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Visualization of Through-Plane Blood Flow Measurements Obtained from Phase-Contrast MRI

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The purpose of this work was to develop a visualization method for concurrent observation of both velocity and magnitude data obtained from through-plane velocity measurements using phase-contrast magnetic resonance imaging. Magnitude and velocity images were combined using an opacity transfer function (OTF) where the opacity was a function of a velocity range defined by the velocity encoding (v_{enc}) parameter. Measured velocities were color-coded according to a predefined color scale and then combined into one image with the gray-scale magnitude image according to the OTF. In the combined images, simultaneous information of velocity and anatomy was presented. The proposed visualization method facilitated the understanding of how the measured blood flow was related to the underlying anatomy. Results are shown where the method is used to visualize blood flow measurements in the ascending aorta and the aortic valve. Adjustments of the OTF render possible identification of the peak velocities and their localization. Forward and backward blood flow is easily shown when applying appropriate OTF and color-coding. An advantage when using the proposed method is the ability of developing standardized protocol settings since the velocity information is quantitative and not relative as is the case for data obtained from the magnitude images. The intended application of the visualization method is the analysis of common flow studies used in the diagnosis of different cardiovascular diseases.

KEY WORDS: Magnetic resonance imaging, image visualization, digital image management, MR imaging, user interface

INTRODUCTION

The blood flow in the larger human vessels can be quantitatively measured by using the phase-contrast technique in magnetic resonance imaging (MRI).[1] When using the phase-contrast technique or velocity mapping as it is also referred to in the literature,[2] velocity images are acquired together with magnitude images that depict the anatomy (see Fig. 1). In order to temporally resolve the blood flow changes during one cardiac cycle, several images are acquired that together encompass a complete heartbeat.[1,3]

The phase-contrast imaging technique allows the measurement of all three orthogonal velocity components, but for many applications, only one velocity component is sufficient. In through-plane blood flow measurements, only the velocity component perpendicular to the image plane is measured, implying that both forward and backward blood flow is detected. The maximum measurable velocity is called velocity encoding (v_{enc})[4] and is set by the operator before the examination starts. Measurements where velocities exceed v_{enc} lead to inaccurate values due to aliasing,[5] while a too high v_{enc}, compared to the actual velocities, implies an increased noise level in the measurement since the standard deviation in the measured velocity is proportional to the v_{enc}.[6]

The magnitude and velocity images represent two sources of information that are presented separately. There are different visualization techniques[5,7,8] depending on the number of velocity components being measured. Pathlines and stream-

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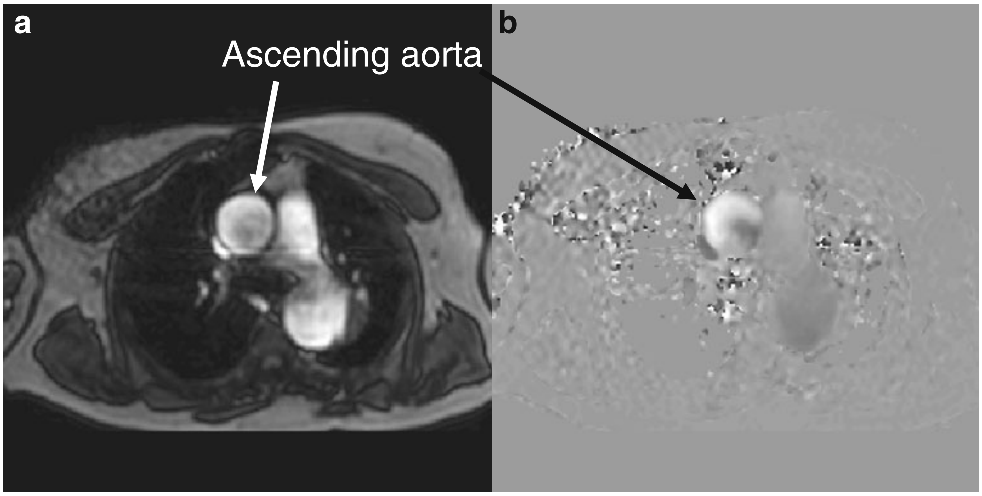


Fig 1. a Magnitude image and (b) velocity image obtained when applying the phase-contrast technique. The images shown were obtained during the systolic phase when the blood flow in the ascending aorta is high. In this example, the through-plane velocity component was measured.

lines are two illustrative alternatives to visualize blood flow when all three velocity components have been measured temporally. Vector plots are feasible visualization methods of the velocity information if at least two velocity components have been measured. If a single velocity component is measured, the available option for visualization is to color code the velocity. In through-plane velocity measurements, which is currently the most common application of phase-contrast imaging in clinical practice, only one velocity component is detected. Consequently, the possibility for visualizing the velocity from through-plane velocity measurements is to apply color-coding, which today is done by applying the gray scale.

The volume-rendering technique (VRT) is often used for visualization of medical volumetric data. VRT has become an important tool in the management of the extensive amount of data that is generated by computed tomography using modern multislice techniques. An opacity transfer function (OTF) is set based on the classified data of which the volume consists when applying the VRT.[9] By defining opacity for the classified data, it becomes feasible to combine information from a volume of data into one single image.

The purpose of this study was to develop a visualization method where the information from both the magnitude and velocity images were combined and presented in a single image, making it possible for simultaneous examination of both blood flow and anatomy.

METHODS

Visualization

The OTF, which assigns opaque properties to the volume data, is an integral part in the volume-rendering equation used for conveying 3D datasets in 2D images.[10] In this work, the visualization of the obtained velocity and magnitude images were performed based on a model containing two semitransparent layers, each with a specified opacity (see Fig. 2).

The velocity image constitutes the first layer in the model, while the second layer corresponds to the magnitude image. The opacity for each layer is determined by an OTF where the opacity is a function of the measured velocity (see Fig. 2b). An advantage of using the velocity as the classification parameter instead of the magnitude value is the fact that the velocity is a quantitative value while the magnitude value is relative which leads to difficulties in the classification and usage of standardized settings. The total opacity for the two layers is equal to 1. Thus, the resultant signal intensity, $\bar{S}$, in a pixel in the combined image is given by:

$$\bar{S} = \mathrm{op}(v) \times \bar{S}_{\mathrm{vel}} + (1 - \mathrm{op}(v))\bar{S}_{\mathrm{mag}} \quad (1)$$

where $\mathrm{op}(v)$ is the opacity value for a given velocity (v), $\bar{S}_{\mathrm{vel}}$ is the color signal in the velocity

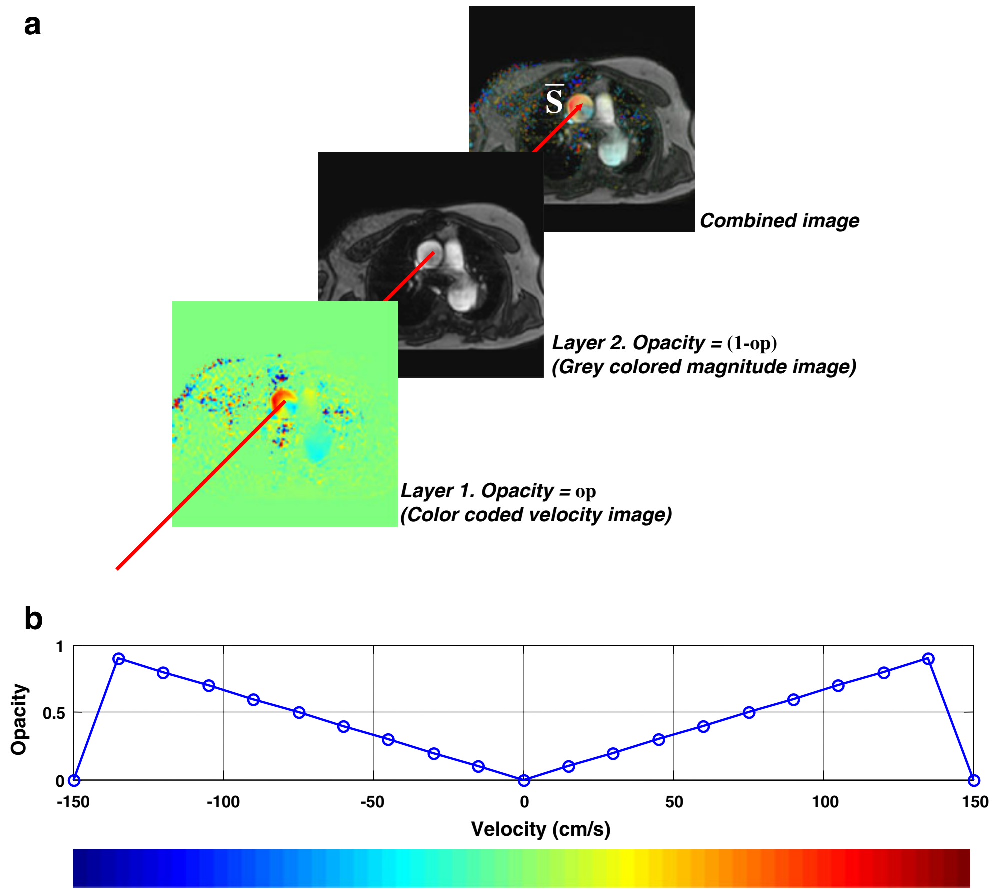


Fig 2. **a** Illustration of the implemented visualization model where the combined image contains information from the velocity image (*layer 1*) and the magnitude image (*layer 2*). The *red arrow* illustrates how information from *layers 1* and *2* are weighted by the opacity to give a resultant combined image. The velocity image in this example is color-coded using the same color scale ("jet") as presented in Figure 3. **b** The opacity transfer function op(v) was used in this illustration.

image, and $\bar{S}_{\text{mag}}$ is the color signal in the magnitude image.

Color-Coding of Magnitude and Velocity Images

When using the RGB model, a color can be represented by the three components: red, green, and blue. The RGB color model is typically handled by computer monitors and was chosen to be applied in this study. A color signal can, according to the RGB model, be represented as a vector given by:

$$\bar{S} = s_{\text{Red}}\mathbf{a}_{\text{Red}} + s_{\text{Grn}}\mathbf{a}_{\text{Grn}} + s_{\text{Blu}}\mathbf{a}_{\text{Blu}} = (s_{\text{Red}}, s_{\text{Grn}}, s_{\text{Blu}}) \quad (2)$$

where ($\mathbf{a}_{\text{Red}}$, $\mathbf{a}_{\text{Grn}}$, $\mathbf{a}_{\text{Blu}}$) are the three unit vectors red, green, and blue in the RGB color space, and (s_{Red}, s_{Grn}, s_{Blu}) are the components of $\bar{S}$ ranging from 0 to 1, respectively.

In this study, the color-coding in the magnitude images was chosen to follow the gray scale, i.e., equal RGB values, since MR images are almost exclusively represented as gray-scale images. Each pixel value in the magnitude image $\bar{S}_{\text{mag}}$ was normalized, yielding pixel values (p) in the range $\{p \in R;\ 0 \leq p \leq 1\}$ where R stands for real numbers.

Contrary to the magnitude images, the velocity images were color-coded according to a defined color scale. The range of velocities in the velocity image $\{v \in R;\ -v_{\text{enc}} \leq v \leq v_{\text{enc}}\}$ was set to encompass the whole color scale, implying a certain RGB value for a specific velocity (see the illustration in Fig. 3). As seen in Figure 3, the color signal in the velocity image, $\bar{S}_{\text{vel}}$, depends on the measured velocity and the applied color scale. Forward and backward blood flow can be clearly visualized by

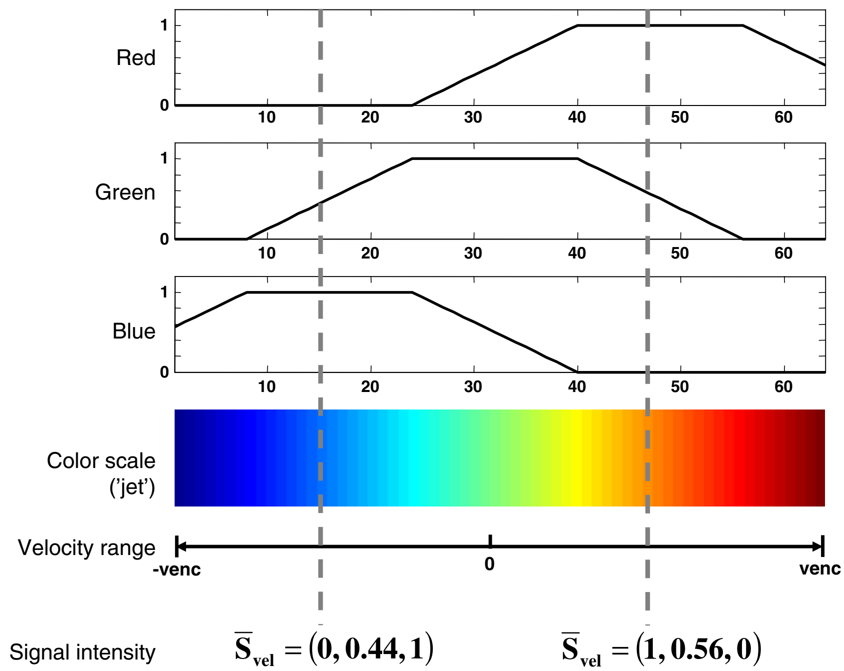


Fig 3. The color scale and the measured velocity determine the resulting color signal in the velocity image. In this example, the color scale "jet" was applied (the color bar is displayed using 64 levels). Each color in the color scale is a specific combination of the three colors: red, green, and blue. A unique combination from the red, green, and blue channels is obtained giving the color signal $\bar{S}_{vel}$ for a specific velocity, here indicated with a *gray dashed line*.

choosing a color scale that enables discrimination of measured velocities according to both direction and magnitude. The color scale "jet," shown in Figure 3 and applied in Figures 2 and 4, uniquely labels the velocities to give an unambiguous color-coding of the blood flow in the combined image. Other color scales than "jet" with different RGB components can be applied as long as the requirement of unambiguous color-coding is met.

The visualization method and the color-coding of the magnitude and velocity images were implemented in Matlab (MathWorks, Natick, MA, USA).

Image Acquisition

Through-plane phase-contrast imaging was performed using a 1.5-T Achieva system (Philips Medical Systems, Best, The Netherlands) with a 33-mT/m gradient system. The time-resolved phase-contrast image pulse sequence was applied during breath-hold (expiration) using retrospectively triggered electrocardiogram. Data from two different examinations were used for the evaluation of the visualization method. Both patients were examined in supine position, and a five-channel cardiac coil was used for signal detection. The image plane for the examination of blood flow in the ascending aorta was determined using a coronal view of the ascending aorta and the left ventricle,[11] and the cross-sectional image of the aortic valve was planned using the coronal view together with two other image planes depicting the aortic valve: the left ventricular outflow tract and the basal short axis view. The v_{enc} was set to 250 cm/s in the examination of the aortic valve and to 150 cm/s for the flow measurement in the ascending aorta. For each examination, v_{enc} was adjusted by the MR technician during the examination to ensure non-aliased velocity measurements. The examinations in this study were approved by the local ethics committee.

RESULTS

The blood flow through the aortic valve during systole is visualized by applying the proposed method (see Fig. 4). The OTF is set to promote visualization of forward flow in the range of 40 to 130 cm/s and for backward flow in the range of −10 to −50 cm/s. During systole, there is a major forward blood flow through the valve, but a

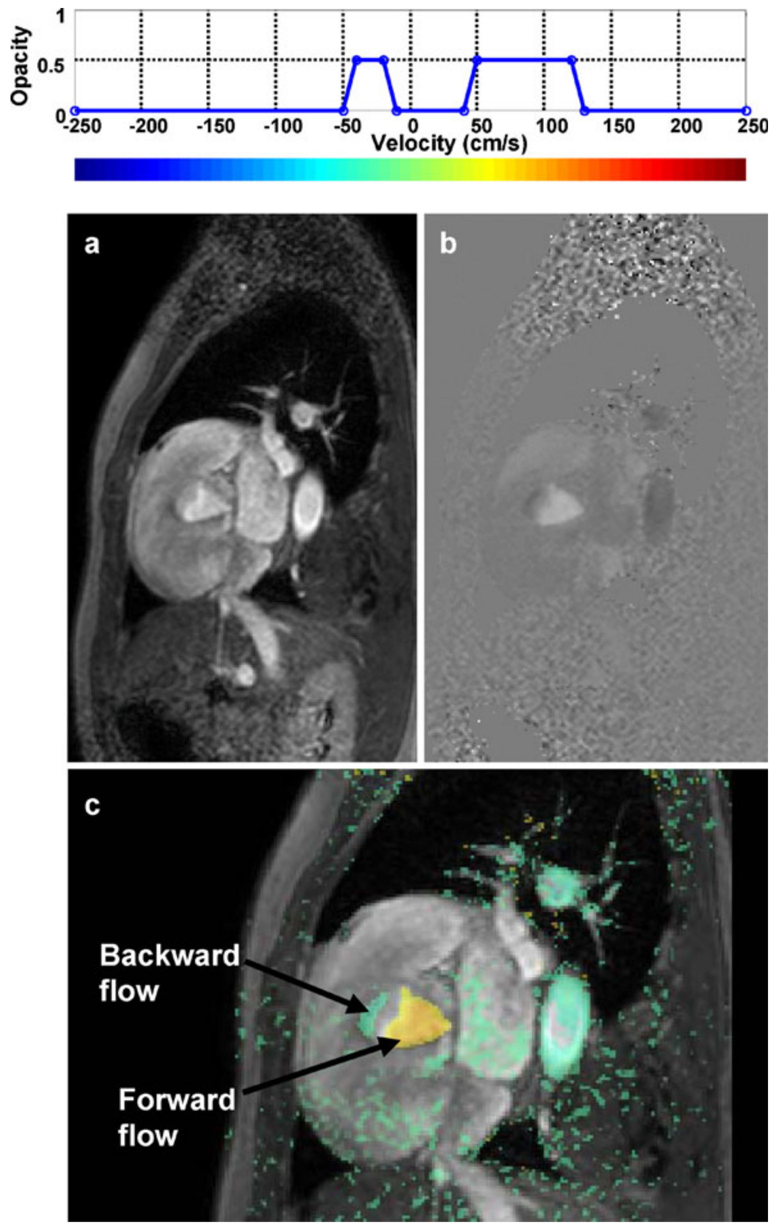
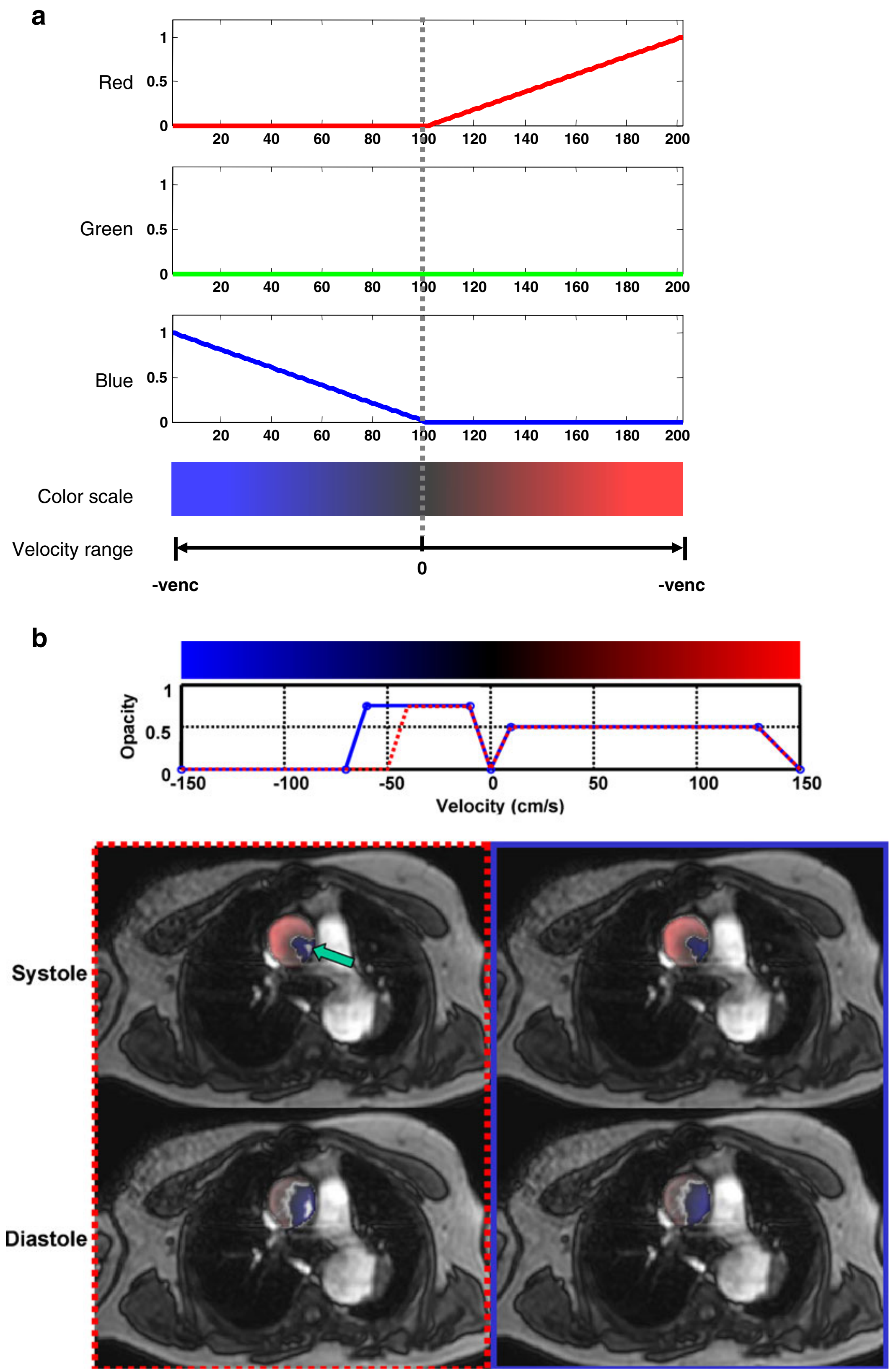


Fig 4. The *blue line* in the graph shows the opacity transfer function (OTF), and the *color bar below the graph* shows the velocity for each color encoding. The applied color scale was the same as shown in Figure 3. All three images (a–c) show the aortic valve during systole when the valve is open and blood is pumped from the left ventricle to the aorta. The magnitude image in (a) displays the anatomy, while the velocity image in (b) shows the measured velocities. In (c), the velocity information has been color-coded according to the OTF and combined with the magnitude image into one single image. The *arrows* in (c) point at forward and backward flows that appear simultaneously during systole. The backward flow, indicated with an *arrow*, occurred in the noncoronary sinus.

backward flow can also be observed. The formation of backward (retrograde) flow in the noncoronary sinus during systole is in accordance with findings seen using time-resolved 3D phase-contrast imaging.[12] In the combined image (Fig. 4c), the retrograde flow in the noncoronary sinus is better related to the anatomical structure (Fig. 4a) compared to the alternative of merely looking at the velocity image (Fig. 4b).

The blood flow in the ascending aorta is known to have a skewed profile that changes during the cardiac cycle.[13] By applying the visualization method to flow measurement in the ascending aorta, the skewed velocity profile becomes con-



a
Red
Green
Blue
Color scale
Velocity range
0
-venc
-venc
b
Opacity
Velocity (cm/s)
Systole
Diastole

Fig 5. a Illustration showing the applied color scale and the contribution from each individual color. The color scale was bicolored since the green component was 0 for the whole range of velocities (the color bar is displayed using 202 levels). b Combined magnitude and velocity images showing the blood flow in the ascending aorta during systole (*upper row*) and diastole (*lower row*). Two different opacity transfer functions (OTFs) were applied. The OTF according to the *blue line* resulted in the color-coded images in the *right column*, while the *red dotted line* gave rise to the images in the *left column*. For the purpose of illustration, only the lumen of the ascending aorta was color-coded. The *green arrow* points out the localization of maximum backward flow velocities.

spicuous in the combined image (see Fig. 5). The color scale and OTF used in Figure 5 differ from the example shown in Figure 4. Altering the OTF, as seen in Figure 5, reveals that both localization and magnitude of the retrograde flow could be visualized in an intuitive way. In this example, the maximum measured retrograde flow velocities in the ascending aorta were in some areas slightly higher than 50 cm/s during systole, which is in accordance with published data.[13] A comparison of the combined images in Figure 5 reveals how the proportion of retrograde flow, related to the total aortic lumen area, increases when going from the systolic frame to the diastolic frame. This agrees with observations previously described in the literature.[14]

In both visualization examples shown in Figures 4 and 5, the opacity was set to 0 or low values for velocities around 0. This was done in order to suppress signal from stationary tissue.

DISCUSSION

The possibility of combining anatomical images with flow measurements makes MRI a very useful tool in the evaluation of different cardiovascular diseases. Information about the blood flow has been shown to be of importance in the assessment of different vascular diseases, for example, aortic valve stenosis and insufficiency,[15,16] aortic dissection,[17] and aortic coarctation.[18]

Magnitude and flow images from through-plane flow measurements are usually displayed separately. In this study, a method is presented that combines the anatomical and blood flow information into one combined image. By applying an OTF, both flow and anatomy can be observed concurrently. Adjusting the opacity can alter the influence from either the flow or magnitude images.

As seen in Figure 5, the method is useful for the determination of both the magnitude and localization of peak blood flow velocities. The measurement of peak velocities is of importance in the assessment of vascular constrictions where the pressure gradient over the constriction can be calculated according to the simplified Bernoulli equation where the peak velocity is used.[19] In this work, it is shown how adjustments of the OTF, as demonstrated in Figure 5, can be used in the identification of peak velocities.

In the method presented, the opacity is a function of the range of velocities that is set by the parameter v_{enc}. Since the velocity image contains quantitative values, it is possible to develop predefined protocol settings that can be standardized depending on the type of examination. It is an advantage to use the velocity range, set by v_{enc}, for protocol setting since the signal intensities in the magnitude images are relative and vary between patients and examinations.

The possibility of concurrently studying flow and anatomy in a combined image may facilitate clinical investigations of different cardiovascular diseases with through-plane studies.

A limitation of the proposed visualization method is the applicability on high-resolution gray-scale monitors.

CONCLUSION

In the present study, a visualization method is proposed for through-plane MR flow measurements. Magnitude and velocity images are combined into one single image where the velocities are color-coded and set to a predefined opacity given by a transfer function. The proposed method facilitates the understanding of how the measured flow information is related to the underlying anatomy.

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