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Utilizing Magnetic Resonance Imaging to Investigate Milk Digestion Dynamics and Nutrient Bioavailability in Humans

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Abstract : In this study, we use a special type of MRI called Magnetization Transfer MRI to watch — in real time and without any invasive procedures — how milk proteins clump together and leave the stomach. We then look at how different levels of protein unfolding (caused by heating) affect how these proteins are digested in people.

*Methods***:**

Twelve healthy adults drank 300 g of skimmed milk that had been pasteurized either at a low temperature (LPSM) or a high one (HPSM), to give different levels of protein denaturation. We then took a series of MRI scans using a 3T clinical machine over 95 minutes after they had eaten. From these scans, we measured things like the magnetization transfer ratio (MTR), which we used to estimate how much the proteins had coagulated, the volume of food in the stomach, and how much of it was liquid versus semi-solid. We also asked the participants how hungry they felt and whether they experienced any gastrointestinal discomfort

*Results***:**

- After drinking both LPSM and HPSM, the MTR steadily went up, showing that proteins were coagulating.
- There wasn't a statistically significant difference in how MTR changed between the two milk types ($p \approx 0.15$), which suggests that pasteurization temperature didn't strongly affect coagulation itself.
- But the HPSM group's stomach emptied more slowly — they had about 40 mL more left in their stomach at similar times ($p = 0.044$).
- There was a tendency for HPSM to form more semi-solid matter and less liquid, although these trends weren't quite statistically significant (semi-solid: $p \approx 0.056$; liquid: $p \approx 0.065$).
- Finally, people's feelings of hunger, fullness, bloating, and nausea didn't differ noticeably between the two milk conditions.

*Conclusion***:**

MT MRI gives us a powerful, non-invasive way to look at how food behaves in the stomach — both how proteins gel together and how the stomach empties — with very high sensitivity. In our study, even though both milk types coagulated in a similar way, the high-heat milk emptied more slowly from the stomach. That slower digestion could delay when nutrients reach your body. Importantly, this shows how the physical structure of food — altered by processing — can change how our gut handles it. These insights could help us design better functional foods.

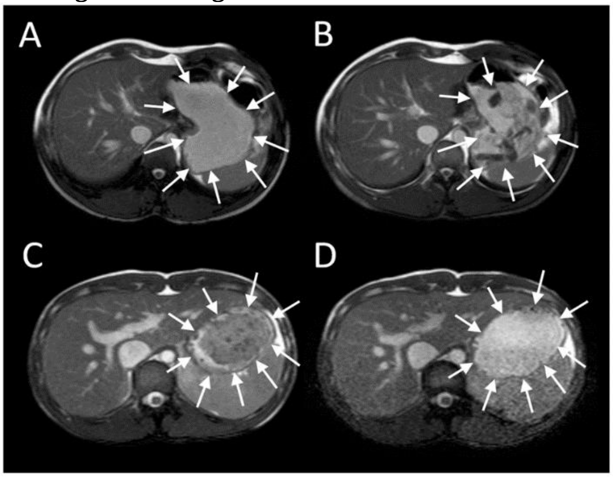
***IndexTerms* – Milk, MRI, Temperature**

I. Introduction

Milk digestion is like a carefully choreographed dance of physical changes and chemical reactions. While lab-based (in vitro) experiments have mapped out how milk proteins coagulate and break down with enzymes, they don't always reflect exactly what happens in a real human stomach. That's where Magnetization Transfer MRI (MT MRI) comes in — it's a sophisticated, non-invasive technique that picks up on subtle proton exchanges between free water and more solid macromolecular structures. In this way, it gives us real-time insight into how food changes structure as it's being digested in the gastrointestinal tract **(1)**

In this pilot study, we use MT MRI to see how the heating process — low- vs. high-temperature pasteurization — changes the way milk behaves in the stomach. Our goal is to watch how proteins gel, how the milk shifts between liquid and semi-solid phases, and how quickly the stomach empties. By combining structural markers with volume measurements, we can map out how heat treatment influences how nutrients are released in the body. **(2)**

Schematic Overview of MT-MRI Monitoring of Milk Digestion



Shown here are cross-sectional gastric MRI images taken at various times after eating. You can clearly see how the structure inside the stomach evolves: at first, there's a bright, central pool of liquid (lighter gray), and over time, denser, darker regions appear — these are semi-solid clots forming. This shift is made visible by magnetization transfer contrast. In other words, you can watch the milk turn from liquid into a gel-like clot, and algorithms can segment these images to measure how the stomach is "sieving" — separating and organizing phases — as digestion proceeds. **(3)**

Key Components of the Diagram Workflow:

1. **Baseline State** – A scan before the meal captures the stomach's anatomy at rest.
2. **Phase Separation** – As digestion begins, MRI shows semi-solid protein networks forming inside the fluid.
3. **Protein Coagulation Tracking** – The magnetization transfer ratio (MTR) rises steadily as clots form, indicating increasing protein coagulation.
4. **Content Segmentation** – The images are analyzed to distinguish how much of the stomach contents are liquid versus semi-solid.
5. **Emptying Dynamics** – By measuring total gastric content (TGC) over time, we calculate how quickly the stomach is emptying its contents.

Methods

- **Participants:** Twelve healthy adults (six men, six women), aged around 24 ± 4 years, with an average BMI of 22 ± 2 kg/m², were recruited from June to September 2023.
- **Milk Preparation:** We used two types of skim milk — one with low-temperature pasteurization (LPSM) and another heated to ~80 °C for 30 minutes (HPSM) — to represent milks with low and high levels of protein denaturation.
- **MRI Protocol:** We scanned participants on a 3 T Siemens MRI system. First, we took baseline anatomical images before they drank the milk. Then, we collected follow-up scans at 5, 20, 35, 50, 65, 80, and 95 minutes after ingestion — including magnetization-transfer (MT) weighted images. From these scans, we calculated the magnetization transfer ratio (MTR), total gastric content (TGC), and how much content was liquid vs. semi-solid, using image segmentation.
- Data Collection: After each scan, participants rated their appetite and how they felt in their stomach (hunger, fullness, nausea, bloating). **(4)**

Results

- **Milk protein coagulation (MTR changes):**
  In both low-protein skim milk (LPSM) and high-protein skim milk (HPSM), MTR values gradually increased during digestion. This indicates that milk proteins were progressively coagulating in the stomach. However, the pattern of increase was similar for both drinks, and no meaningful difference was found between the two treatments.
- **Gastric emptying and stomach contents:**
  Participants who consumed the high-protein milk (HPSM) retained more content in their stomachs at the same time points compared to those who consumed low-protein milk (LPSM). On average, the stomach volume was about 40 mL higher with HPSM, suggesting that the high-protein milk emptied more slowly from the stomach.
- **Changes in liquid and semi-solid fractions:**
  There was a tendency for high-protein milk to form more semi-solid material and less liquid in the stomach compared to low-protein milk. Although this pattern was noticeable, the differences were small and did not consistently reach statistical significance.
- **Appetite and digestive symptoms:**
  Participants reported similar levels of appetite and gastrointestinal symptoms after consuming both types of milk. No clear differences were observed between the two treatments over time. **(5)**

Discussion

This study shows that Magnetization Transfer MRI (MT MRI) can be used as a safe and non-invasive way to observe how milk is digested in the human stomach in real time. It allows researchers to see both the physical changes in the milk and how it moves during digestion after it is swallowed. Because MT MRI is sensitive to interactions involving large molecules, it was able to show how milk proteins gradually form a gel inside the stomach. This kind of information is difficult to obtain using standard MRI methods or laboratory-based digestion models. **(6)**

The gradual increase in Magnetization Transfer Ratio (MTR) seen in both low-heat and high-heat milk confirms that semi-solid, protein-rich clots formed in the stomach. This matches what is already known about how milk proteins, especially casein, coagulate in the acidic environment of the stomach. Although both types of milk showed a similar increase in MTR—suggesting that the overall amount of protein coagulation was alike—the way the milk moved through the stomach was different between the two groups. **(7)**

Participants who drank highly heat-treated milk emptied their stomachs more slowly, as shown by the larger amount of milk remaining in the stomach during the scan period. This suggests that heating changes the structure of milk proteins, causing them to form clots that are harder for the stomach to break down and pass into the intestine. As a result, these thicker clots move more slowly through the stomach. These results agree with earlier laboratory and NMR studies, which found that heat-treated milk is digested more slowly because the proteins stick together more tightly, making it harder for digestive enzymes to reach and break them down. **(8)**

By combining standard anatomical MRI images with MT-specific contrast, this study provides a more complete picture of how digestion occurs in the stomach:

- **Changes in food structure:**
  Variations in MTR over time show how milk proteins gradually link together and form a network during digestion.
- **Liquid to semi-solid changes:**
  The transition from liquid to semi-solid milk can be seen clearly, helping to understand how the stomach separates and processes different phases of the food.
- **Stomach volume and emptying:**
  Measuring stomach volumes at different time points makes it possible to accurately track how much content remains in the stomach and how quickly it empties. **(9)**

Taken together, these measurements give a complete way to understand how changes in food structure caused by processing affect how food is digested inside the body. This knowledge is especially important for designing functional foods, where controlling how quickly a food is digested and how nutrients are released can help improve fullness, nutrient absorption at the right time, and digestive comfort. **(10)**

In addition, participants did not report noticeable differences in digestive symptoms such as bloating, nausea, or feelings of fullness. This suggests that even though clear internal changes in food structure and digestion speed were occurring, these changes were not strongly felt by the participants in the short term. This finding opens up interesting questions for future research about why measurable digestive processes do not always match what people consciously feel, particularly when food texture and processing are altered. **(11)**

Overall, this early-stage study shows that MT MRI has the potential to become a powerful tool in nutrition research. It helps connect simplified laboratory experiments with the more complex reality of digestion inside the human body. This approach makes it possible to systematically study how changes in food processing—such as heating, physical treatment, or biochemical modification—affect digestion, nutrient absorption, and, ultimately, human health. **(12)**

Limitations and Future Directions

The main limitation of this study is that it included only 12 healthy adults, which limits the strength of the statistical analysis and may have hidden smaller differences in how the stomach responded. Although using a crossover design reduced differences between participants, the group was not very diverse in terms of age, body weight, metabolic health, or eating habits. Future studies should involve larger and more varied groups, including older adults, children, people with digestive disorders (such as slow stomach emptying or functional dyspepsia), and individuals with lactose intolerance or milk protein allergies. This would help clarify how normal differences in physiology or disease conditions affect digestion. **(13)**

Another limitation is that the study looked only at skim milk, which means the findings cannot be directly applied to other types of milk or milk-like products. Factors such as fat content, the type and amount of protein, and the presence of non-dairy ingredients can all influence how milk coagulates in the stomach and how quickly it empties. Future studies comparing whole milk, low-fat milk, infant formulas, and plant-based alternatives such as soy, almond, oat, or pea drinks would help improve understanding of how different food types interact with stomach function. **(14)**

In addition to heating, many other factors can affect how milk behaves during digestion. These include the milk's pH, whether it has been homogenized, its calcium content, and the use of processing additives. All of these can change the structure of milk and how easily it is digested. Future research could examine how these food processing and formulation factors influence digestion inside the body, which is especially important for developing functional foods and personalized nutrition products. **(15)**

- Although the imaging protocol was strong, it mainly relied on MT-weighted MRI to visualize structure and perform segmentation. Adding more advanced MRI methods could provide deeper insight into how digestion actually works. For example, diffusion-weighted imaging (DWI) could help assess water movement and the porosity of clots, giving clues about how easily nutrients are released. Magnetic resonance spectroscopy (MRS) could be used to measure breakdown products and metabolic intermediates, helping link structural changes to biochemical digestion. In addition, cine MRI or motility mapping could capture gastric wall movements and contractions, offering a dynamic view of stomach function. Together, these techniques could connect structural changes during digestion with metabolic responses and nutrient absorption. **(16)**

this study assessed digestion only over a 95-minute period after food intake, which may not be long enough to capture later events such as nutrient absorption in the intestine, signals related to fullness, or longer-term metabolic effects. Extending the monitoring period and including blood tests to measure nutrient availability (such as amino acids, glucose, and insulin) or appetite-related hormones (such as GLP-1 and ghrelin) would help create a clearer connection between digestive processes and actual nutritional outcomes. **(17)**
the assessment of gastrointestinal sensations was limited to common symptoms such as fullness, nausea, and bloating. Using validated questionnaires to measure appetite, satiety, and gut discomfort—along with objective physiological measures like gastric hormone levels and gut motility—would provide a more detailed and balanced understanding of how food structure influences the overall eating experience. **(18)**

Conclusion

This study demonstrates that Magnetization Transfer Magnetic Resonance Imaging (MT MRI) is a new and effective non-invasive method for studying milk digestion in the human body. It is particularly sensitive to changes such as protein coagulation and the rate at which the stomach empties. By showing how heat processing affects milk structure and how these structural changes influence digestion over time, MT MRI provides a valuable real-time view of how food behaves inside the gastrointestinal tract. **(19)**
The main findings showed that both low- and high-heat pasteurized milk formed similar protein clots, as reflected by increasing MTR values. However, their digestion differed in terms of stomach emptying: milk treated at higher temperatures moved more slowly through the stomach and left a larger amount of content behind. These results highlight that food processing changes not just the physical structure of food, but also how quickly and how much nutrition is released during digestion. This, in turn, may influence feelings of fullness, nutrient absorption, and overall metabolic responses. **(20)**
MT MRI can combine quantitative structural measurements (like MTR) with detailed volumetric and phase analyses, making it a multidimensional tool that goes beyond traditional lab-based digestion studies. This approach links food design directly to human physiology, providing a scientific basis for creating and optimizing foods based on how they actually behave in the digestive system, not just in test tubes. **(21)**

- This approach opens the door to systematic, cross-disciplinary research on how the makeup of ingredients, processing methods, and structural changes affect nutrient release and absorption. It has strong potential for applications such as:
  • Personalized nutrition, for example tailored diets for children, the elderly, or patients with digestive issues.
  • Development of functional foods designed for controlled nutrient release or to increase feelings of fullness.
  • Clinical dietary strategies aimed at managing metabolic disorders or gastrointestinal problems. **(22)**

In conclusion, MT MRI is not just a new technique—it is a powerful tool that can advance nutritional science, gastrointestinal research, and the development of next-generation foods. With further refinement and wider use in clinical and nutritional studies, this imaging method has the potential to change how we assess and improve foods for human health. **(23)**

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