Received: 28 April 2019 | Revised: 25 September 2019 | Accepted: 25 September 2019

DOI: 10.1111/nmo.13747

ORIGINAL ARTICLE

Neurogastroenterology & Motility NGM WILEY

Assessment of fasted and fed gastrointestinal contraction frequencies in healthy subjects using continuously tagged MRI

Catharina S. de Jonge[1] | André M. J. Sprengers[2] | Kyra L. van Rijn[1] | Aart J. Nederveen[1] | Jaap Stoker[3]

[1]Department of Radiology and Nuclear Medicine, Amsterdam UMC, Location Academic Medical Center, Amsterdam Gastroenterology & Metabolism, University of Amsterdam, Amsterdam, The Netherlands

[2]Department of Biomedical Engineering & Physics, Amsterdam UMC, Location Academic Medical Center, Amsterdam Gastroenterology & Metabolism, University of Amsterdam, Amsterdam, The Netherlands

[3]Department of Radiology and Nuclear Medicine, Amsterdam UMC, Location Academic Medical Center, Amsterdam Gastroenterology & Metabolism, Cancer Center Amsterdam, University of Amsterdam, Amsterdam, The Netherlands

Correspondence
Dr. Catharina S. de Jonge, Department of Radiology and Nuclear Medicine (G1-227), Amsterdam UMC, Location Academic Medical Center, University of Amsterdam, Meibergdreef 9, Amsterdam NL-1105 AZ, The Netherlands.
Email: c.s.dejonge@amsterdamumc.nl

Funding information
This study was in part supported by a grant from the Center for Translational Molecular Medicine (CTMM). CTMM had no influence on the study design, data acquisition, data analysis, and reporting.

Abstract

Background: Continuously tagged MRI during free breathing can assess bowel motility at frequencies as low as the slow wave, motility pattern range. This study aimed to evaluate noninvasive gastrointestinal-tagged MRI for small bowel motility assessment and to observe the physiological response to a 300-kcal meal challenge in healthy, overnight-fasted volunteers.

Methods: After overnight fasting, 16 healthy subjects (7 women, mean age 25.5, range 19-37 years) underwent a free breathing, tagged MRI scan to capture small bowel motility. Each subject underwent a (a) baseline motility scan, (b) food challenge, (c) postchallenge scan, and (d) second postchallenge scan (after 20 minutes). Motility was quantified using a frequency analysis technique for measuring the spectral power of the strain, referred to as motility score. Motility score was assessed in 20 frequency intervals between 1 and 20 contractions per minute (cpm), and the data were analyzed with linear mixed-effect models.

Key Result: The stimulation protocol demonstrated an immediate, food-induced, motility response in the low-frequency range (2-10 cpm), which is consistent with the stomach and small bowel frequency range (3-12 cpm).

Conclusions and Inferences: This study shows that this MRI tagging technique is able to quantify the fasted-to-fed response to a 300-kcal meal challenge within the specific small bowel motility frequency range in healthy subjects. The food provocation MRI protocol provides a tool to explore the gut's response to a stimulus in specific motility frequency ranges in patients with gastrointestinal dysmotility and functional disorders.

KEYWORDS

dynamic MRI, food challenge, motility, small bowel, SPAMM-tagged MRI

Abbreviations: bFFE, balanced fast field echo; cpm, contractions per minute; MRI, magnetic resonance imaging; SPAMM, spatial modulation of magnetization.

1 | INTRODUCTION

Small bowel dysmotility is present in a number of gastrointestinal diseases and syndromes.[1] The reference standard for small bowel motility assessment is antroduodenal manometry. This is an invasive technique, and it is only available in specialized centers.[2,3] Other techniques, such as radioopaque markers, ingestible wireless capsules, breath tests, scintigraphy and ultrasonography, have numerous limitations, challenging motility assessment in a clinical setting.[2,3] Since detection and quantification of motility can aid in diagnosis and patient management, the use of magnetic resonance imaging (MRI) is increasingly explored for this purpose as developments in MRI techniques have made the technology more powerful whilst retaining its noninvasive and patient-friendly character.[4-6]

Recently, a tagged MRI sequence was presented for motility assessment during free breathing.[7,8] This motion encoding technique, also referred to as SPAMM (spatial modulation of magnetization),[9] can be used to quantify bowel motion patterns in the frequency domain. The continuously added tag pattern to the abdominal scan facilitates motion tracking during free breathing.[10] The movements within the abdomen comprise a broad spectrum of frequencies originating from respiration (~16-25 per minute),[11] cardiac activity (~60-100 per minute),[12] and bowel motion (~3-12 per minute).[13,14] By applying automated imaging analysis methods, these can be distinguished from one another and thereby facilitate intestinal motility assessment.

Gastrointestinal motility is highly complex, it comprises fasted and fed (postprandial) motility patterns occurring over hours.[14] Two electrical patterns are fundamental for the occurrence of contractions along the gastrointestinal tract, known as slow waves and spikes. The frequency of motility at a specific site of the intestine is directly related to the slow wave frequency in that region. A technique that is able to measure motility-induced displacements at specific frequencies is therefore able to point at specific regions of the small bowel.

Tagged MRI is noninvasive, and it allows motility assessment during free breathing and prolonged monitoring (minutes versus seconds) of motility-induced displacements, facilitating advanced motility assessment in the range of the slow wave motility pattern at frequencies as low as 1 contraction per minute (cpm).[7,8] However, practical limitations of MRI prohibit data acquisition duration in the range of hours. Therefore, a stimulation challenge is used to trigger a gastrointestinal response in a short time frame. This allows assessment of the response by comparing pre- and poststimulation, this response may be altered in disease.[15,16] The ability to quantify the spectrum of frequencies in the intestine with MRI and capture the presence or absence of specific frequencies after a stimulation challenge could distinguish healthy from diseased bowel motility.

The aim of this study was to investigate whether a MRI tagging technique could be used to observe the fasted-to-fed response to a 300-kcal meal challenge within the specific small bowel motility frequency range in healthy subjects.

Key Points

- Gastrointestinal motility measurements are complex and current clinical methods are invasive. In this study, we evaluate the noninvasive gastrointestinal tagged MRI scan and frequency analysis method for motility assessment with a food-stimulation protocol in healthy, overnight-fasted, volunteers.
- The stimulation protocol demonstrated an immediate, food-induced, motility response that manifested in the gastric and small intestinal frequency range.
- Tagged MRI has the potential to provide new insights into the underlying processes of gastrointestinal motility of which much has not yet been fully understood.

2 | MATERIALS AND METHODS

2.1 | Ethical permission

Data were collected at Amsterdam UMC, location Academic Medical Center (AMC), University of Amsterdam, The Netherlands. The study protocol was approved by the Medical Ethics Committee of the AMC (NL54884.018.15), and all subjects gave full written informed consent.

2.2 | Volunteers

Healthy volunteers were recruited prospectively as part of a larger MRI motility study that ran between 2016 and 2017. The study was designed to gain insight in healthy bowel motility quantified with MRI.[15,17] For inclusion in this study, we selected all participants that did not receive bowel preparation, resulting in the enrollment of sixteen healthy subjects. Inclusion criteria included healthy, human volunteers who were willing to undergo minimal bowel preparation and MRI. Exclusion criteria were contraindications to undergo MR imaging, age younger than 18 years or older than 45 years, history of abdominal surgery, gastrointestinal diseases, or current gastrointestinal symptoms.

2.3 | Study design

All volunteers underwent dynamic MRI in the morning to capture small bowel motility after an overnight fast of approximately 10 hours. The following protocol was applied for all subjects: (a) a baseline motility scan followed by (b) a food challenge, (c) a post challenge scan immediately after the food challenge (post 1), and (d) a second post challenge scan after approximately 20 minutes (post 2).

2.4 | MRI protocol

With the subjects placed in supine position, scans were acquired with a 3T Philips Ingenia MRI scanner (Philips, Best, The Netherlands) using a combination of a posterior coil located in the table and an anterior torso-coil covering the entire abdominal region. After initial survey sequences, a continuously tagged coronal 3D balanced fast field echo (bFFE) motility sequence of the bowel was acquired, covering a fraction of the total abdominal volume. The positioning of the scan was aimed at capturing as much small bowel as possible.

The spatiotemporal resolution of this sequence was optimized to capture the complex motion occurring in the abdominal region during free breathing, that is, temporal sampling sufficient to reach a spectral resolution capable of resolving the three sources of motion in the abdomen: respiratory motion (~16-25 per minute), cardiac motion (~60-100 per minute), and gastrointestinal motility (~3 to 12 per minute). The motility scan was acquired during 3.1 minutes of free breathing. The scan parameters were as follows: TE/TR: 1.25/2.5 ms, flip angle: 10°, FOV: 400x400x15 mm (FHxLRxAP), and spatial resolution: 2.5 × 2.5 × 2.5 mm (six slices), resulting in a dynamic scan time of 0.374 seconds. The tagging prepulse was set at a tag spacing of 9 mm and a delay of 50 ms, resulting in a temporal resolution of 2.7 frames per second.

2.5 | Test meal

For the caloric challenge, a standardized test meal was used, consisting of 200 mL of Nutridrink (Juice style, apple flavour, NV Nutricia, Zoetermeer, The Netherlands), containing 300 kcal per bottle. The nutrient content of the meal/100 mL was as follows: energy 150 kcal, protein 3.9 g, carbohydrate 33.5 g, and fat 0 g. This meal was chosen for its well-tolerated and calorie-dense content, expected to provide a stimulus to the digestive system, thereby inducing the postprandial phase and as a result increasing motility.

2.6 | Motility analysis

In SPAMM, a short prepulse periodically saturates the magnetization prior to image acquisition, resulting in a line-shaped or tag pattern in the image (Figure 1A). As this line pattern is directly imprinted in the tissue, all deformation in the tissue will directly result in deformation of the line pattern. These lines can deform during the period between the prepulse and readout sequence as a consequence from tissue deformation. As such, the tissue motion can be derived and quantified from the deformed line pattern. To prevent artifact intrusion in the analysis, the outer slices (slices 1 and 6) of the 3D scan are excluded, because these slices are most susceptible to artifacts in a 3D acquisition. The line pattern in the scans is tracked using a scale space–based tracking algorithm.[10] From the deformed lines, strain maps are calculated per slice.[18] Fourier analysis is done on these strain maps per voxel in temporal direction, providing a strain spectrum with a range of 0-1.34 Hz with a spectral resolution of 0.0053 Hz, 250 bins in total. Spectra are then resampled to a resolution of 0.0178 Hz or approximately 1 cpm. The spectral power (ie, the magnitude of the strain variation as a function of frequency) is normalized to 1 for each volunteer. The primary outcome measure "motility score" is defined as the spectral power per bin of 1 contraction per minute and averaged over the complete field of view. The spectral power directly relates to the magnitude of the local strain variation induced by the pressure wave in the small bowel. This analysis is completely automated, and no delineation of regions of interest or any form of manual scoring or landmark indication is necessary.

2.7 | Statistical analysis

Number of subjects needed for this study was based on estimation since no previous data was available on these tagging measurements and we did not know what to expect from the difference in motility score between pre- and postfood challenge. The subject characteristics were summarized as mean, standard deviation, minimum, maximum, and quartiles for quantitative variables and as frequencies and percentages for ordinal variables.

Change between fasted and postprandial motility was analyzed with linear mixed-effect regression models, with the restricted maximum likelihood method, using volunteer as random effects and interval number as fixed effect. Interval number was modeled as a factor variable, and the best covariance structure was found by minimizing the Akaike information criterion (AIC). We used a hierarchical testing procedure preserving the 5% significance level by first testing the general null hypothesis of "no change for all intervals"; only when this null hypothesis was rejected, we evaluated change for individual intervals.

All statistical analyses were performed with Rstudio (Rstudio Inc, Boston, MA), package lme4. The significance level was set at $P < .05$.

3 | RESULTS

Sixteen healthy subjects were included (7 women, mean age 25.5 [range 19-37 years], mean BMI 23.5 [range 20.5-30.1], mean fasting time 10.6 hours [range 7.7-12.7 hours]). The preparation and scan protocol were well-tolerated, and no adverse effects were observed. Figure 1A visualizes an acquired dataset for one subject in x–y plane and in the temporal direction; Figure 1B-E visualize the abdominal motion that is captured in the dynamic datasets. This is the input for the frequency analysis (Figure 1F), see Video S1 for an example of a tagged MRI scan (obtained immediately after the food challenge). Figure 2 visualizes the obtained frequency data for the same subject in more detail to provide insight in this type of data. The regions shown in this figure illustrate the possibility of doing regional analyses using our methods and provide insight in the acquired data. However, no separate regions were used for the actual analysis, the power spectrum of the complete field of view, as shown in Figure 1F,

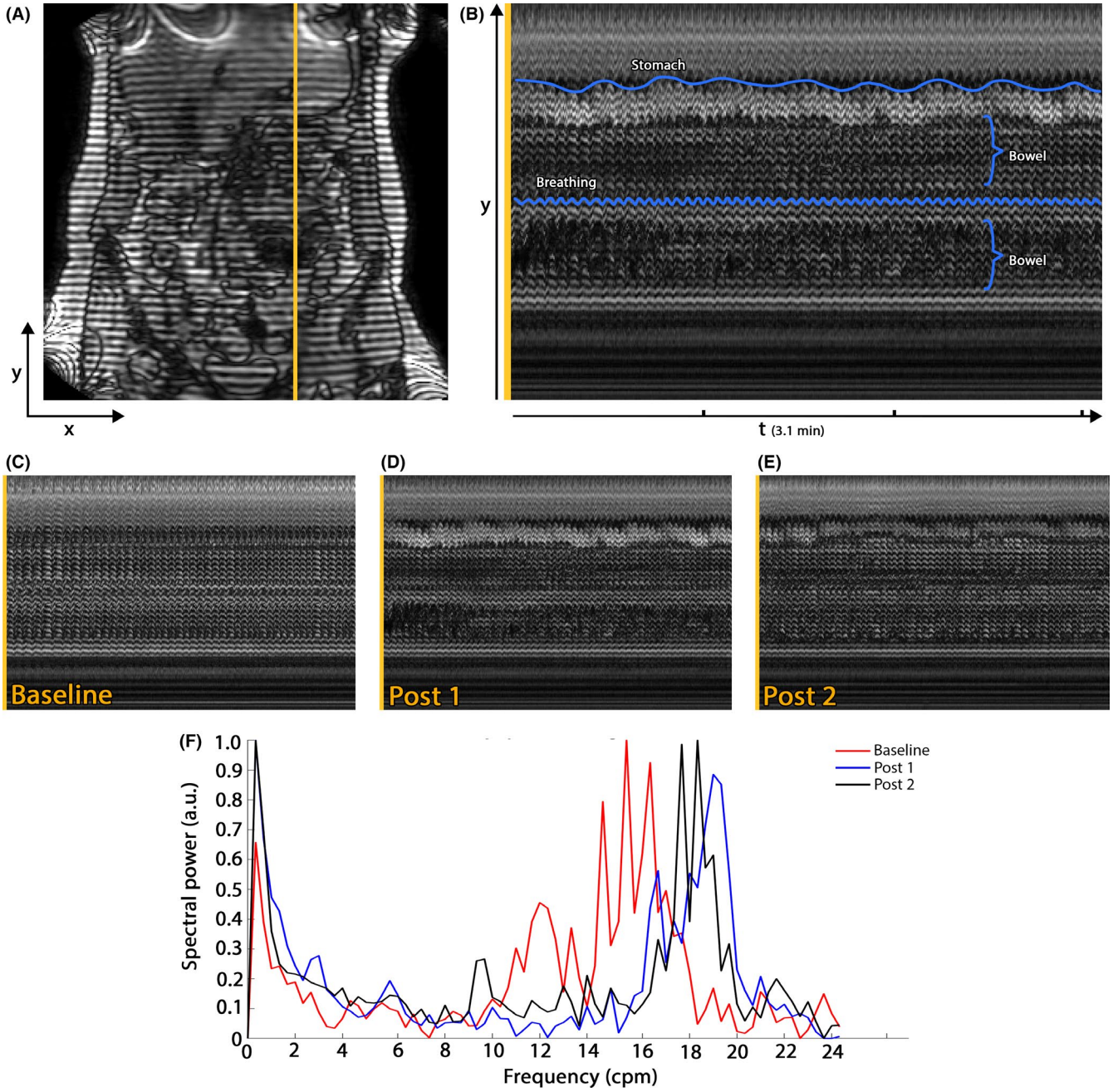

FIGURE 1 (A) Anatomical coronal image in *x*–*y* plane immediately after the food challenge (post 1), (B) resliced in the time direction (y-t) to visualize the acquired data in one subject at one position (orange line). The blue shapes visualize the types of motion captured in this dynamic acquisition, like breathing, stomach, and bowel motion. Breathing is only delineated at one location for visualization purposes but is present in the complete figure. Image (B) shows 9 gastric contractions (3 cpm) and 57 breathing cycles (around 19 per minute), bowel movement is more complex and frequency analysis is needed for the interpretation. The lower images (C-E) visualize the acquired data in the same subject for baseline (C), immediately after the food challenge (post 1, D) and approx. 20 min after the challenge (post 2, E). Visually, bowel and stomach movement is smallest during baseline measurements and increases after the food challenge (post 1 and 2). Image (F) visualizes the spectral power obtained after frequency analysis of the following scans, baseline (red line), immediately after the food challenge (post 1, blue line), and 20 min after the challenge (post 2, black line)

was used for statistical testing. There were no missing values for statistical testing.

Figure 3A illustrates measured mean motility scores at baseline, immediately after the food challenge, and approximately 20 minutes after the challenge in all twenty frequency intervals. Visual comparison between fasted (baseline) and immediate postprandial motility (post 1) showed an increase in spectral power (motility) for all spectral intervals between 1 and 11 cpm. Above 11 cpm, the motility response to the food challenge is less pronounced and more diffuse. Figure 3A also reveals that the difference between fasted and late postprandial motility (post 2), 20 minutes after the challenge, is smaller. This suggests that motility is on a gradual return to baseline activity

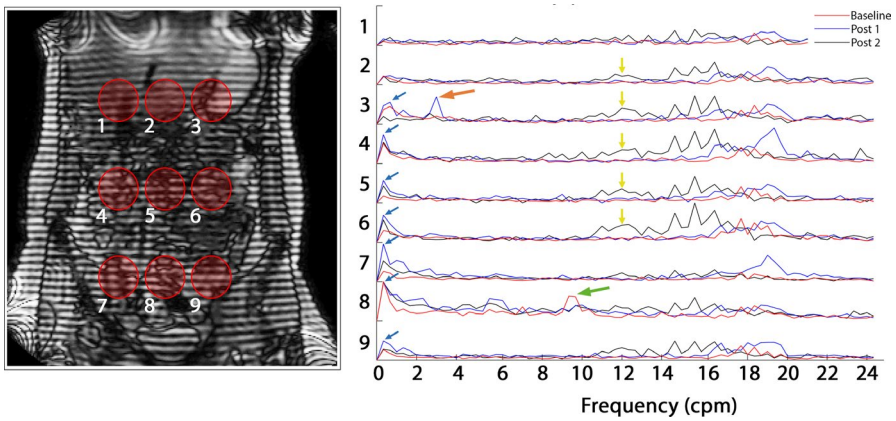

FIGURE 2 Visualization of the frequency data (spectral power) obtained for one healthy volunteer (same volunteer as in Figure 1) at nine regions, illustrating regional analysis as opposed to complete field of view analysis as visualized in Figure 1F. On the left, the anatomical image in x–y plane with nine red cycles delineating regions. These regions are linked to the spectra on the right obtained after frequency analysis for baseline (red line), immediately after the food challenge (post 1, blue line), and 20 min after the challenge (post 2, black line). All spectra show activity around the breathing frequency, in this healthy volunteer between 14 and 20 cpm. The spectra of circles 3-9 show activity in the very low-frequency domain (0-4 cpm, small blue arrows), the post 1 spectrum of circle 3, location of the stomach, shows a peak at 3 cpm (orange arrow). In this specific example, the frequency spectra correlating with the small bowel range (9-12 cpm) show a peak in circle 8 in the baseline scan (green arrow) and in circles 2-6 in the spectra 20 min after the food challenge (post 2) (yellow arrow)

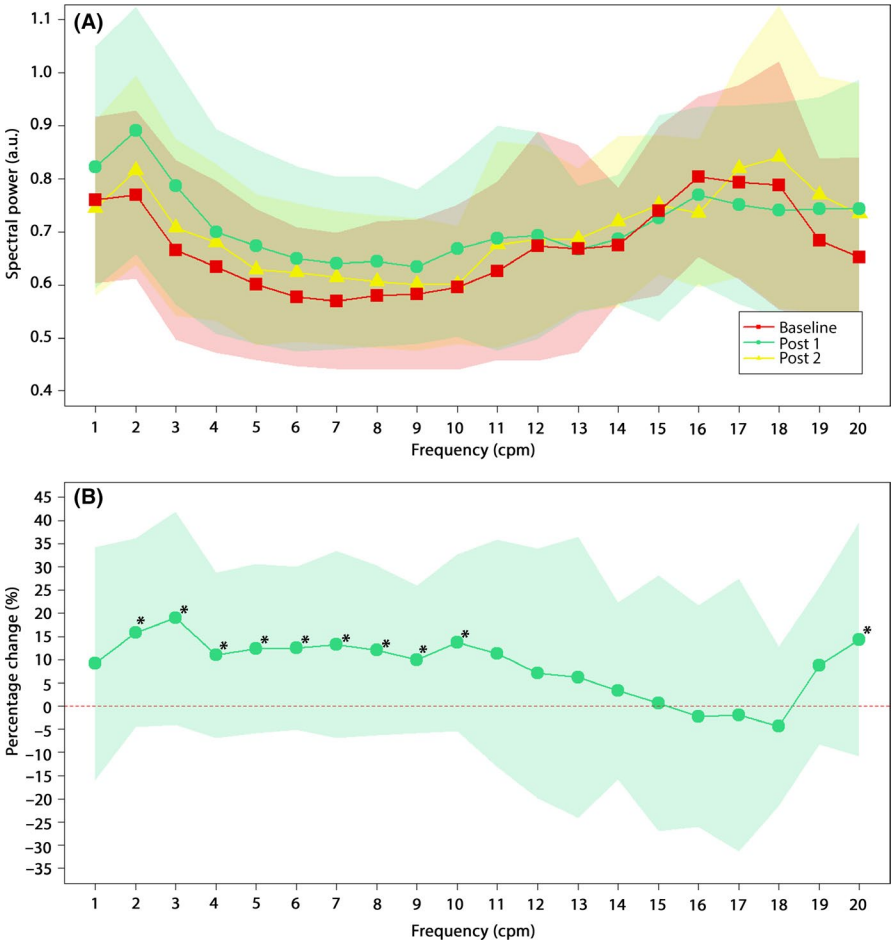

FIGURE 3 (A) Motility score (spectral power) for all volunteers ranging over 20 spectral intervals visualizing small bowel motility in fasted subjects at baseline (red), immediately after the food challenge (post 1, green), and approx. 20 min after the food challenge (post 2, yellow). Mean spectral power and standard deviation are visualized by the lines and surrounding bands. Image (B) presents test meal-induced changes in motility scores (difference between immediate postprandial and fasted values) for all volunteers ranging over 20 spectral intervals. The test meal elicited a significant response in the low-frequency intervals, which is consistent with the gastric and small intestinal frequencies. Mean percentage change and standard deviation of each interval are visualized in green, and significant motility difference ($P < .05$) is illustrated with black asterisks (2-10 cpm and 20 cpm)

after 20 minutes. For individual motility scores Appendix S1 can be consulted.

Significant response to food was found between baseline and immediately after the food challenge. Figure 3B illustrates the percentage change per interval. The evaluation of change per individual interval revealed response in the low-frequency intervals 2-10 contractions per minute (P ranging from .004 to.03), which is consistent with gastric and small bowel frequencies. A significant response was also revealed at 20 contractions per minute ($P = .04$).

4 | DISCUSSION

In this study, we demonstrate that a 300 kcal test meal immediately increased motility in the low-frequency range of 2-10 contractions per minute in healthy overnight-fasted subjects. No differences were found in the higher frequency range (11-19 contractions per minute), which primarily contains breathing motion, with an exception at 20 contraction per minute.

In a previous study,[15] we demonstrated that a simple food stimulus elicits a contractile response in fasted small bowel and that this response can be detected with MRI. Using delineations of the entire small bowel and a displacement mapping technique called GIQuant™ (Motilent, Ford, UK),[19-22] a median effect of 30% could be demonstrated. The latter study used breath-hold acquisitions of 20 seconds with a frame rate of 10 per second. It shows the ability of MRI, using image intensity bases nonlinear registration of motion, to observe changes in mean motility intensity in narrow timescales.

In the study presented here, the same healthy subjects were included as in the study referred to above, but the fundamental different approach is to monitor motility at substantially longer timescales (3 minutes vs. 20 seconds) and examine motility behavior in the frequency domain. The tagged MRI acquisition technique in combination with the frequency analysis showed a mean effect ranging from 10% to 19% over nine spectral intervals (2-10 cpm). Although the effect size is different (median vs. mean), the main conclusion of the results in these two studies is similar; an immediate small bowel motility response to the Nutridrink was assessed with dynamic MRI. The fact that comparable results are found with two completely different MRI techniques (both with respect to acquisition and post-processing) corroborates that we are indeed measuring small bowel motility and its response to the food challenge. This is important information since in the present study we lack a reference standard to which these MR motility assessment techniques can be compared. In a study by Khalaf et al,[16] a comparable food-intervention MRI experiment over 270 minutes was performed and they also found a maximum motility response immediately after ingestion of a test meal, again underlining our results.

A food provocation MRI protocol might be a useful clinical tool to explore the intestinal motility response to food in patients with gastrointestinal dysmotility and functional disorders, since these patients frequently experience symptoms after ingestion of food. Considering that the largest response can be measured immediately after the food challenge,[15,16] a short MRI protocol could suffice in a clinical setting. Continuing to explore ways to use MRI for bowel motility assessment is of importance since the bowel is a complex organ that is hard to assess in a noninvasive manner. Over the past three decades, cine MRI for gastrointestinal motility assessment has been in constant development. Several acquisition and postprocessing techniques have been developed and evaluated, as elaborated on in our review[4] 'Evaluation of gastrointestinal motility with MRI', all with their own advantages and disadvantages.

The gastrointestinal tagging technique presented in this paper is relatively independent of bowel preparation, as the image contrast is superimposed onto the image by the SPAMM prepulse. Using this technique, the contrast present in the image itself becomes less important, allowing to focus on speed and resolution in sequence and protocol optimization.

The main advantages of this tagging technique over other MR motility assessment techniques is the extent to which it is fully automated and the ability to measure the motility score as a function of frequency. Therefore, this technique can pick up on specific frequencies occurring, disappearing, increasing, or decreasing after challenging the gastrointestinal tract. Data analysis in this study was performed without defining regions of interest or segmenting intestinal structures, as the method in this study applies spectral separation of motion phenomena. This circumnavigates the cumbersome challenge of segmenting intestinal tissue and defining various regions. Further, it provides information about the presence or absence of specific frequencies in the scanned field of view.

The individual motility scores in Appendix S1 highlight the variability within healthy subjects. Apart from variability in breathing frequencies between subjects and within subjects, similar variability may be present in bowel frequencies and in the timing of the physiological response to the food challenge. For example, many subjects showed immediate response to the food challenge in the bowel frequencies, while others seem to respond later (post 2), or not at all. This can be further studied by comparing the reported motility scores to a reference measurement.

Another distinguishing characteristic of the tagging technique compared with other MR motility assessment techniques is the ability of data acquisition in free breathing. This makes longer monitoring feasible, which in turn facilitates the detection of low-frequency patterns and underlines the suitability for measurements in the gastrointestinal motility frequency domain. Therefore, this technique has the potential to provide new insights into the underlying processes of in vivo gastrointestinal motility of which much has not yet been fully understood.

The frequency analysis technique described in this paper is a novel approach to motility assessment with MRI. There are other tagged MR applications being explored for the gastrointestinal field, but these techniques focus on flow velocity and direction instead of contraction frequency.[23] Challenges of our approach involve nonperiodic highly complex behaviour of the gastrointestinal motility and the sustained timescale over which the fasted and postprandial motility patterns take place (hours). This study has demonstrated that tagged MRI can measure small bowel motility response in healthy subjects when a food challenge is presented. For an in-depth assessment of motility phases and identifying the different regions of the GI tract by frequency patterns, methods have to be developed capable of distinguishing healthy from diseased motility behavior in terms of frequency characteristics. To develop such methods, challenges have to be overcome concerning practical difficulties related to data acquisition, analysis, and storage when aiming for long scan times at high frame rates. Furthermore, there is a considerable set of parameters such as tag spacing, time delay, spatiotemporal resolution, signal-to-noise, contrast-to-noise ratio that are all interconnected and have a strong influence on the result, which should be further optimized.

A limitation of our study is the relative short acquisition time of approximately 3 minutes. Although this is long enough to distinguish contraction frequencies as low as 1 per minute, contractions are not expected to be cyclic all the time, especially after food intake; therefore, longer acquisition times are expected to provide more accurate frequency analysis.

From previous manometric studies, we know that the highest frequency of duodenal contractions is between 11 and 12 cpm.[13,14] In our study, we did not find a difference in this frequency range, one explanation could be that duodenal contraction rate in the included subjects was not as high as 11-12 cpm due to subject variation. Another explanation could be that intestinal motility and breathing frequencies overlapped. In that case, the frequency analysis technique is less sensitive for distinguishing duodenal motility. The presence of a response at 20 contractions per minute could be an effect of changes in the breathing pattern after the food challenge. Alternatively, this difference may be explained by the presence of higher harmonics in the motility pattern. These topics should be explored in future studies, because we could not tackle all of these questions in this one study as the SPAMM acquisition was part of a larger study and did not include separate respiratory and cardiac frequency measurements. However, the changes upon a food challenge, studied in this work, predominantly affect motility and not respiratory motion; therefore, we assume that the presence of overlap does not compromise our methods.

In conclusion, the gastrointestinal-tagged cine MRI stimulation protocol demonstrated an immediate, food-induced motility response in the low-frequency range of 2-10 contractions per minute in healthy overnight-fasted subjects. In the absence of a method to compare MRI to the reference standard, this work substantiates previous gastrointestinal MRI motility assessment and offers additional spectral information.

ACKNOWLEDGMENTS

We thank Dr. Rolf Lamerichs (Philips) for his work on the SPAMM patch and sequence development. We thank Paul de Groot, Dr. Kerry Zhang, and the 3T MRI group from the Amsterdam UMC, location Academic Medical Center, for technical support. We thank Prof. Dr. Koos Zwinderman from the Amsterdam UMC, location Academic Medical Center, for statistical support and Prof. Dr. André J.P.M. Smout from the Amsterdam UMC, location Academic Medical Center, for his valuable input.

AUTHOR CONTRIBUTIONS

CSJ performed the research; KLR assisted in MRI scanning; CSJ, AJN, and JS designed the research study; CSJ and AMJS analyzed the data; AMJS contributed the essential postprocessing pipeline; CSJ and AMJS wrote the manuscript; KLR, AJN, and JS revised the manuscript.

DISCLOSURES

JS is research consultant for Robarts Clinical Trials and has a research agreement with Takeda.

ORCID

Catharina S. de Jonge https://orcid.org/0000-0002-3921-0895

REFERENCES

1. Paine P, McLaughlin J, Lal S. Review article: The assessment and management of chronic severe gastrointestinal dysmotility in adults. *Aliment Pharmacol Ther*. 2013;38(10):1209-1229.
2. Grønlund D, Poulsen JL, Sandberg TH, et al. Established and emerging methods for assessment of small and large intestinal motility. *Neurogastroenterol Motil*. 2016;2017:1-9.
3. Bredenoord AJ, Smout A. Advances in motility testing-current and novel approaches. *Nat Rev Gastroenterol Hepatol*. 2013;10(8):463-472.
4. de Jonge CS, Smout A, Nederveen AJ, Stoker J. Evaluation of gastrointestinal motility with MRI : Advances, challenges and opportunities. *Neurogastroenterol Motil*. 2018;30(1):1-7.
5. Alyami J, Spiller RC, Marciani L. Magnetic resonance imaging to evaluate gastrointestinal function. *Neurogastroenterol Motil*. 2015;27(12):1687-1692.
6. Hoad C, Clarke C, Marciani L, Graves MJ, Corsetti M. Will MRI of gastrointestinal function parallel the clinical success of cine cardiac MRI? *Br J Radiol*. 2018;20180433.
7. van der Paardt MP, Sprengers A, Zijta FM, Lamerichs R, Nederveen AJ, Stoker J. Noninvasive automated motion assessment of intestinal motility by continuously tagged MR imaging. *J Magn Reson Imaging*. 2014;39(1):9-16.
8. Sprengers A, van der Paardt MP, Zijta FM, et al. Use of continuously MR tagged imaging for automated motion assessment in the abdomen: a feasibility study. *J Magn Reson Imaging*. 2012;36(2):492-497.
9. Axel L, Dougherty L. Modulation of motion with of magnetization' spatial. *Radiology*. 1989;171(3):841-845.
10. Sprengers A, Caan M, Moerman KM, Nederveen AJ, Lamerichs RM, Stoker J. A scale space based algorithm for automated segmentation of single shot tagged MRI of shearing deformation. *Magn Reson Mater Physics, Biol Med*. 2013;26(2):229-238.
11. McGee S. Respiratory rate and abnormal breathing patterns. *Evid-Based Phys Diag*. 2012;145-155.
12. Michail M, Brown AJ. Physiology of the normal heart. *Medicine*. 2018;46(8):427-430.
13. Husebye E. The patterns of small bowel motility: Physiology and implications in organic disease and functional disorders. *Neurogastroenterol Motil*. 1999;11(3):141-161.
14. Quigley E. Gastric and small intestinal motility in health and disease. *Gastroenterol Clin North Am*. 1996;25(1):113-145.
15. de Jonge CS, Menys A, van Rijn KL, Bredenoord AJ, Nederveen AJ, Stoker J. Detecting the effects of a standardized meal challenge on small bowel motility with MRI in prepared and unprepared bowel. *Neurogastroenterol Motil*. 2019;31(2):1-8.
16. Khalaf A, Hoad CL, Menys A, et al. MRI assessment of the postprandial gastrointestinal motility and peptide response in healthy humans. *Neurogastroenterol Motil*. 2018;30(1):e13182.
17. de Jonge CS, Gollifer RM, Nederveen AJ, et al. Dynamic MRI for bowel motility imaging–how fast and how long? *Br J Radiol*. 2018;91(1088):20170845. https://doi.org/10.1259/bjr.20170845
18. Sprengers A, Caan M, Buitink SJ, et al. *Measurement of Lagrangian strain and Eulerian flow in the abdomen using Continuously Single Shot Tagged Magnetic Resonance Imaging*. Proc 22rd Annu Meet ISMRM, Milan, Italy. 2014;5707.
19. Motilent Ford, UK. www.motilent.co.uk. Accessed October 4, 2017.
20. Odille F, Menys A, Ahmed A, Punwani S, Taylor SA, Atkinson D. Quantitative assessment of small bowel motility by non-rigid registration of dynamic MR images. *Magn Reson Med*. 2012;68(3):783-793.

21. Menys A, Hamy V, Makanyanga J, et al. Dual registration of abdominal motion for motility assessment in free-breathing data sets acquired using dynamic MRI. *Phys Med Biol*. 2014;59(16):4603-4619.
22. Menys A, Taylor SA, Emmanuel A, et al. Global small bowel motility: Assessment with dynamic MR imaging. *Radiology*. 2013;269(2):443-450.
23. Pritchard SE, Paul J, Major G, et al. Assessment of motion of colonic contents in the human colon using MRI tagging. *Neurogastroenterol Motil*. 2017;29(9):1-8.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: de Jonge CS, Sprengers AMJ, van Rijn KL, Nederveen AJ, Stoker J. Assessment of fasted and fed gastrointestinal contraction frequencies in healthy subjects using continuously tagged MRI. *Neurogastroenterol Motil*. 2020;32:e13747. https://doi.org/10.1111/nmo.13747