**, 1 (2014).

[15] K. M. Lüdeke, P. Röschmann, and R. Tischler, Magn. Reson. Imaging **3**, 4 (1985).

[16] N. Ahmed and K. Kr. Das, Int. J. Phys. Sci. **8**, 39 (2013).

[17] H. N. Sabbah, F. Khaja, J. F. Brymer, T. M. McFarland, D. E. Albert, J. E. Snyder, S. Goldstein, and P. D stein, Circulation **74**, 2 (1986).

[18] S. Muzzarelli, P. Monney, K. Obrien, F. Faletra, T. Moccetti, P. Bogt, and J. Schwitter, Eur. Heart J. **15**, 1 (2014).

[19] C. J. Bergin, G. H. Glover, and J. M. Pauly, Radiology **80**, 3 (1991).

[20] Xiang He and D. A. Yablonskiy, P Natl. Acad. Sci. USA **106**, 32 (2009).