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Quantification of Gastric Contractions Using MRI with a Natural Contrast Agent

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Abstract— **Gastric motility has an essential role in mixing and the breakdown of ingested food. It can affect the digestion process and the efficacy of the orally administered drugs. There are several methods to image, measure, and quantify gastric motility. MRI has been shown to be a suitable non-invasive method for gastric motility imaging. However, in most studies, gadolinium-based agents have been used as an oral contrast agent, making it less desirable for general usage. In this study, MRI scans were performed on 4 healthy volunteers, where pineapple juice was used as a natural contrast agent for imaging gastric motility. A novel method was developed to automatically estimate a curved centerline of the stomach. The centerline was used as a reference to quantify contraction magnitudes. The results were visualized as contraction magnitude-maps. The mean speed of each contraction wave on the lesser and greater curvatures of the stomach was calculated, and the variation of the speeds in 4 regions of the stomach were quantified. There were 3-4 contraction waves simultaneously present in the stomach for all cases. The mean speed of all contractions was 2.4±0.9 mm/s, and was in agreement with previous gastric motility studies. The propagation speed of the contractions in the greater curvature was higher in comparison to the lesser curvature (2.9±0.8 vs 1.9±0.5 mm/s); however, the speeds were more similar near to the pylorus. This study shows the feasibility of using pineapple juice as a natural oral contrast agent for the MRI measurements of gastric motility. Also, it demonstrated the viability of the proposed method for automatic curved centerline estimation, which enables practical clinical translation.**

Clinical Relevance— **MRI is able to non-invasively provide dynamic images of the contraction patterns of the stomach, providing a novel clinical tool for assessing functional motility disorders. The use of a natural oral contrast agent such as pineapple juice, as opposed to a gadolinium-based contrast agent, makes MRI more widely accessible. Our semi-automated methods for quantifying contraction magnitude and speed will streamline analysis and clinical diagnosis.**

I. Introduction

The stomach has a significant role in the mixing and breakdown of ingested food. The mixing and grinding the food particles inside the stomach are carried out by muscular wave-like contractions coordinated, in-part, by rhythmic electrical events which occur in the human stomach walls approximately every 20 s [1]. The contractions originate in the upper stomach (fundus) and propagate toward the pylorus, exerting forces on the digested food [2]. In addition to the breakdown of foods, the efficacy of orally administered drugs can be highly affected by gastric mechanics [3].

Medical imaging techniques can provide an improved understanding of the processes occurring within the stomach. Previously, most methods for imaging the stomach were invasive or hard to tolerate for the patients [4]. In 1992, magnetic resonance imaging (MRI) was proposed as a radiation-free alternative to scintigraphy for gastric emptying measurements [5]. Not long after, MRI was also used to capture gastric motility and was proposed as an alternative to manometry and scintigraphy [6]. These measurements were possible due to advancements in MRI technology and the introduction of sequences that can capture images at a higher frequency [7].

Gadolinium-based agents are commonly used to increase the contrast and clarity of the gastrointestinal tract [8]. However, the effects of these contrast agents on gastric motor activities are yet to be studied. As a natural alternative for gadolinium-based contrast agents, pineapple juice can be used. A comparison between different natural fruit juices as oral contrast agents revealed the viability of using pineapple juice as an oral contrast agent in MRI [9].

To capture gastric motility, multiple MR images can be taken from a single plane of the stomach during a period of time (usually less than 1 minute). Researchers have used different methods to measure and quantify gastric motility. A common technique to measure the deformations of the stomach wall is to use a constant spatial reference for all time steps. The stomach centerline can serve well for this purpose. Different methods for centerline estimation and measurements were used in previous studies. In one study a straight line was placed by the user starting from the mid-fundus extending to within 2 cm of the pylorus [10]. The frequency of the contractions was calculated, and spatio-temporal maps of the normalized contractions were generated. In another study, a straight line was automatically generated based on segmented MRI data [11][12]. In a more recent study, a curved centerline was manually placed [13]. This centerline did not incorporate the fundus and distal antrum of the stomach and was fixed for all time steps. The contractions were calculated based on the position of the centerline, and a motility score was calculated

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based on the magnitude of the contractions [13]. All of the mentioned studies used gadolinium-based contrast agents.

In the current study, MRI was used for data acquisition using pineapple juice as the contrast agent. The centerline of the stomach was automatically estimated. Contraction speeds in different parts of the stomach were quantified, and local contraction speeds on lesser and greater curvature were calculated.

II. Materials and Methods

A. MRI Data Acquisition

Ethical approval for this study was granted by the University of Auckland Human Participants Ethics Committee, and all participants provided informed consent. The scans were carried out at the Centre for Advanced Magnetic Resonance Imaging (CAMRI) at The University of Auckland using 3 T and 1.5 T Siemens MRI machines. Participants were selected from healthy volunteers with no history of abdominal surgery.

Participants were asked to fast for at least 6 hours prior to the scans. Before the scans, each participant was provided with a test meal of 250 - 500 g and 300 - 500 ml of pineapple juice as the natural contrast agent to enhance the clarity of the gastric tract border. After meal ingestion, the participants laid supine in the MRI machine. The TrueFISP [7] imaging sequence was used to image a plane near the center of the stomach that was able to intersect the pyloric valve, and the lesser and greater curvatures. This plane was imaged for 17 s at a frequency of 1.5 Hz resulting in 25 images for each participant. The slice thickness was 4 mm to reduce the blurriness of the stomach borders due to stomach movements. To minimize the breathing artefacts, participants were asked to hold their breath.

B. Data Processing

The centerline of the stomach was used to calculate movements and deformations of the stomach wall due to contractions. The steps used to generate the stomach centerline are illustrated in Fig. 1. First, all the MR images in the time series were segmented, and the lesser and greater curvatures were divided into 200 equally spaced points. In the second step, circles were fitted within the stomach boundary for all time points comprising at least one point from the lesser and greater curvatures in the MR image. In the final step, a 5th order polynomial was fitted to the center of the fitted circles for all time steps, and 200 equally spaced points were distributed along the centerline. The fitted line was used as a reference and was assumed to be stationary for all time steps.

All the calculations were performed using MATLAB R2018a (MathWorks, Natick, MA, USA).

C. Contraction Quantification and Visualization

For every time step, each point on the lesser and greater curvatures was paired to a corresponding point on the centerline. The distance between each wall point and the paired centerline point was calculated and stored for all time steps. For all the points on the lesser and greater curvatures, the time-averaged distance to the centerline was calculated.

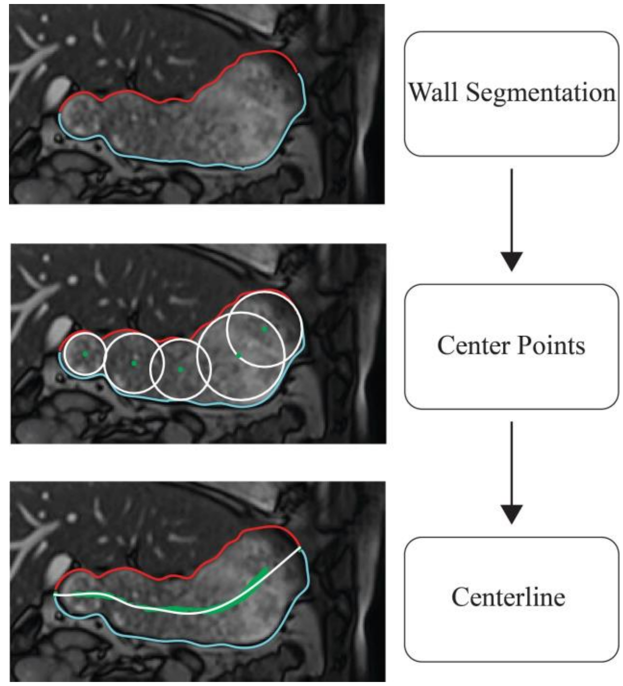

Fig. 1: Steps used to generate the centerline of the stomach. First, the lesser and greater curvatures of the stomach for all time steps were segmented. In the second step, circles that fitted within the stomach and have at least one point located on the lesser and greater curvature were determined for each time step. In the final step, a line was fitted to all the center points of these circles in the whole time series and used as the stomach centerline.

Then, for every time step, the magnitude of the contraction (MoC) for each point on the walls was calculated as shown in (1),

$$MoC = \frac{Dc_t - \sum_{t=0}^{tmax} Dc_t/tmax}{\sum_{t=0}^{tmax} Dc_t/tmax} \times 100 \qquad (1)$$

where Dc_t is the distance of the curvature point to the paired point on the centerline at time step t, and $tmax$ is the number of time steps in the MRI recording. The MoC was calculated across all time points, and the values in the lesser curvature and greater curvature were plotted as in the form of a 'magnitude-map' to visualize and quantify contraction speeds and directions.

To isolate each contraction wave in a magnitude map, a threshold of 5% MoC was applied. Then, a straight line was fitted to represent each contraction wave, and the speed was determined from the slope of the line.

To assess the variation in speeds of the propagating contraction across different stomach regions, the centerline was divided into four equal length parts. The corresponding points to each part of the centerline on lesser and greater curvature form four regions for the stomach. The mean and standard deviation of the contraction speeds on curvature points of each region was calculated.

III. Results

MRI scans were acquired from 4 healthy volunteers (2 males, 29±4 years, 79.5±17.1 kg, height 180±13 cm, and BMI of 24.3±1.8 kg/m^2).

The stomach and contractions size varied in each of the 4 participants, as shown in Fig. 2. The 2D images illustrate the differences in magnitude, position, size, and shape of the contractions. However, in each case, these parameters varied as the contractions passed through different regions of the stomach. The propagation of the contractions over time and the magnitude of the contractions in each part of the stomach can be seen in the magnitude-maps of a representative subject in Fig. 3. As the Y-axis represents time and the X-axis represents the position of the contraction, the slope of each contraction region (red lines) was used to estimate the speed of the contraction wave.

Contraction propagation speeds varied in different regions of the stomach. The speeds in the lesser and greater curvature for different regions of the stomach across all subjects are shown in Fig 4. The propagation speeds were higher in the greater curvature and especially in the corpus of the stomach, where the effect of the curvature was most prominent. The mean speeds of the contractions in the lesser and greater curvatures were 1.9±0.5 mm/s and 2.9±0.8 mm/s, respectively. On the lesser curvature of the fundus, only one participant had detectable contractions. The speed of contractions between the lesser and greater curvatures was more varied near the fundus with the maximum difference around 3.5 mm/s. Near the pylorus, the difference in speed between the lesser and greater curvature was less than 2 mm/s.

IV. Discussion and Conclusion

This study demonstrates the feasibility of using MRI with a natural contrast agent to measure and quantify gastric motility in human participants. TrueFISP sequence allowed imaging at 1.5 Hz with sufficient border clarity for gastric imaging without a gadolinium-based contrast agent, making it suitable for gastric motility research. Using a novel and automatic centerline estimation method, gastric motility patterns were quantified.

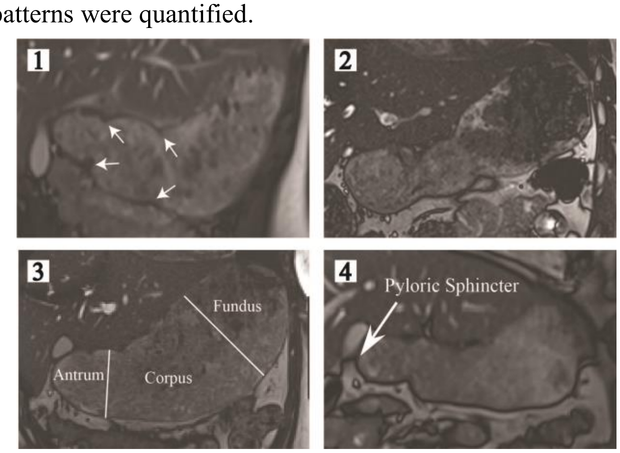

Fig. 2: MR images of the stomach for 4 participants. Two contractions on the greater and lesser curvature of the stomach have been identified for Participant 1. Regions of stomach have been identified for Participant 3. The position of the pyloric sphincter is identified for Participant 4.

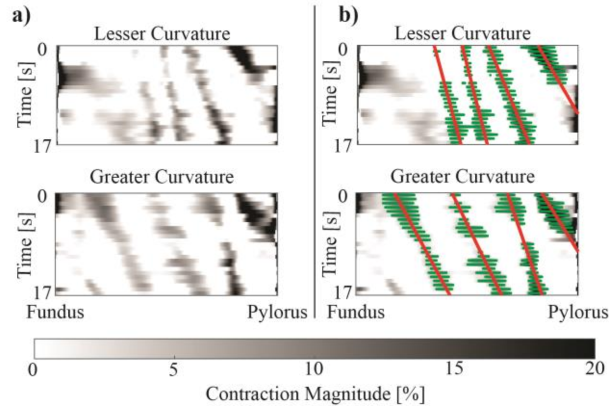

Fig. 3: Contraction magnitude-maps are shown for a representative subject for the (a) lesser and greater curvature and (b) corresponding methods for determining contraction speed. The color bar indicates the magnitude of the contraction. The green regions in (b) represent the contractions, and the red lines are used to determine the average speed of each contraction.

In this study, a curved centerline for the stomach was generated automatically, which is an enhancement to the previous methods where a simple straight line [11][12] or manually placed centerlines [10][13] were used. Automatic generation of the centerline increases reproducibility and enables these methods to be more convenient for clinical usage. The differences in the shape and size of the stomach and the contractions, as shown in Fig. 1, signifies the importance of patient-specific models to understand gastric motility.

The mean speed of the contractions was 2.4±0.9 mm/s, which was in line with previous MRI-based studies of gastric motility (1.6 – 2.7 mm/s) [10][11][14]. The speed of the contractions was variable between subjects and also variable in different regions of the stomach. Similar slow wave speeds have been reported from the gastric slow wave mapping studies in the corpus and antrum (3.3 mm/s) [15]. However,

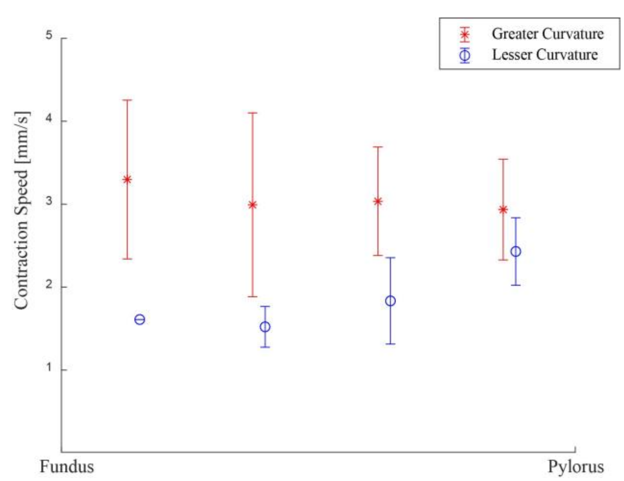

Fig. 4: Variation of contraction speed in different regions of the stomach along the lesser (blue) and greater curvatures (red) for all subjects. Closest to the fundus region, the speed of contraction of the lesser curvature was detected only in one case, thus no deviation is shown.

the reported increase in the contraction propagation speed in the antrum region [15] was only noticeable on the lesser curvature. This might be due to the temporal resolution of the measurements and calculations in this study compared to HR mapping. The results showed that the speed of the contractions was higher in the greater curvature in the fundus and corpus area. However, in the antrum, there was no contraction speed difference between the greater and lesser curvature. The main reason is that the contraction has to travel more distance near the greater curvature in the fundus and corpus. However, in the antrum, the lengths of the two curvatures are similar, as can be seen in Fig. 1.

D-maps are spatio-temporal maps that illustrate the changes in diameter and are commonly used to visualize the diameter changes in the intestine. However, unlike the intestine, the diameter of the stomach is variable along its length. These variations in diameter make the D-maps impractical for the stomach. In this study, rather than visualizing the spatio-temporal changes in the stomach wall using D-maps, magnitude-maps were used to quantify the variations in the stomach diameter. The calculated MoC shows the amount of contraction from the average position of the stomach walls. Using the average position resulted in better tracking of the contractions, specifically near the start and end points of the stomach, where the diameters are smaller.

In this study, to minimize the breathing artefacts, only breath-hold sequences were analyzed. This limited the scan time to approximately 17 s. In future studies, the analysis of free-breathing data will be investigated. MRI limitations in this study were the temporal resolution of the imaging (1.5 Hz) and single 2D plane scans for dynamic imaging. In addition, the study was limited to 4 subjects, and more data is needed to validate the heterogeneous speeds across the stomach.

In conclusion, the results of this study indicate the feasibility of MRI scans using a natural contrast agent for the assessment of gastric motility. In addition, the capability of the proposed automatic centerline estimation method was demonstrated. Finally, the regional propagation speeds of the contractions in the lesser and greater curvature of the stomach were reported.

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