

VENTRICULAR FUNCTION

Application of spatial modulation of magnetization (SPAMM) to children: the effect of image resolution on tagging pattern

JOHN C. HASELGROVE, PH.D.^{2,3} and MARK A. FOGEL, M.D.^{1,2,3,*}

¹Division of Cardiology, Department of Pediatrics (MAF), The Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, USA

²Department of Radiology (JH), The Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, USA

³The University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania, USA

Background and Objective. Spatial modulation of magnetization (SPAMM) is a valuable magnetic resonance imaging technique for studying ventricular biomechanics. In order to track the intersection points of the stripes to calculate regional wall motion and strain, the stripe spacing should be at most half the wall thickness, yet sufficiently larger than the image pixel size in order that the stripes be well resolved. These conflicting requirements, that the grid spacing be much smaller than the wall thickness yet much larger than the pixel size, are relatively easy to meet in adult subjects but are difficult in children because of their small size. The purpose of this study was to delineate the effect of pixel size relative to SPAMM grid spacing on the stripe pattern produced by SPAMM with application towards its use in children and to present a new approach to the analysis of these images. Methods. We performed SPAMM imaging on a 1.5 Telsa Siemen's Vision MR system on a phantom, using an artificial ECG (R-R interval = 450 ms for triggering), holding the pixel size constant and varying the degree of stripe spacing. We used both square (1 mm) and rectangular (1 mm by 2 mm) pixels. We express the ratio of grid to pixel size as the ratio of the center-center spacing of the grid lines to the horizontal pixel size. We retrospectively reviewed the SPAMM images on 10 patients with a ratio of grid to pixel size $\sim 4:1$ and 10 with a ratio of grid to pixel size $\sim 8:1$. We further performed SPAMM imaging in four patients with different grid to pixel size ratios in the same patient. Finally, we tested a new algorithm to track the signal intense regions rather than the signal poor intersection points of the grid lines, which were compared on three ventricles with SPAMM tagging. *Results*. In a phantom, the effect of decreasing the separation between stripes while keeping the resolution of the image constant changed the stripe pattern from a series of two parallel lines perpendicular to each other to a "checkerboard" pattern. With a relative grid:pixel ratio of 8:1 as used with adult studies, the dark bands and the crossing points are well defined. As the ratio decreases from 8:1 to 6:1, the black band is less well resolved. When the resolution is reduced further to a grid; pixel ratio of 4:1, the image appears to be a checkerboard of white and dark squares. This occurred with both square and rectangular pixels. The effect in vivo is similar. When the ratio is approximately 8:1, all patients demonstrated a stripe pattern as a set of parallel lines perpendicular to each other. When the ratio was approximately 4:1, all patients demonstrated the stripe pattern as checkerboard. This was found to be the case in the same patient, whether varying the pixel size by changing the field of view or matrix or by changing the grid spacing. We also found that tracking the signal intense regions was equivalent to tracking the signal poor intersection points of the grid, and this approach was much easier to implement. Conclusion. With decreasing ratio of grid spacing to pixel size, SPAMM stripe patterns change from a set of parallel lines perpendicular to each other to a "checkerboard" pattern. This effect has implications for tracking techniques to determine strain and wall motion. At smaller ratios, as is needed sometimes in children, it is easier to track the signal intense regions rather than the "intersection" points of the stripes. Both these approaches to tracking are equivalent.

Key Words: Magnetic resonance imaging; Spatial modulation of magnetization (SPAMM); Pixel size; Grid spacing; Children; Congenital heart disease

1. Introduction

Spatial modulation of magnetization (SPAMM) (1-3) is a valuable magnetic resonance imaging technique for studying

cardiac biomechanics such as regional strain and wall motion (4-7). At a predefined time in the cardiac cycle, a short pulse sequence ("SPAMM pulse") is used to saturate myocardial tissue along two sets of parallel stripes that are perpendicular to each other, generating a grid pattern that is distorted by tissue motion. Assessment of myocardial motion and deformation is achieved by tracking the distortion of the grid between images obtained at successive intervals throughout the cardiac cycle. Typically, the SPAMM stripe pattern is generated using a five-pulse sequence (3, 6) that generates stripes with a thickness about one quarter the stripe spacing.

1097-6647 © 2005 Taylor & Francis Inc.

Received 14 September 2001; accepted 17 August 2004.

^{*}Address correspondence to Mark A. Fogel, M.D., Division of Cardiology, Department of Pediatrics (MAF), The Children's Hospital of Philadelphia, Main Bldg., 2nd Floor, 34th St. and Civic Center Blvd., Philadelphia, PA 19104, USA; Fax: (215) 590-4127; E-mail: fogel@email.chop.edu

The black lines are thus well defined and the crossing points are used as tracking points.

In order to follow wall thickening as well as wall movement, the stripe spacing should be at most half the thickness of the heart wall (ideally, much smaller), yet it should be sufficiently larger than the image pixel size so that the stripes can be well resolved. These conflicting requirements that the grid spacing be (much) smaller than the thickness of the heart wall yet (much) larger than the pixel size are relatively easy to meet in adult subjects, but are difficult in children.

In adult subjects, the wall thickness of the heart is about 10-15 mm and can be on average, by some reports, as high as 19 mm (8, 9). Good results can be obtained using stripes with a thickness about 1.5-2 mm separated by about 6-7 mm (3, 7, 10, 11). This separation is less than half the width of the myocardial wall while still significantly greater than the pixel size of 1 mm. The crossing points of the black lines are well defined and are used to track and follow the motion of the heart wall (2, 3, 7, 10).

In children, because the myocardial wall is much thinner, the situation is somewhat different (4–6). With a typical thickness of 4–10 mm, the spacing of the lines should be less than 2–5 mm if wall motion is to be followed. To keep imaging times short and to obtain useful signal-to-noise ratios, a matrix size of 128×256 is typically used, which yields a rectangular pixel with dimensions of approximately 1×2 mm. Following these guidelines, the grid spacing would be barely larger than the pixel size, which, as opposed to the typical grid spacing of 4–5 mm, is impractical. Even with a grid spacing of 4–5 mm, the pixel size is a significant fraction of the size of the SPAMM grid.

This study investigates the effect of pixel size, shape and grid spacing on the SPAMM images and expands on the work of Peters, Epstein, and McVeigh, which investigated undersampled projection reconstruction (12). We hypothesized that the different appearance of SPAMM imaging in some children relative to those found in adults is a result of the ratio of the grid spacing to pixel size (SP) ratio. These findings have implications to the automatic tracking algorithms used to analyze these images and this study explored the utility of one such algorithm. It is very simple to implement and differs from previous approaches by viewing the SPAMM image as a series of signal-intense markers (dots) rather than a lattice of black lines.

2. Methods

2.1. Phantom experiments

A series of studies was performed on a doped, water-filled phantom. Images of the phantom were obtained using both rectangular and square pixels, in which the relative size of the grid spacing and the pixel size was varied by holding the image pixel size fixed and varying the grid spacing. A 1.5 T Siemens Vision and Sonata whole body system was used for all imaging, using a matrix size of either 128×256 or 256×256 , producing rectangular and square (13) pixels, respectively. The Siemens image generation software interpolates the 128×256 matrix so that the final images in all cases have a 256×256 matrix. Conventional SPAMM sequences were performed as described previously. In brief, a SPAMM presaturation pulse consisting of two, five-pulse sequences was applied immediately following the R wave. The SPAMM pulses used for the different studies were identical in terms of the flip angles of each five-pulse sequence $(12^\circ, 28^\circ, 42^\circ, 28^\circ, 12^\circ)$ and the timing of the pulses (0.5 ms pulses every 1.5 ms). They differed only in the amplitude of the gradients applied in between the pulses used to control the separation of the grid lines. Then, 12 images were acquired at 50-ms intervals using a triggered cine FLASH sequence (TE = 7 ms). An artificial ECG signal with an R-R interval of 450 ms for the triggering was used during phantom experiments. The head coil was used in this experiment. Bandwidth was 260 Hz/px. No segmentation was used.

The SP ratio was expressed as the ratio of the center– center spacing of the grid lines to the horizontal pixel size.

2.2. Patients

We retrospectively examined the ventricular short-axis SPAMM images obtained from a total of 20 patients with various forms of congenital heart disease who underwent MRI imaging at The Children's Hospital of Philadelphia from January, 1995-December, 2000. Ten patients had SPAMM imaging with an SP ratio of 7-8 and 10 patients had SPAMM imaging with an SP ratio of 3-4. In addition, ventricular short-axis SPAMM imaging scans on four patients with congenital heart disease were performed by varying the SP ratio by changing the field of view and grid spacing in the same patient. Subjects' ages ranged from 2 months to 15 years with a mean (\pm standard deviation) of 4.3 \pm 4.1 years. Heart rates were 110 ± 41 beats per minute. Subjects had to be able to undergo a 1-hour magnetic resonance imaging scan under sedation. All patients were in normal sinus rhythm and had no evidence on surface ECG of altered electrical activation. No patient had any arrhythmias that precluded study in the scanner. Imaging parameters were nearly identical to the ones used in the phantom described above. Both head and body array coils were utilized. No segmentation was used. Patients did not use breath holding and the number of averages = 3. If < 7 years old, patients were sedated as per hospital protocol (Institutional Review Board approval was obtained).

2.3. Tracking algorithm

The algorithm exploits the fact that it is simpler to determine the position of one of the white dots by finding a local maximum than to determine the crossing points of the black lines—which is a "saddle." We currently define the "position" of the dot as the pixel in an interpolated, smoothed image that has the maximum intensity. However, it is easy to use other algorithms for defining the position of the dot, such as finding the centroid. All that is necessary for the dot-position-algorithm is that it can begin with any coordinate and determine the "position" of the nearest dot.

In our application the original images with a 256×256 matrix are expanded to a 1024×1024 matrix. They are then smoothed with a filter that approximates the shape of the dots. The exact shape of the kernel is not critical. We use an 11×11 filter generated from the cross-product of the vector (1,2,3,4,5,6,5,4,3,2,1) and its transpose.

The computer displays the first expanded, smoothed image of the set, and the user indicates each white dot in the region of interest by means of a cursor. The user does not have to indicate the center, merely any point that is clearly on the selected dot. As each dot is indicated, the computer tracks its position through all the images by iterating the following two steps:

- 1. The position of the dot is found. We currently search the pixels surrounding the start point, to determine the position of the closest local maximum intensity.
- 2. This position is registered as the position of the dot on that image, and is then used as the starting point for the position search on the next image.

The algorithm works excellently for dots that are clearly distinguished in every image of the series, but suffers from the same disadvantage experienced by any technique that relies on local features for tracking. Features (dots) that are clear on the initial images can smear with time and disappear on later images of the series. Nonetheless, a human operator can still sometimes recognize the positions using multiple complex features such as inflection points and general features of the surrounding image. We therefore make provision for the user to edit the results of the automatic tracking manually, to add, remove, or to adjust the positions of points.

We compared the results of automatic tracking with manual analysis on three ventricles with SPAMM imaging from the patient population described above.

3. Results

3.1. Phantom experiments

An image with an SP = 20 (grid spacing of 20 mm and pixel size of 1×1 mm) is shown in Fig. 1A. The matrix of orthogonal dark bands is clearly visible. The light line running along the center of the dark band arises from the use of a pulse sequence that gives a total excitation flip angle of 122° along that line, so the magnetization at the center of the band is partially inverted but appears bright in a magnitude image.



Figure 1. Phantom experiments. (A) A high resolution image of the grid spacing with SP = 20 (grid spacing of 20 mm and pixel size of 1×1 mm). The matrix of orthogonal dark bands is clearly visible. (B and C) Images obtained using a square pixel with varying resolution are shown in the top row of images of the figures and rectangular pixels are shown in the bottom row of images. This is demonstrated for both integer (B) and noninteger (C) values of SP. Clearly, when an SP value of 8 typical of adult studies is used, the crossing points of the dark bands are still well defined even though the white stripes along the center of the black band are no longer resolved. However, when SP is decreased to about 4 as needed for studies with small children, the image appears as a checkerboard of white and dark squares. The images indicate the expected result that for a given SP ratio, the rectangular pixels do appear more checkerboard-like than the equivalent image obtained with square pixels.

Images obtained using a square pixel with varying resolution are shown in the top row of images of Fig. 1B and 1C, and confirm the phenomenon seen in vivo. When an SP value of 8 typical of adult studies is used, the crossing points of the dark bands are still well defined even though the white stripes along the center of the black band are no longer resolved. With decreasing SP (i.e., 6), the black bands appear to be transitioning to a geometry other than two sets of parallel lines perpendicular to each other. When SP is decreased to about 4 as needed for studies with small children, the geometry of the tags appears as a well-defined checkerboard of white and dark squares.

The effect of using rectangular pixels instead of square pixels is shown in the lower set of images in Fig. 1B and 1C. The SP for the rectangular pixel is defined using the shorter (horizontal) dimension of the pixel. The results are similar to those seen using a square pixel (top row of images in Fig. 1B and 1C). An SP of approximately 8 produces images in which the black bands are still clearly recognizable as bands. However, as SP decreases to about 4, the bands become broader to the point that the image appears to be checkerboard. Although we have made no attempt to quantitate the "degree of checkerboardness," the images do indicate the expected result that for a given SP ratio, the rectangular pixels do appear more checkerboard-like than the equivalent image obtained with square pixels.

3.2. In vivo studies

In our retrospective review (Fig. 2), the average SP ratio in the SP 7–8 ratio group was 7.4 ± 0.46 and was 3.8 ± 0.76 for the SP 3–4 ratio group (ratios of 3–4). In all patients in the SP 7–8 ratio group, the SPAMM grids were in the form of two sets of parallel stripes perpendicular to each other, and in the SP 3–4 ratio group, all patients demonstrated SPAMM



Figure 2. Retrospective review of SPAMM studies. The images shown are representative of the groups as a whole. A high SP ratio example is demonstrated on the left while a low SP ratio is demonstrated on the right. Both patients are single left ventricle (LV) patients; however, the one on the left is status post (S/P) a Fontan operation while the one on the right is after a hemiFontan procedure. Pt = pateints. All values are mean \pm standard deviation.



Figure 3. Series of SPAMM sequences in the same patient. With rectangular pixels (A), it is evident that at an SP = 8 (upper right), a group of parallel stripes perpendicular to each other is seen while at an SP = 4 (upper left and bottom), a checkerboard pattern is produced independent of the grid spacing and field of view. With square pixels (B), an SP of 8 (upper left) or 4 (upper right and lower left) produced a group of parallel stripes perpendicular to each other, while at an SP of 2 (lower right), this became a checkerboard pattern. This was independent of grid spacing and field of view like the rectangular pixels in (A) and is consistent with our phantom observations in Fig. 1. A side-by-side comparison of rectangular to square pixels is made for a given SP (C), by simply changing the matrix. It is seen from this that rectangular pixels become more like a checkerboard than square pixels for an equivalent SP.

grids in the form of a checkerboard pattern. Figure 2 demonstrates a typical example from each group. TR ranged from 25-70 msec, TE was 7 msec, FOV ranged from 160-300 mm, slice thickness ranged from 4-7 mm.

Figure 3A–C demonstrate the typical findings in the group of patients who had multiple SPAMM sequences applied at two SP ratios by varying the grid spacing and the field of view (FOV). With rectangular pixels (Fig. 3A), it is evident that at SP = 8, a group of parallel stripes perpendicular to each other is seen while at SP = 4, a checkerboard pattern is produced independent of the grid spacing and field of view. With square pixels (Fig. 3B), an SP of 8 or 4 produced a group of parallel stripes perpendicular to each other, while at an SP of 2, this became a checkerboard pattern. This was independent of grid spacing and field of view like the rectangular pixels and is consistent with our phantom observations that rectangular pixels become more like a checkerboard than square pixels for an equivalent SP. This is readily seen in Fig. 3C, where rectangular and square pixels are compared side by side for a given SP by simply changing the matrix.

3.3. Tracking algorithm

Figure 4 is an example of manual tracking of the intersection points and automatic tracking of the signal intense region from the same patient. Figure 4A displays the results of manual tracking that was performed in the conventional manner by tracking the position of the intersections of the black lines on images that were interpolated but not smoothed. Figure 4B displays the results of automatic tracking that tracked the positions of the white dots. The crosses and squares indicate the positions of the tracked features in the first image while the tail projecting from each dot is the track of the positions of the feature in the following images. There are positions where an expected dot is absent from the automatically tracked data. This absence is due to the fact that a dot that is clearly visible in the first image is not discernible in the last image. The tracks from such dots are easy to identify because they either merge with an adjacent track or travel to an obviously erroneous position. The operator can delete such dots from the data set. Other than to delete spurious tracks, the automatically tracked data of Fig. 4B has not been edited.

The manual and automatic data sets are very similar, but because they track different features, it is not possible to perform a direct point-by-point comparison. To compare the two methods, we have made an assumption that the displacement of any dot measured automatically between the first and last images, Da, should be approximately the same as the average displacement of the four adjacent lineintersection points measured manually, Dm. We therefore analyzed the movement of all dots for which there are four surrounding crossing points that could be measured manually. The relationship between the automatic and manual displacements is plotted in Fig. 5A. The correlation between the





Figure 4. Manual tracking of intersection points (A) vs. automatic tracking of white dots (B). The crosses and squares indicate the positions of the tracked features in the first image while the tail projecting from each dot is the track of the positions of the feature in the following images.

displacements derived from manual and automatically tracked SPAMM points is excellent.

$$Dm = 1.02 * Da + 0.05 r = 0.98$$

The Bland and Altman (14) plot shown in Fig. 5B compares the differences in the displacements, (Da - Dm), with the



The differences we have noted at various SP ratios are applicable to the problem of SPAMM tagging in children. Both pixel sizes and grid tag spacing are smaller in children than in adults for the obvious reason that children are smaller. However, the decrease in grid tag spacing needs to be greater than the decrease in pixel size when SPAMM tagging is performed in children. Imaging small ventricular walls requires that the pixel size be large relative to the SPAMM stripe spacing (e.g., 1 mm:4 mm.). This study quantifies this phenomenon as the SP ratio.

The "checkerboard" SPAMM tagging phenomenon is not new. Thomsen reported two methods of obtaining this kind of pattern by altering SPAMM pulse sequences using two orthogonal gradients in the same sequence (15). The actual images appear similar to the ones reported in this study, although in our study, the typical SPAMM sequences were not altered; the checkerboard pattern was produced just by changing the pixel size and grid spacing.

Peters, Epstein, and McVeigh examined the results of myocardial wall tagging with undersampled projection reconstruction (12). In their phantom experiments, by keeping the field of view and grid spacing constant and decreasing the matrix size in one dimension (essentially decreasing the SP with a rectangular pixel shape), they demonstrated that the grid tagging changed from two sets of parallel stripes perpendicular to each other when the "number of views" are reduced from 256 to 64.

Our work expands on previous studies in the literature in a number of ways:

- Our study shows this phenomenon's clinical applicability to pediatrics because of the smaller size of the heart in children and the technical limitations imagers have to work under in present commercial MRI scanners.
- Children have unique requirements in myocardial tagging, and we used no special pulse sequence algorithms as the works of Peters et al. (12) and Thomsen (15) did to obtain our findings.
- In addition to in vitro work, we retrospectively reviewed our experience with 20 children where the works of Peters et al. (12) and the Thomsen (15) only had one in vivo study.
- We quantify our results in pixel size to grid spacing ratio, terms that are in general use and easily available in commercial scanners.
- Our study investigates pixel shape in addition to size and grid spacing.

In the SP = 20 image, we demonstrated that a light line ran along the center of the dark band. It was postulated that this arises from the use of a pulse sequence that gives a total excitation flip angle of 122° along that line, so the magnetization at the center of the band is partially inverted

Figure 5. Comparison of manual tracking of intersection points vs. automatic tracking of white dots. (A) This scatter plot compares both techniques using linear regression and Pearson correlation (Dm = 1.02 * Da + 0.05, R = 0.98) (B) Bland-Altman plot of the difference between displacements with the average displacement.

average displacement, (Da + Dm)/2. It is readily seen that the variations between the measurements are independent of the displacement. The root mean square value of the difference is 0.41 mm.



6

10



Δ

but appears bright in a magnitude image. This progressive loss of definition of the sharp black line is to be expected because signal intensity is averaged over the area of each pixel. The pixel can therefore be thought of as a smoothing and sampling filter. The smoothing operation spreads any sharp features (the grid lines) in space and makes them appear broader. As the pixel becomes a larger fraction of the object (the unit cell of the grid), the broadening of the sharp lines becomes greater.

4.1. Potential solutions

There are two ways in which SPAMM imaging in children may be dealt with when confronted with the "checkerboard" pattern:

- 1. *Alter image generation:* Two different approaches may improve the tagging methods described in this manuscript. In one, two complementary sets of tags can be created in different directions with the tag placed in the high resolution read-out direction where information from both sets are combined during tag analysis (16). The other approach may be to use the technique of undersampled projection reconstruction as described by Peters et al. (12) referenced earlier.
- 2. Alter the algorithm used to analyze the images: The change in the structure of the SPAMM grid has ramifications for the algorithms used for automatic tracking of the myocardial tags. The algorithms for finding the positions of the crossing points of the black lines, and for tracking them between images can be relatively complex and difficult to implement. It seems inappropriate to use algorithms that track the crossing points of narrow black lines when no such lines appear in the image. Simpler algorithms, as has been demonstrated in this study, can be developed to utilize the center of the white dots for tracking. Automatic tracking algorithms are likely to be most successful when they track the sharpest salient feature of the image, and in the SP 3–4 ratio images, the salient features are the white dots.

The novel feature in the tracking algorithm described in this study lies in viewing the SPAMM image as a series of white dots rather than a series of black lines. Conventional manual and automatic techniques track the crossing points of the black lines that are designed to be narrower and sharper than the white intervening region (7, 17). The sharpness of the lines aids a human operator to position the crossing points accurately. Nonetheless, we have chosen to follow the movement of the centers of the white dots because of the ease with which a dot can be made to have a defined maximum by using a simple smoothing filter. Conventional image processing wisdom dictates that the filter kernel should be matched to the shape of the dot. But the dot shape changes during the period of the study due to strains in the heart, to T1 relaxation and to diffusion effects (10), so no single kernel can be matched to all the dots on all images. We find that any broad kernel approximating the size and shape of the dot is suitable. The dot's "position," as defined here, will rarely lie at the center of the lattice cells defined by the black lines, because variation in the intensity of the underlying image modulates the intensity distribution within the dot. Nonetheless, the position is well defined and can be followed from image to image. Since the strain-analysis routines make no assumptions about where on the heart the tracked points originate, tracking the positions of the white dots is equivalent to tracking the black cross-over points.

Comparison of the manual and automatic tracking methods presented in Figs. 4 and 5 indicates that accuracy of the automatic tracking routine is at least as good as the manual method. The root mean square, variation in the displacements of about 0.5 mm, should be considered upper limits because they incorporate both the errors in measurements per se, and errors in the assumption that the displacement of a feature is equal to the average displacement of the four surrounding features. The variations are in the same range as the values of 0.5 to 1.0 mm for an automatic "snake" analysis (7), and are significantly less than the resolution (1.25 mm \times 2.5 mm) with which the images were acquired.

It is to be expected that an algorithm as simple as this does not have the ability to track all the features that can be followed by a skilled operator. Nonetheless, it is easy to implement, easy to use, as accurate as our current manual method, and serves to reduce most of the effort required by a completely manual technique. In normal use, the automatic tracking is supplemented by some manual editing by the operator.

The current demonstration of the automatic tracking routine made use of images acquired with pulse sequences designed to give narrow dark lines specifically for optimal tracking of the cross-over points. The profile of the white dots produced by this sequence is probably not the best profile for tracking the dots using a simple smoothing filter. Simple sinusoidal profiles generated by two pulses will be fast and easy to apply and may generate a dot profile that gives more accurate positions when tracked automatically. However, the sequence designer must bear in mind the fact that the automatic routines cannot yet track as many points as can a practiced human operator, and that supplemental manual tracking will still be necessary.

5. Conclusion

SPAMM tagging using the same pulse sequence may result in either: 1) two sets of parallel lines perpendicular to each or 2) a "checkerboard" pattern. The pattern is a function of the grid-spacing to pixel size ratio (SP), which must be interpreted in light of the pixel shape (square or rectangle). For both square or rectangular pixels, the higher the SP, the more the patterns resemble two sets of parallel lines perpendicular to each (e.g., SP > 8). As the SP decreases, the pattern increasingly becomes more like a "checkboard" (e.g., SP < 4). As the SP decreases, rectangular pixels qualitatively seem to become more "checkerboard-like" quicker than square pixels.

Knowledge of this phenomenon is useful when applying SPAMM tagging techniques in children, where the pixel size makes up a significant portion of the grid spacing. Additionally, the two patterns have implications for automatic tracking algorithms used to analyze these images. At smaller ratios, as is needed sometimes in children, it will be necessary to track the signal-intense regions rather than the "intersection" points of the stripes. We have demonstrated such an algorithm in this study.

References

- Young AA, Axel L, Dougherty L, Bogen DK, Parenteau CS. Validation of tagging with MR imaging to estimate material deformation. Radiology 1993; 188:101–108.
- 2. Axel L, Dougherty L. MR imaging of motion with spatial modulation of magnetization. Radiology 1989; 171:841-845.
- Axel L, Dougherty L. Heart wall motion: improved method of spatial modulation of magnetization for MR imaging. Radiology 1989; 172:349-350.
- Fogel MA, Weinberg PM, Fellows KE, Hoffman EA. A study in ventricular-ventricular interaction: single right ventricles compared with systemic right ventricles in a dual chambered circulation. Circulation 1995; 92:219–230.
- Fogel MA, Gupta KB, Weinberg PW, Hoffman EA. Regional Wall Motion and Strain Analysis Across Stages of Fontan Reconstruction by Magnetic Resonance Tagging. Am J Physiol 1995; 269(Heart Circ Physiol 38):H1132–H1152.
- 6. Fogel MA, Gupta K, Baxter MS, Weinberg PM, Haselgrove J,

Hoffman EA. Biomechanics of the deconditioned left ventricle. Am J Physiol 1996; 271(Heart Circ Physiol 40):H1193–H1206.

- Young AA, Imai H, Chang NC, Axel L. Two-dimensional left ventricular deformation during systole using magnetic resonance imaging with spatial modulation of magnetization. Circulation 1994; 89:740-752.
- Lauer MS, Larson MG, Levy D. Gender-specific reference Mmode values in adults: population-derived values with consideration of the impact of height. J Am Coll Cardiol 1995; 26:1039–1046.
- Lauer MS, Larson MG, Evans JC, Levy D. Association of left ventricular dilatation and hypertrophy with chronotropic incompetence in the Framingham heart study. Am Heart J 1999; 137:903–909.
- Axel L, Goncalves RC, Bloomgarden D. Regional heart wall motion: two dimensional analysis and functional imaging with MR imaging. Radiology 1992; 183:745–750.
- Hatabu H, Gefter WB, Axel L, Palevsky HI, Cope C, Reichek N, Dougherty L, Listerud J, Kressel HY. MR imaging with spatial modulation of magnetization in evaluation of chronic central pulmonary thromboemboli. Radiology 1994; 190:791–796.
- Peters DC, Epstein FH, McVeigh ER. Myocardial wall tagging with undersampled projection reconstruction. Magn Reson Med 2001; 45:562–567.
- Stuber M, Scheidegger MB, Fischer SE, Nagel E, Steinemann F, Hess OM, Boesiger P. Alterations in the local myocardial motion pattern in patients suffering from pressure overload due to aortic stenosis. Circulation 1999; 100:361–368.
- Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurements. Lancet 1986; (I):307-310.
- Thomsen C. "Chess-board pattern" spatial modulation of magnetization. Assessment of myocardial function. Acta Radiologica 1992; 33:16–33.
- McVeigh ER. MRI of myocardial function: motion tracking techniques. Magn Reson Imaging 1996; 14:137–150.
- Maier SE, Fischer SE, McKinnon GC, Hessom Krayenbuehl HP, Boesiger P. Acquisition and evaluation of tagged magnetic resonance images of the human left ventricle. Comput Med Imaging Graph 1992; 16:73–80.