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Improved CT-detection of acute bowel ischemia using frequency selective non-linear image blending

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Abstract

Background: Computed tomography (CT) as a fast and reliable diagnostic technique is the imaging modality of choice for acute bowel ischemia. However, diagnostic is often difficult mainly due to low attenuation differences between ischemic and perfused segments.

Purpose: To compare the diagnostic efficacy of a new post-processing tool based on frequency selective non-linear blending with that of conventional linear contrast-enhanced CT (CECT) image blending for the detection of bowel ischemia.

Material and Methods: Twenty-seven consecutive patients (19 women; mean age = 73.7 years, age range = 50–94 years) with acute bowel ischemia were scanned using multidetector CT (120 kV; 100–200 mAs). Pre-contrast and portal venous scans (65–70 s delay) were acquired. All patients underwent surgery for acute bowel ischemia and intraoperative diagnosis as well as histologic evaluation of explanted bowel segments was considered "gold standard." First, two radiologists read the conventional CECT images in which linear blending was adapted for optimal contrast, and second (three weeks later) the frequency selective non-linear blending (F-NLB) image. Attenuation values were compared, both in the involved and non-involved bowel segments creating ratios between unenhanced and CECT.

Results: The mean attenuation difference between ischemic and non-ischemic wall in the portal venous scan was 69.54 HU (reader 2 = 69.01 HU) higher for F-NLB compared with conventional CECT. Also, the attenuation ratio between contrast-enhanced and pre-contrast CT data for the non-ischemic walls showed significantly higher values for the F-NLB image (CECT: reader 1 = 2.11 (reader 2 = 3.36), F-NLB: reader 1 = 4.46 (reader 2 = 4.98)]. Sensitivity in detecting ischemic areas increased significantly for both readers using F-NLB (CECT: reader 1/2 = 53%/65% versus F-NLB: reader 1/2 = 62%/75%).

Conclusion: Frequency selective non-linear blending improves detection of bowel ischemia compared with conventional CECT by increasing attenuation differences between ischemic and perfused segments.

Keywords

Computed tomography (CT), bowel ischemia, contrast enhancement, non-linear blending

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Introduction

Acute bowel ischemia is a major gastrointestinal (GI) emergency requesting prompt, accurate diagnosis followed by surgical intervention. Mortality related to bowel ischemia is high, in particular in cases with delayed diagnosis (1). Due to the fact that major clinical symptoms are non-specific, imaging often plays a

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decisive role in management of these patients. As time correlates with patient's survival, abdominal CT as a fast and reliable diagnostic technique is the imaging modality of choice. Generally, such CT examinations are performed using negative (mostly water) or no oral contrast coupled with non-enhanced and contrast-enhanced phases, the latter usually acquired in the portal-venous phase (2). Among the many proposed imaging features of bowel ischemia, segmental hypo- or non-enhancement of the bowel wall is the most reliable sign for detecting acute ischemic and/or non-viable GI-segments (3,4). This finding may, however, be very difficult to depict on CECT due to low attenuation differences between ischemic and perfused segments. The reasons for the great challenge with this diagnosis are usually of technical nature and manifold: low energy levels used; low volume of contrast agent; low concentration of contrast medium; inadequate delay time; intramural hemorrhagic changes accompanying ischemia; and great amount of luminal distension with thinned bowel wall.

Many attempts have been made recently for achieving increased conspicuity in detecting bowel wall attenuation. Some of them used dual-energy CT (DECT), generating virtual monochromatic images that significantly increase bowel wall attenuation and the contrast to ischemic bowel segments (2,5). However, monochromatic virtually generated DECT can be blended only linearly, influencing the contrast of all image pixels. Besides using narrower soft-tissue window settings by linear image blending, the innovative frequency selective non-linear blending algorithm (F-NLB) post-processing technique propagates a non-linear scaling function on a predefined range of Hounsfield units (HU), enhancing contrast differences in low-contrast tissues and therefore it is expected to better disclose hypoattenuated ischemic areas by contrast to the normally perfused bowel segments (6,7).

In this study, we set out to compare the diagnostic efficacy of a new post-processing tool based on frequency selective non-linear blending of portal-venous CECT scans with that of conventional linear blending in patients with acute bowel ischemia using intraoperative findings as well as histologic evaluation of resected bowel segments as a standard of reference.

Material and Methods

Study population

The ethics committee of our institution approved this retrospective study with a waiver for the need for informed consent.

We first started a database search in our Pathology Department looking for cases of bowel ischemia diagnosed histologically in recent years (between February 2010 and June 2016). All patients who underwent preoperative (within hours) CT imaging, including unenhanced and portal-venous phase enhanced CT images, were retrospectively analyzed. All other patients were excluded.

Reference standard

Intraoperative findings were additionally confirmed by histologic workup. The reference standard for diagnosing ischemia was the presence of any of the following findings in the surgical report (e.g. discoloration, loss of bowel wall vitality, and compromised loop vitality) confirmed by the pathologic report: transmural ischemia or necrosis. For this purpose, areas of obvious necrosis and areas with preserved compartments neighboring ischemic zones were harvested for histology (HE staining). Additional sections of afferent vessels and of intestinal and vascular resection margins were taken.

Imaging

CT images were obtained with a 64/128 or 256-slice detector machine (Somatom Sensation 64; Somatom Definition Flash; Somatom AS+ Somatom Force; Siemens Healthcare, Forchheim, Germany), using 120 kV; 1–1.375 pitch, thin collimation, 3 mm reconstructed slice thickness. Dose-modulation software was used to determine the milliampere-second value on the basis of body weight (CareDose, 150–250 mAs). Images were first acquired non-enhanced and subsequently using i.v. contrast material. Iodinated contrast agent (Ultravist 370 (Bayer Vital, Leverkusen, Germany) was injected intravenously at a flow rate of 2 mL/s followed by a saline flush of 30 mL NaCl at 3 mL/s. Start delay was 70 s. Contrast medium was administered by using a dual-head pump injector (Stellant, Medtron, Saarbruecken, Germany).

Frequency selective non-linear blending (F-NLB) image post-processing

F-NLB post-processing was done by using commercial software (Syngo Best Contrast CT Body, Siemens Healthcare).

The F-NLB post-processing algorithm has been described in previous studies (8–10). F-NLB images were computed using a new algorithm enabling non-linear blending in image space. The algorithm first divides image information into low and high frequencies, whereas high frequencies represent the main part of image noise and low frequencies include contrast information. Second, a non-linear scaling function is propagated to low frequencies to highlight pixel intensities in a defined subset of the entire dynamic range (delta).

Intensity of highlighting can be influenced by adapting the slope and delta of the subset. The best settings of tissue contrast differentiation, using this new algorithm, was set at an averaged center of 40 HU and an averaged delta of 5 HU at a slope of 20.

Image analysis

One senior gastrointestinal radiologists (25 years of experience) and one junior radiologist (three years of experience) independently reviewed each CT image. Multiplanar reconstruction was always available. The radiologists knew that patients had acute bowel ischemia but were blinded to all other patient data, in particular to the location and extent of ischemic changes.

First, each radiologist read the contrast-enhanced images in a predetermined random order that was separately determined for each radiologist looking for decreased or even absent bowel wall enhancement by comparison with neighboring healthy bowel loops. The observers identified the involved GI segments (jejunal, ileal, right hemi-colonic, transverse colon, or left hemicolonic). In addition, both readers placed regions of interest (ROIs) in the bowel wall for measurements of bowel wall attenuation (in HU) in the pre-contrast and in the portal-venous scans in both hypo- and normally attenuated bowel. The ROIs were kept small in order to avoid partial volume averaging, but were always identical for the two image series. The bowel wall enhancement was calculated by subtraction. Additionally, ratios were calculated for each patient by dividing HU values from portal-venous phase through HU values from pre-contrast phase in both ischemic and non-ischemic bowel segments.

Subsequently both readers did the same using F-LNB.

Statistical analysis

Statistical analyses were performed using SPSS statistical software (IBM SPSS Statistics 24, Armonk, NY, USA).

Assessment of diagnostic accuracy in terms of accuracy, sensitivity, and specificity was performed using pathology as reference standard. Inter-observer agreement was assessed by Cohen's kappa (k). For all tests, P values < 0.05 were considered statistically significant.

Results

Patient cohort

The database search in our Pathology Department for bowel wall and ischemia provided 213 patients. Of these, 27 patients (eight men, 19 women) had acute bowel ischemia that underwent surgery with subsequent histologic analysis and all had a preoperative CT scan including unenhanced and portal-venous phase enhanced CT images. Median age was 73.7 years (age range = 50–94 years).

The causes of bowel ischemia were: acute thromboembolism of superior mesenteric artery (SMA) (n = 16); inferior mesenteric artery (IMA) (n = 1); portal vein (n = 1); non-occlusive acute severe mesenteric ischemia (n = 1); and obstructive ileus due to postoperative adhesions (n = 8).

CECT and F-NLB diagnosis

In the ischemic bowel wall, the mean wall enhancement from the pre-contrast to the post-contrast phase measured in the CECT was 6.12 HU (reader 1) and 6.71 HU (reader 2) with a ratio of 1.27 for reader 1 (reader 2 = 1.57) (Table 1). For F-NLB, the measured mean enhancement values in the ischemic wall was 4.71 HU (reader 1) and 6 HU (reader 2) with a ratio of 1.23 for reader 1 (reader 2 = 1.34).

For the non-ischemic bowel wall, we registered a mean enhancement in the CECT of 33.67 HU (reader 1) and 41.7 HU (reader 2) with a ratio of 2.11 (3.36 for reader 2), whereas for F-NLB, the measured values were 101.8 HU (reader 1) and 148.8 HU (reader 2), with a ratio of 4.46 for reader 1 (4.98 for

Table 1. HU values and enhancement ratios for CECT and F-NLB for both readers.

	CECT		F-NLB	
	Ischemic	Non-ischemic	Ischemic	Non-ischemic
Reader 1	27 HU* –> 33.12 HU†, Δ 6.12 HU (r = 1.27)	34.97 HU* –> 68.64 HU†, Δ 33.67 HU (r = 2.11)	25.26 HU* –> 29.97 HU†, Δ 4.71 HU (r = 1.23)	33.15 HU* –> 135 HU†, Δ 101.8 HU (r = 4.46)
Reader 2	17.36 HU* –> 24.07 HU†, Δ 6.71 HU (r = 1.57)	25.23 HU* –> 66.93 HU†, Δ 41.7 HU (r = 3.36)	18 HU* –> 24 HU†, Δ 6 HU (r = 1.34)	38.8 HU* –> 148.8 HU†, Δ 110 HU (r = 4.98)

*Pre-contrast scan.
†Portal-venous scan.
Δ, attenuation difference between portal-venous and pre-contrast scan; r, ratio between portal-venous and pre-contrast scan; HU, Hounsfield units.

reader 2). The difference in the enhancement was significant ($P < 0.05$).

The mean difference in the bowel wall attenuation between ischemic and non-ischemic bowel wall in the portal venous scans was 27.55 HU (reader 2 = 34.99 HU) for CECT and 97.09 HU (reader 2 = 104 HU) for F-NLB. This means a mean lower attenuation difference of 69.54 HU (reader 2 = 69.01 HU) for CECT compared with F-NLB, which was statistically significant ($P < 0.05$).

With F-NLB, readers 1 and 2 detected significantly more ischemic segments than with CECT (reader 1 = 55 versus 45, reader 2 = 43 versus 39). Moreover, a patchy bowel involvement was found in three (11%) patients solely by F-NLB reading. One patient with bowel ischemia was classified normal on CECT by reader 2, but not by reader 1.

The sensitivity/specificity for detection of ischemic segments was 53.3%/87.2% for reader 1 (65%/81% for reader 2) with CECT. For F-NLB, we calculated a sensitivity/specificity of 61.9%/87.8% for reader 1 (74.6%/82.8% for reader 2). There was a significant difference between the sensitivity for both readers ($P < 0.05$). There was no significant difference for the specificity.

The accuracy increased for both readers with F-NLB (reader 1 = 74.6% –> 77.7%, reader 2 = 74.2% –> 79.6%). However, this increase was not significant ($P > 0.05$). Both reading methods (CECT and F-NLB) showed a moderate inter-observer agreement (k = 0.5 for CECT, k = 0.48 for F-NLB).

Figs. 1 and 2 are two visual examples for the better delineation of ischemic areas when reading the F-NLB images.

Discussion

Results of our study demonstrate that bowel wall attenuation in the post-contrast phase can be significantly enhanced by using F-NLB compared with conventional linear blending, thus allowing for more confident diagnosis of bowel ischemia and better delineation of involved bowel segments. This knowledge could have clinical implications for the improvement of CT diagnosis of bowel ischemia in the preoperative setting.

F-NLB is a new post-processing technique which imitates a narrow window of conventional linear blending, affecting only a predefined range of HU values, without increasing the image noise. The spreading is performed

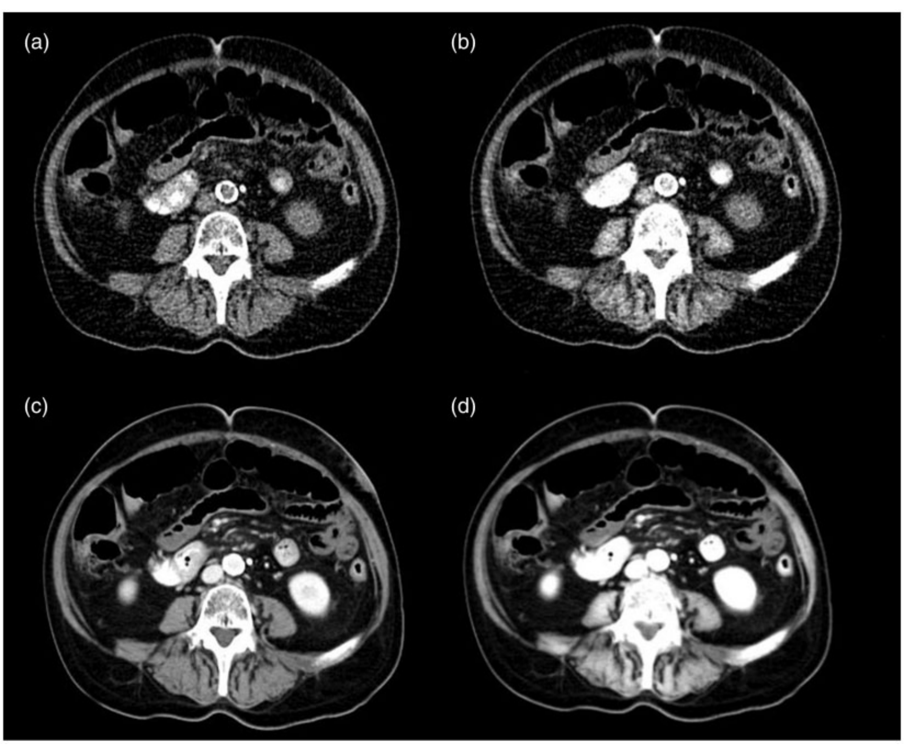

Fig. 1. A 76-year-old female patient with acute thromboembolism of the superior mesenteric artery (SMA) and bowel ischemia involving the jejunum, ileum, and right hemi-colon. There is no/only subtle contrast enhancement in the infarcted bowel wall (b) compared to the native scan (a). For the non-ischemic bowel wall in the descending colon enhancement is more pronounced in the F-NLB imaging (d) compared with CECT (c). The ratios for the non-ischemic wall were 2.06 for CECT and 5.10 for F-NLB.

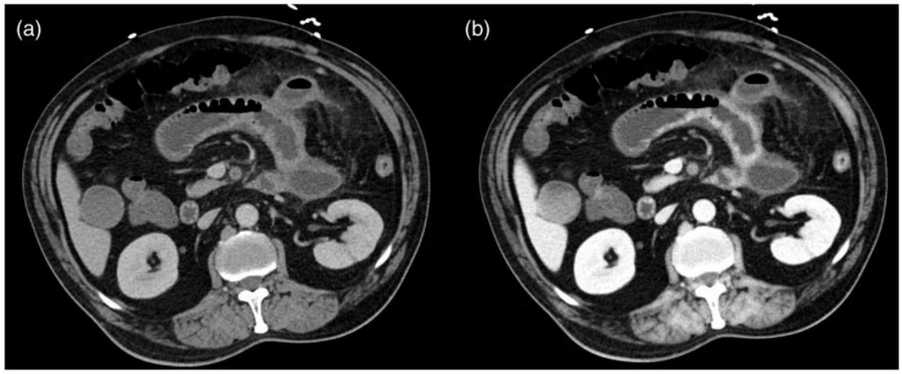

Fig. 2. A 51-year-old male patient with atrial fibrillation. CECT performed in the portal-venous phase poorly delineates ischemia (a) using linear windowing. On the contrary, with F-NLB both enhancing and non-enhancing bowel segments are easy to differentiate (b). The ratios for the non-ischemic wall were 3.06 for CECT and 7.05 for F-NLB imaging. With F-NLB there were four involved segments, with CECT there were three involved segments.

by the use of a non-linear function, whereas the slope of this function describes the strength of resulting contrast enhancement. The resulting images shows increased contrast in the preselected range of HU as set in this study focusing on improved assessment of bowel wall enhancement. The resulting images imitate a narrow window of conventional linear blending, but only affecting a predefined range of HU values. Increased image contrast in the preselected range of HU results in an improved tissue contrast and anatomical orientation, compared with standard linear blending (10).

Different attempts have been made for improving confidence in the radiologic diagnosis of acute bowel ischemia. Direct and indirect signs of mesenteric ischemia such as bowel wall thickening ± lumen dilatation/paralysis, high attenuation of the bowel wall on unenhanced CT, mesenteric edema, reduced enhancement in the SMA, IMA or corresponding veins, target sign, small bowel feces, intestinal pneumatosis, peritoneal free fluid, gas in the portal vein, and others have been tested for their sensitivity and specificity (11). Among them, the finding with the highest sensitivity and specificity for intestinal ischemia is the hypo- or non-enhancement of the bowel wall (4,12). Therefore, improved detection of the hypo-enhanced bowel wall in the clinical setting of acute bowel ischemia has major clinical relevance and should prevent missing a threatening bowel necrosis as the window for surgical interventions is knowingly short and delayed diagnosis is associated with high mortality (13).

Visual assessment of decreased bowel enhancement alone is often sufficient. Nevertheless, its diagnostic value has been criticized due to its subjective and poorly reproducible character (14). Shedy et al. reported a high specificity (94%) but very low sensitivity (14.8%) of CT for the prospective evaluation of acute bowel ischemia (12). In order to circumvent this limitation, quantification of bowel wall attenuation has been advocated by many previous reports (5,11,15). Anecdotic reports focused on automated CT detection of ischemia using computerized extraction of features of the regions of interest in the CT images with subsequent classification of attenuation patterns (16). Based on extraction features, machine-learning algorithms are being trained with these data to carry out the diagnostic identification (17).

Improved image contrast has been increasingly reported in the last time using virtual monochromatic low kV images obtained with help of the DECT technique (2,5). Virtual low kV monochromatic images generate greater attenuation difference between perfused and non-perfused tissue at lower energy levels, resulting in improved conspicuity of hypo-enhancing tissue. This beneficial effect results from the increased attenuation of iodine which is dependent on energy and enhances at lower kV levels (approaching the K-edge of iodine) because of the predominance of the photoelectric effect (18,19). However, DECT scanners are not available everywhere and are generally more expensive.

Several attempts of non-linear blending in single energy CT have been undertaken in recent decades. Lehr et al. visualized the whole image information with one blending setting by a histogram-based approach (20). However, the detectability of low-contrast liver lesions was reduced at that time due to the limited grayscale of CT images. John et al. proposed a method to display chest CT in lung and mediastinal window simultaneously and could thereby show an improvement of operational efficiency (21). Nevertheless, due to insufficient efficacies of all the previous approaches of non-linear blending of CT images none of these methods have ever found their way to clinical routine.

In our study, the mean attenuation differences between normally perfused and ischemic bowel segments on CT images measured using frequency selective non-linear blending were significantly higher in comparison with those measured on conventional CECT images ($P < 0.05$). This was expectedly more accentuated in the non-ischemic bowel segments leading to an increased contrast to the ischemic bowel wall and thus, to a more accurate detection of ischemia. This was truth for both readers, but the inter-observer agreement proved only moderate, which suggests that training in using this post-processing tool is necessary in order to sensitize the radiologist in contemplating these new generated image data. Notably, one case of bowel ischemia was totally overseen by the less experienced reader on CECT but not on F-LNB. F-LNB additionally disclosed a patchy involvement pattern of bowel wall ischemia in 11% of our cases that was not visible on CECT and that could be confirmed later by histology.

Limitations of this study included the relative small number of patients and the retrospective character of the study.

In conclusion, F-NLB improved the conspicuity of the ischemic bowel compared with conventional CECT by increasing attenuation differences between ischemic and perfused segments.

Declaration of conflicting interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: HD is employed by a commercial company (Siemens AG Healthcare Sector). Since the manuscript is based on the application of a new software, the co-author gave technical support, but he and his organization did not play a role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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