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Gradient-enhanced volume rendering: an image processing strategy to facilitate whole small bowel imaging with MRI

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Abstract MRI of the small bowel with positive contrast from orally administered contrast agent is a promising non-invasive imaging method. The aim of our study was to introduce small bowel MRI in a display format that clinicians are accustomed to and that maximizes the amount of information visualized on a single image. Twelve healthy volunteers, median age 32 years (range 18–49 years) participated in the study. A mixture of 20 ml Gd-DOTA (Dotarem), 0.8 g/kg body weight psyllium fibre (Metamucil) and 1.2 l water were sequentially administered over a period of 4 h. Imaging was performed on a 1.5 T unit (Philips Gyroscan, Intera). Fat-saturated, 3D, gradient echo imaging was performed while the patient was in apnea (30 s). Bowel motion was reduced with 40 mg intravenously administered scopolamine (Buscopan). A 3D, gradient-enhanced, volume rendering technique was applied to the 3D data sets. Standard projections [left anterior oblique (LAO), right anterior oblique (RAO), supine and prone] resembling conventional enteroclysis were successfully generated within fewer than 10 min processing time. Reconstructions were reproducible and provided an entire overview of the small bowel. In addition thin-slab volume rendering allowed an overlap-free display of individual structures. Positive contrast from orally administered contrast agent, combined with a gradient enhanced volume rendering method, allows the reconstruction of the small bowel in a pattern resembling conventional double-contrast enteroclysis. Segmental display without overlay is possible.

Keywords MR imaging · Small bowel · Reconstruction · Post-processing · Volume rendering

Introduction

MRI of the small bowel, with either a catheter-based small bowel distension method (enteroclysis) or peroral filling with various distenders such as gelifiers or hyperosmolar solubilizers, are increasingly being used for the investigation of small bowel conditions, such as inflammatory bowel disease, stenoses, polyps, diverticula and tumours [1–5]. As previously described, a very fast, 3D, MR examination technique [3] has been developed that covers the whole abdomen within 30 s, with high spatial resolution for 80 2D image slices. These single MR images, even though they have an excellent soft-tissue contrast, are obviously very different from the images acquired with the conventional X-ray small bowel enema, the reference method in imaging of the small bowel.

Small bowel enteroclysis is a biphasic examination. After image-guided placement of a naso-jejunal tube a diluted barium suspension is applied, followed be the administration of methylcellulose (0.5%). Intermittent conventional X-ray images are taken during the various filling phases of the small bowel, allowing an assessment of the mucosal surfaces due to the specific coating properties of the remaining positive contrast of barium

sulphate [6]. Thus, structural alterations of the bowel wall can be diagnosed [7] during the examination. In a limited fashion, small bowel enteroclysis is able to demonstrate mural and extraluminal abnormalities but only if they have a mass effect on the mucosal surface. Double-contrast of the small bowel should be semi-transparent, be of a milky appearance and give a display of the whole small bowel in one image. There is no possibility for post-examination reconstruction with this method, and the radiation dose is considerable [8], about 21 mSv compared to 11 mSv in abdominal multi-detector computer tomography (MDCT) [9].

In order for conventional X-ray imaging to be replaced, new techniques are needed, but in a display that clinicians are used to and that maximizes the amount of information visualized on a single image. It should look like the double-contrast pictures of a conventional small bowel enema, with barium and methylcellulose allowing a rapid 3D overview.

Such new techniques are found in MDCT of the small bowel, MRI and capsule endoscopy. MDCT of the small bowel with oral and i.v. administration of dedicated contrast medium, the so-called CT enterography [10], is capable of identifying and staging most of the common diseases of the small bowel such as Crohn's disease, ischaemia, obstruction, and neoplasm [11]. However, the use of ionizing radiation, especially in young women, is problematic. Capsule endoscopy, on the other hand, has high sensitivity in detecting small lesions of the mucosa but cannot diagnose changes of the bowel wall and the surrounding tissue [12]. Another problem with capsule endoscopy is the extended reading time for every patient [13]. The absence of ionizing radiation and reduced invasiveness for 3D MRI promises unlimited reconstruction and segmentation of single small bowel loops, with fewer overlays.

The following viewing methods are currently used in small bowel MRI: scrolling through the coronal source images of the 3D data set, multi-planar reconstructions (MPRs) of images, or maximum-intensity projections (MIPs) of an entire 3D volume. In the case of isotropic acquisition, the display of other imaging planes (sagittal or transverse) is possible. All this helps experienced radiologists to assess extra-luminal abnormalities. However, clinicians are not so skilled at looking at small bowel images in this way [14]. What is lacking is an image processing technique that emulates double contrast, with the feature to outline the isolated organ together with its interfaces such as the mucosa. Although MIPs of positively enhanced small bowel loops give a single-view display, they are not very useful because of superimposition of all enhancing structures. On the other hand, images generated with 3D surface rendering only show the outer surface of the bowel content.

With all these classical MR viewing modes, important information about the interface between the bowel wall and the intraluminal content may be lost. Additionally, owing to the anatomical features of the small bowel, segmental overlaps in reformatted views make the diagnosis of small bowel abnormalities a difficult task. Therefore, a modified, 3D, volume rendering technique utilizing the so-called local intensity gradient [15, 16] is evaluated as a display method of small bowel MR data.

Materials and methods

Twelve healthy volunteers (five women/seven men, mean age 32 years, range 18–49 years), mean body-mass index 22 (range 19–29) with no history of gastrointestinal disease or surgery, except appendicectomy, agreed to participate in this prospective clinical study. The Institutional ethics committee approved the study protocol, and written informed consent was obtained from each participant prior to enrollment. In order to optimize small bowel distension and lumen enhancement the participants ingested a mixture of 1,000 ml water spiked with 20 ml of 0.5 mol/l Gd-DOTA (meglumine gadoterate, Dotarem, Guerbet, France) and 0.8 g/kg body weight psyllium fibre (Metamucil regular, Procter & Gamble, USA) ,prior to MRI and after at least 4 h of fasting. This amount was divided into four equal doses and administered over 4 h. MRI was performed with a 1.5 T unit (Philips Gyroscan, NT Intera R8, The Netherlands) with a four-channel, sensitivity encoding (SENSE), phased-array body coil. Volunteers were placed prone and feet first into the scanner, and a single breath hold sequence (30 s) with the following parameters was taken: fat-saturated, 3D, gradient, turbo-field echo sequence with an isotropic resolution of 1.5 mm (TR/TE 4.0/1.1 ms, flip-angle 25°, 80 slices, matrix 256 pixels×256 pixels, field of view (FOV) 400 mm, zero filling). Bowel motion was reduced with a 40 mg scopolamine butyl bromide (Buscopan, Boehringer, Ingelheim, Germany) bolus given intravenously immediately prior to the MR examination. The total imaging time amounted to approximately 30 min, patient placement and sequence planning included.

Post-processing Post-processing was done on a Philips Easy Vision workstation (release 5.1) using the Volume View software package running on a Sun UltraSparc 60 Computer equipped with a 500 MHz alpha processor and 1GB RAM. The time required for processing the source data to obtain four basic views [left anterior oblique (LAO), right anterior oblique (RAO), supine and prone] of the whole small bowel was recorded.

The volume-rendering algorithm originally proposed by Levoy [15, 16] and already implemented on the workstation was used for the post-processing of the small bowel data. It consists of three subsequent user interaction-dependant steps that allowing the user to define the desired display:

1st- segmentation consisting of thresholding and region growing
2nd- gradient-enhanced volume rendering of the segmented data
3rd- global translucency adaptation

Although the volume rendering algorithm [15] generally does not require segmentation of the sample being studied, operator-controlled segmentation was used in this study. This allows one to carve away unwanted boundary tissue such as unsuppressed fatty tissue or overlaying colon.

After the 3D source data were loaded (Fig. 1), a signal intensity threshold was set by the operator. It was based on a signal intensity histogram of the 3D data set, which excluded external structures of low intensity (Fig. 2). To exclude external structures of high signal intensity, the "region-growing" algorithm was used. For this purpose "seeds" were placed by the operator inside the small bowel lumen, defining areas of interest to be included, while other "exclusion seeds" were placed in structures such as the colon, which were to be suppressed.

Subsequently, the gradient-enhanced volume rendering was performed as described by Levoy [15, 16] and further illustrated in Fig. 3. In combination with the initial steps described above the desired projection view (LAO, RAO, prone, supine) could be chosen.

The above histogram of signal intensities was also used for the definition of the opacity classification function. Intensity values below a lower limit were assigned to an opacity equal to zero (i.e. were fully "transparent"), while values above the threshold were assigned to opacity with a value of 1. The intensities in-between were spread on a linear function. The opacity of each pixel was additionally scaled with the local magnitude of the signal intensity gradient or slope along the ray axis, enhancing small bowel contours and suppressing internal iso-intense structures.

The final projection view consisted of the sum of all calculated opacities along the parallel projection rays through the 3D data set.

Finally, in step 3, the operator could adjust the image by setting a global translucency-scaling factor for optimal image display.

Results

All volunteers tolerated the preparation with Metamucil and orally administered Gd-DOTA well. In three cases there was a slight feeling of bloating. No vomiting or nausea occurred. Buscopan was tolerated well by all volunteers, except for the commonly seen side effect of a slight blurring of the vision, which was noticeable shortly after administration. Breath-holds of 30 s for imaging were possible in all cases.

The image data sets of all volunteers were of sufficient quality to initialize the post-processing. Insufficiently distended segments occurred in three volunteers, with a maximum length of 15 cm. These segments were the only ones that could not be post-processed. In two cases residual motion of the bowel caused a slight blurring of the rendered images. This blurring had no effect on the complete overview and reduced the final image quality only slightly.

Processing of the source data with the "Volume View software" from segmentation to final volume rendering was

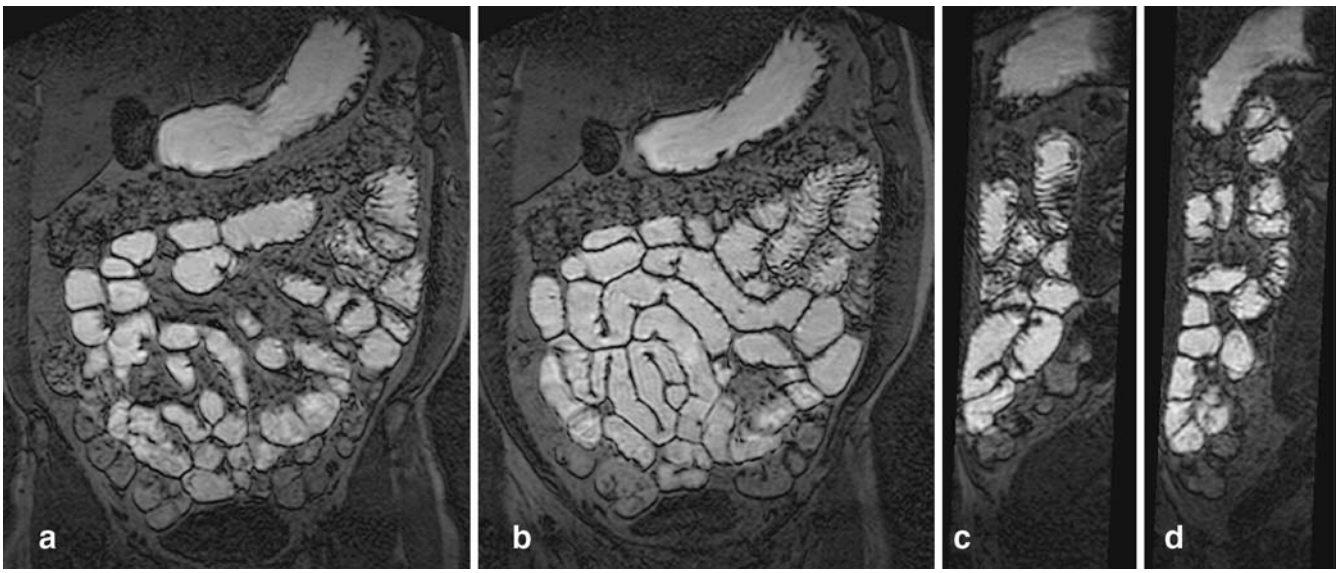

Fig. 1 **a**–**d** Multi-planar display of the small bowel after oral administration of four doses of psyllium fibre (Metamucil) and Gd-DOTA (Dotarem). Isometric, 3D, T1-weighted, gradient-recalled echo (GRE) sequence with the subject in the prone position. Coronal (**a**,**b**) and sagittal (**c**,**d**) reformats of the data set showing an overview of the small bowel and adjacent organs

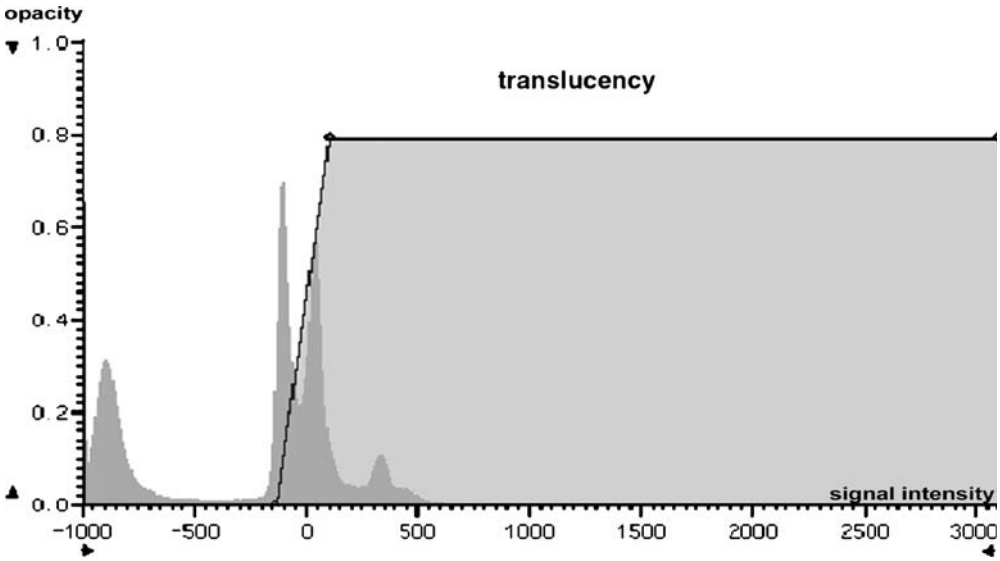

Fig. 2 Post-processing on a Philips Easy Vision workstation (release 5.1) with the Volume View software package, running on a Sun UltraSparc 60 computer with a Sun Solaris operating system. After loading the source data, the operator sets a signal intensity threshold based on a signal intensity histogram of the 3D data set. It allows the exclusion of external structures of low intensity. In a second step a grey-value histogram is applied linearly towards the maximum value, using the block type opacity function providing translucency

applicable in all cases. The four basic views (LAO, RAO, supine and prone) could be realized for all volunteers, and their complete workup took approximately 10 min per study (Fig. 4). The pre-rendering segmentation process alone was, in general, performed in fewer than 5 min. This initial process is the most crucial step and can affect the final reconstruction result. If the applied threshold was too low, too many source data were included, so that rendering was noticeably hampered by overlying tissue, which resulted in a fuzzy image. In contrast, if the applied threshold was too high, virtual holes in the bowel wall or interruptions in the bowel loop continuity were the result in the 3D rendered images.

Owing to the isotropic 3D nature of the source image data, any viewing angle could be reconstructed. It took approximately 1 min per projection. Thin-slab reconstructions were successfully made in order to depict single segments, especially of the terminal ileum, without disturbing overlapping structures, such as other small bowel loops or the ascending colon (Fig. 5). Thus, relevant structures such as the duodenum, terminal ileum, jejunum, as well as other selected small bowel parts, could all be well visualized and separated from overlapping structures each volunteer.

Discussion

MRI of the small bowel, with peroral ingestion of a combination of a distension agent and Gd-DOTA, is an emerging non-invasive technique for detection of small bowel abnormality [3, 17–19]. This non-invasive technique leads to excellent distension, resulting in good delineation of the small bowel wall and the surrounding tissue. It no longer needs the gastro-duodenal tube for distension, has the advantage of high soft-tissue contrast, total lack of ionizing radiation and true 3D imaging. It allows reconstruction to be made in every desirable imaging plane. The distension technique with orally administered psyllium fibres is already in clinical application [20–23] and has been validated. However, to ease the paradigm change from conventional enteroclysis to 3D MRI, the images should be presented in a standardized fashion, allowing a faster overview and improved visualization of boundary surfaces. With this study we would like to introduce the volume-rendering technique [15] in small bowel MR imaging, allowing its pathological findings to be demonstrate in an overview format that clinicians are used to. With this technique, the amount of information on a single image is maximized, instead of a series of 80 and more single slices having to be read. Improved visualization of the mucosal interface between the bowel wall and the luminal content should thus be possible. This technique, although not validated in the current study, might add valuable information to standard cross-sectional small bowel imaging, especially where a general overview is needed. For example, in the case of a subclinical stenosis, subtle calibre changes might not be seen on the standard images, whereas volume rendering gives the clinician a rapid tool of assessment. Similarly, for adhesions, the small extraluminal fixation is not depictable with cross-sectional imaging, while volume rendering displays the folding distortion of the bowel loops. In Crohn's disease, where skip lesions might be missed, this technique promises easy assessment of such surface alterations. Finally, diverticula, which can be difficult to detect on standard MR images without proper contrast from orally administered contrast agent, should be easily depictable with this volume-rendering technique. After oral administration of positive contrast agent, the i.v. use of contrast media for diagnosis in the small bowel wall is limited, since the lumen already has a positive signal. The enhancement of inflammatory,

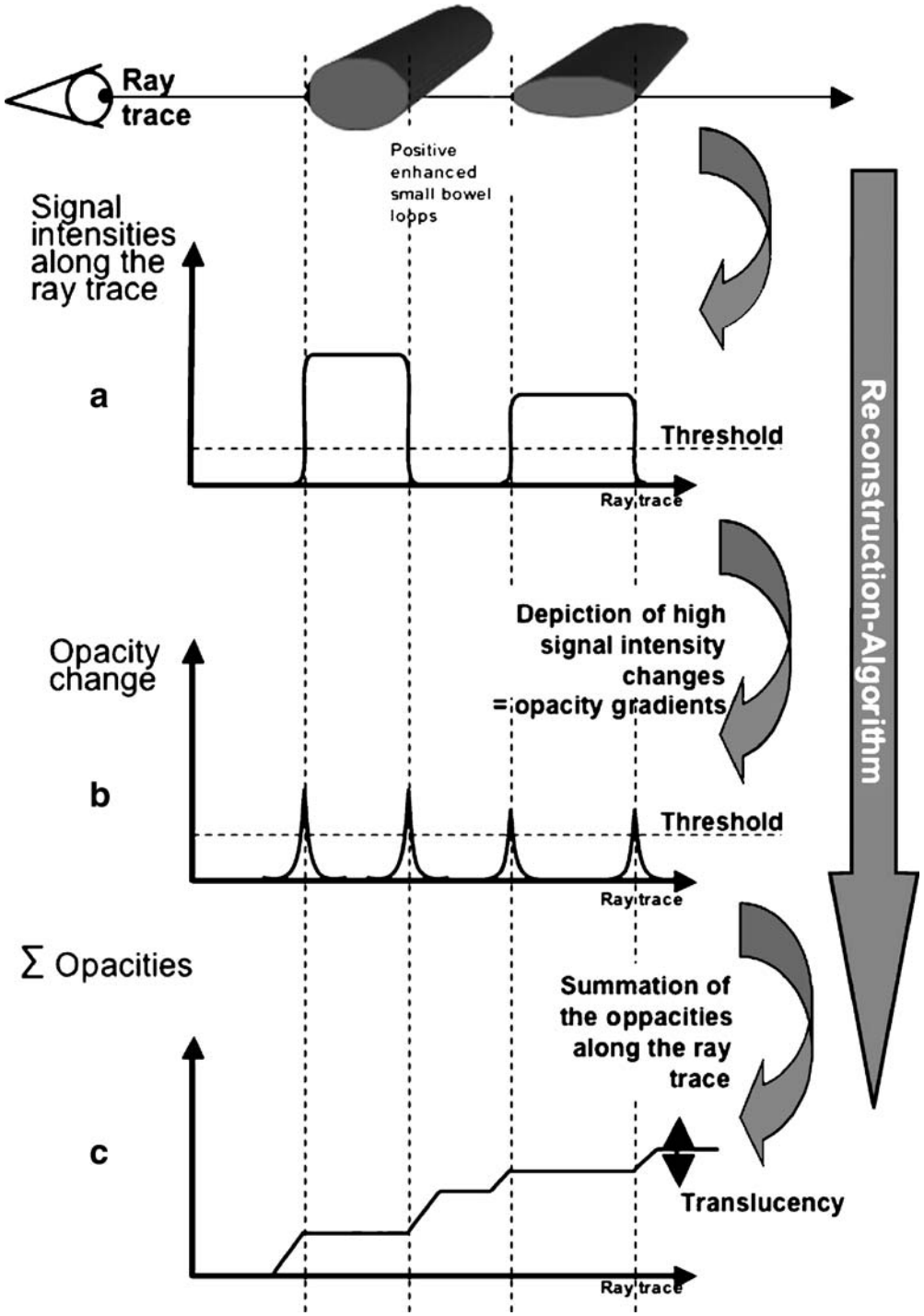

Fig. 3 This graph points out schematically the required steps for the ray trace algorithm to generate a semi-transparent reconstruction of small bowel loops filled with a positive intraluminal contrast agent. As an example, two tubes filled with contrast agent (Gd) are shown. A ray tracing line is placed through these tubes, demonstrating the virtual line of sight defined as the ray trace. From these tubes the signal intensities are displayed (**a**). To obtain only the surfaces, it is important for the operator to calculate the opacities of these tubes (**b**). Finally, in order to achieve a semi-transparent reconstruction, the change in the different opacities is summarized along the ray trace line (**c**)

infectious, ischaemic or tumoral changes within the intestinal wall may be missed, due to the lacking interface towards the lumen [24].

One of the inherent drawbacks of conventional small bowel enema techniques is the overlapping of bowel loops, which impedes diagnostic evaluation. Basically, the same applies to the volume-rendering method. However, despite the ability to rotate the viewing plane freely at will, it is not always possible to display adjacent or overlapping bowel segments as separate structures. Therefore, we chose to use a high-resolution, thin-section, gradient-enhanced, volume rendering method to create 3D volume images of the whole small bowel. This allowed the overlap-free visualization of single small bowel loops. In every volunteer in the study the jejunum, the ileum and, especially, the terminal ileum, could be visualized without overlapping bowel segments.

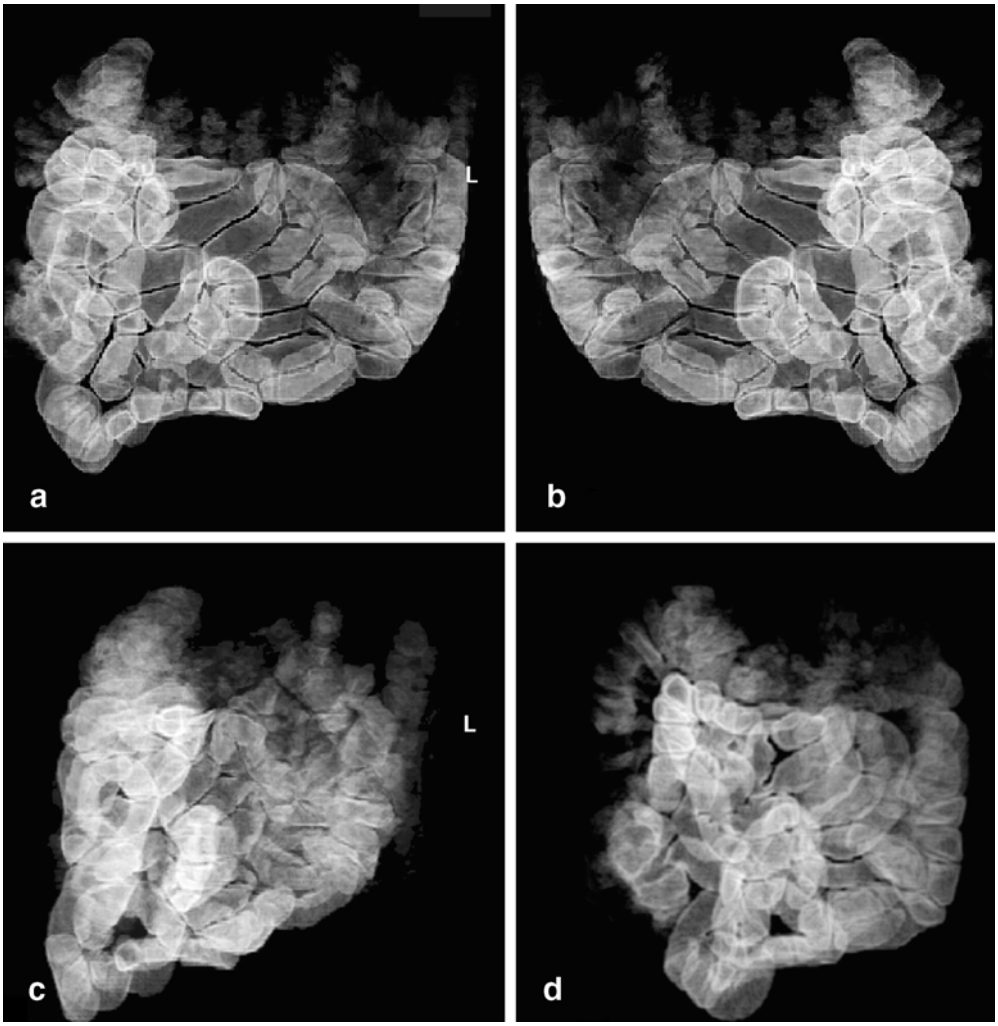

Fig. 4 **a**–**d** Standardized display of four standard projections: supine (**a**), prone (**b**), LAO (**c**) and RAO (**d**), for one volunteer. This figure demonstrates the ability of the image processing method to visualize the whole small bowel in a display similar to conventional double-contrast images, providing a very good overview

The quality of 3D visualization depends on multiple factors, probably with the source data being of highest importance. As spatial resolution is still improving in MRI, due to parallel imaging, new coils, multi-channel approaches, higher gradients and higher matrices, post-processing of the data with the goal to facilitate overview is gaining importance. It must be emphasized that the sequences are acquired with isotropic resolution. This permits lossless image reconstruction in all possible directions. Although the resolution is not as high as it is in MDCT, we present an easy algorithm to facilitate the visualization of the whole small bowel. Because of the length and shape of the small bowel, its assessment with MRI. The proposed post-processing technique permits the

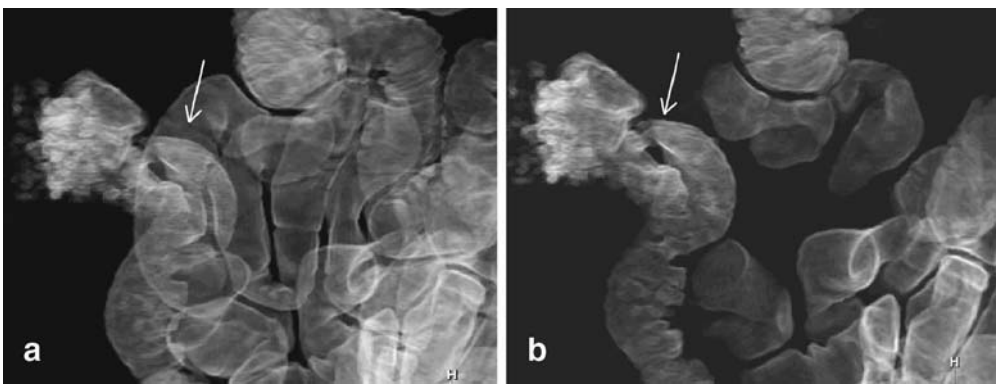

Fig. 5 **a**, **b** Thin-slab reconstructions are made in order to depict single segments (**b**), especially of the terminal ileum, without disturbing overlapping structures, such as other small bowel loops, or the ascending colon (**a**)

outlining of the whole desired volume or selected segments without disturbing surrounding enhancing structures—such as unsuppressed fatty tissue, stomach or colon.

The use of intensity gradient-based volume-rendering techniques of MR images acquired with positive intraluminal contrast permits visualization of the contour of the small bowel wall (Fig. 4). The reconstruction displays zones of high signal alteration, which, in our example, occur between the signal-intense lumen (filled with Gd) and the surrounding low-signal bowel wall. An important prerequisite is a high signal difference between the lumen and surrounding tissue, allowing optimal thresholding. Surrounding fatty tissue is suppressed by fat saturation. Another prerequisite is the homogeneous filling and distension of the small bowel, which is improved by the use of a gelifier. The images produced with this technique emulate those obtained by conventional double-contrast enteroclysis [6]. According to the study by Ha et al. [14], the level of acceptance by radiologists and clinicians, who are used to analysing double-contrast images, can be expected to be high. Additionally, thin-slab volume rendering allows a simple display of individual structures of the small bowel without disturbing overlaps, notably a clear advantage over the conventional X-ray method. However, the definition of thresholds has to be done with care, since incorrect classification can lead to the previously described false displays of the selected tissue [25–27].

One limitation of this reconstruction technique is the reduced spatial resolution, compared to that of conventional radiographs, but this might be improved in the future with increased spatial resolution acquisition techniques. At this moment in technical development, the rendered images are certainly not sufficient alone for use as detailed diagnostic displays of the small bowel or mucosal surfaces. Their goal is to provide a rapid overview, displaying as much information as possible on one single image. The initially acquired 80 coronal, 2D, cross-sectional slices give a sufficiently high enough image quality to allow the diagnosis of small bowel abnormalities.

Another limitation is the lack of dynamic information. While conventional fluoroscopy allows the depiction of motility and dynamic filling, the current MR protocol does not give this information. New techniques are available to monitor motility with MRI and have been published [28]. Such a motility sequence could be done prior to the above-mentioned imaging, since the preparation is the same.

High-quality acquisition of the source data, with no motion artefacts, a high and homogeneous signal intensity of the entire, well-distended small bowel lumen, relative to a low background signal, together with a perfect fat-suppression technique, is an important quality-related prerequisite for an optimal gradient volume-rendered reconstruction of the small bowel. If one of the above factors fails, the resulting quality of the rendered images can be degraded.

Clinical studies that compare conventional X-ray enteroclysis with rendered MRI should be performed for validation.

Conclusion

In summary, this feasibility study using a standardized small bowel distension method combined with peroral administration of positive contrast agent demonstrates that intensity gradient-based volume-rendering reproducibly creates a display of MRI data of the small bowel complementary to the primary axial and coronal source images. This technique imitates conventional double-contrast enteroclysis and generates a semi-transparent overview of the whole small bowel on one single image. The use of thin-slab reconstruction additionally permits the visualization of selected bowel segments without disturbing overlapping segments, which is not possible in conventional X-ray enteroclysis.

This technique may have a clinical impact for all those small-bowel conditions where a general overview of the entire organ is needed, especially of the mucosal interface, for example, for the depiction of ulcers or skip lesions in Crohn's disease, mucosal distortions in tumours, adhesions or stenoses and bulging of the lumen in diverticula.

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