Unraveling Food Digestion -- Challenges and Opportunities for Food Scientists

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Food Chain

Farm to Fork

Drying

Physical Properties

Air-Impingement Systems

Freezing

Modified Atmosphere Packaging

Frying

Thawing

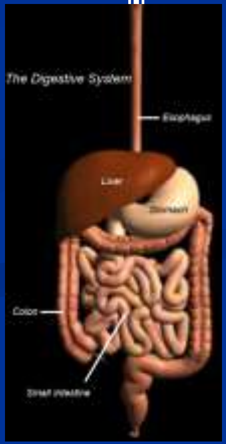
Grilling

Shelf life

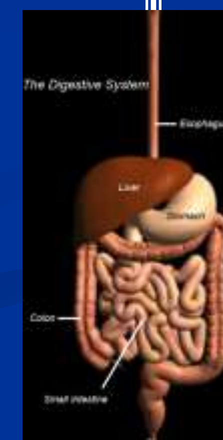
Time-Temperature Integrators

Water Use

Energy Accounting


The Digestive System
Liver
Colon

- Link between physical and material properties of foods and nutrient release from foods in the GI tract?



Food Matrix and Nutrient Bioavailability

Nutrient	Food	Matrix state	Bio-availability	Reference
β-carotene	Carrot	Raw	19-34%	Van het Hof et al. (2000)
	Carrot	Carrot Juice	70% higher than raw	Castenmiller et al (1999)

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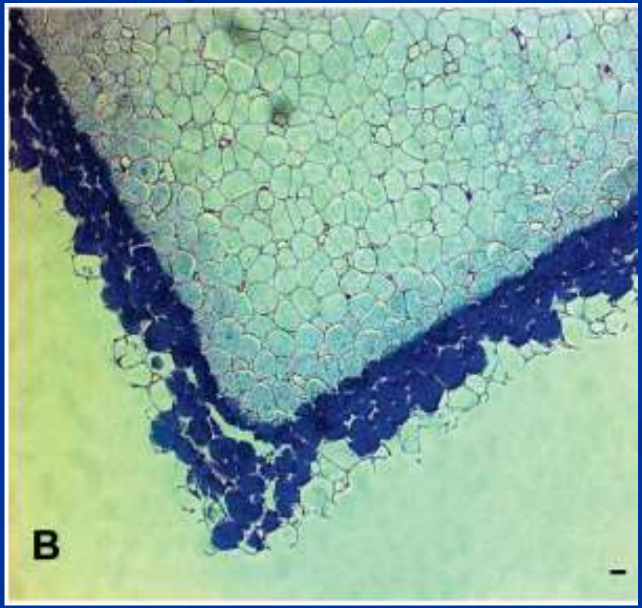
Lutein	Tomato	Tomato paste	22%-380% greater plasma response than fresh tomato	Van het Hof et al. (2000)

- Almonds are one of the richest sources of dietary vitamin E with benefits to reducing risk of CHD and certain cancers.
- Only about 45% of vitamin E was bioaccessible from powdered almonds.

Bioaccessibility

Proportion of a nutrient that can be released from a complex food matrix and potentially available for absorption in GI tract



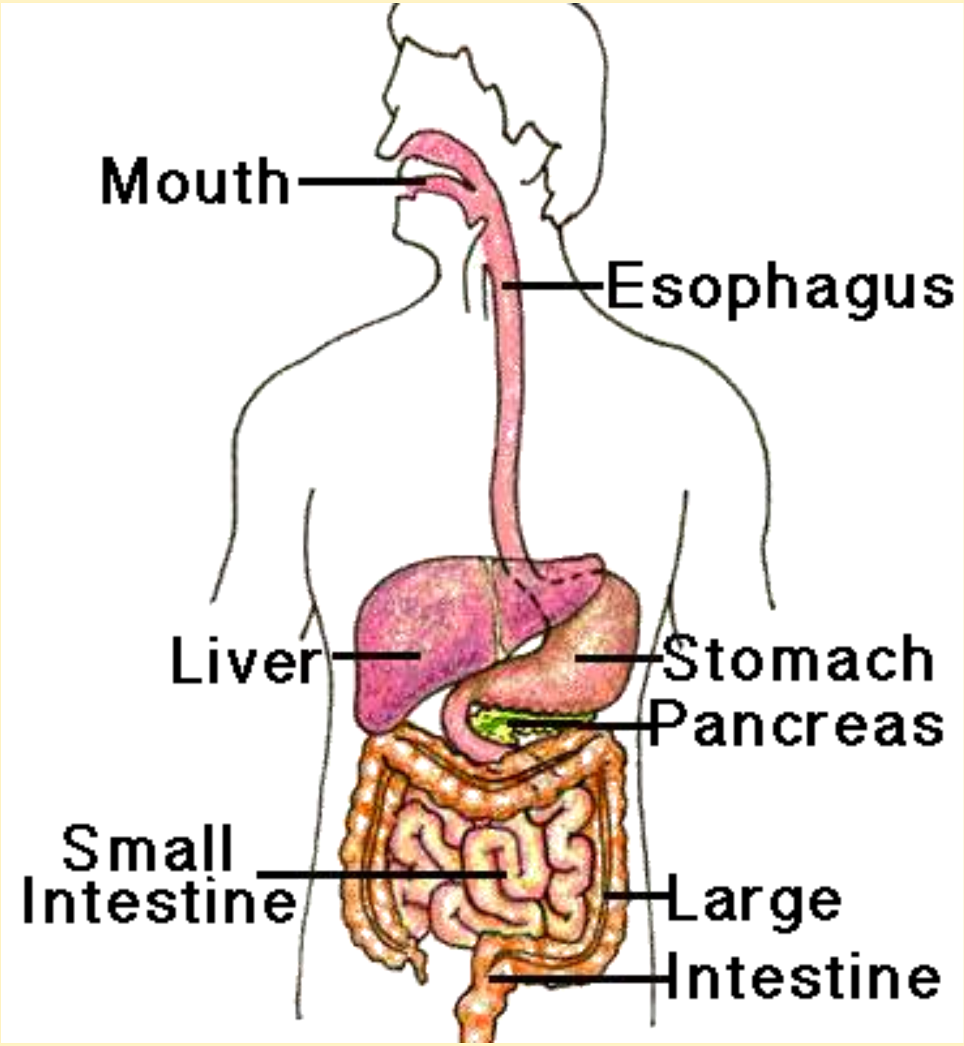
Samples obtained via ileostomy after 3.5 hr of digestion. Volunteers fed 2 mm cube raw almonds

Mandalari et al. (2008) J Ag Food Chem

Food Disintegration in the GI Tract

- Oral processing
- Gastric digestion

Digestion system



- The overall function
  - extract nutrients into useable form
  - absorb nutrients
  - eliminate unneeded materials
- Food takes between 24-36 hours to pass through the gastrointestinal tract

Solid Food Disintegration in the Stomach

-Stomach emptying

-Satiety, Obesity

-Nutrient release

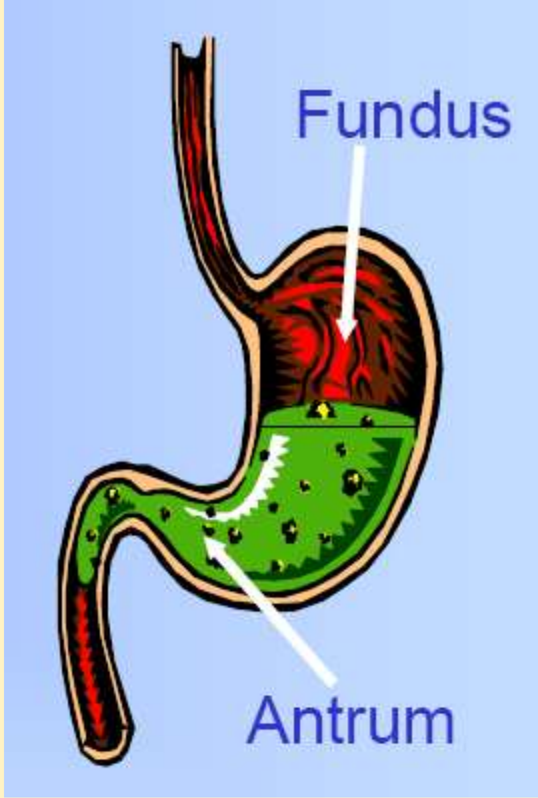
-Food safety:

- Allergens

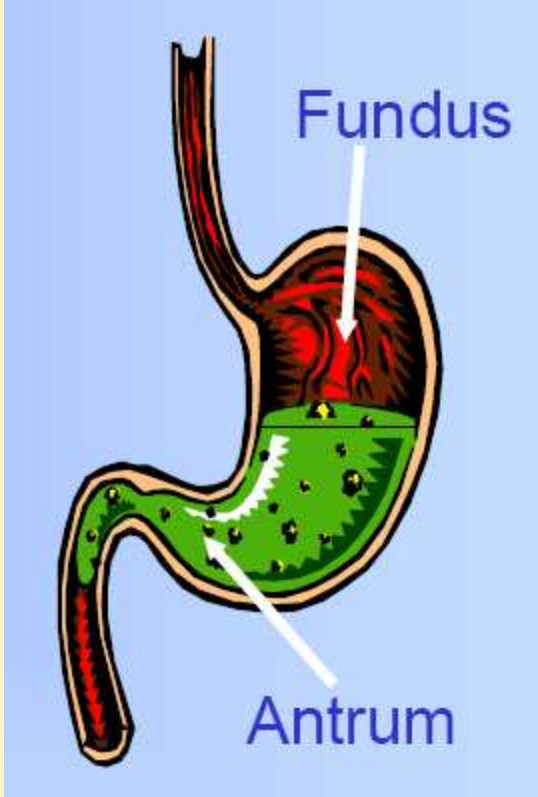
-Nanoparticles

Stomach

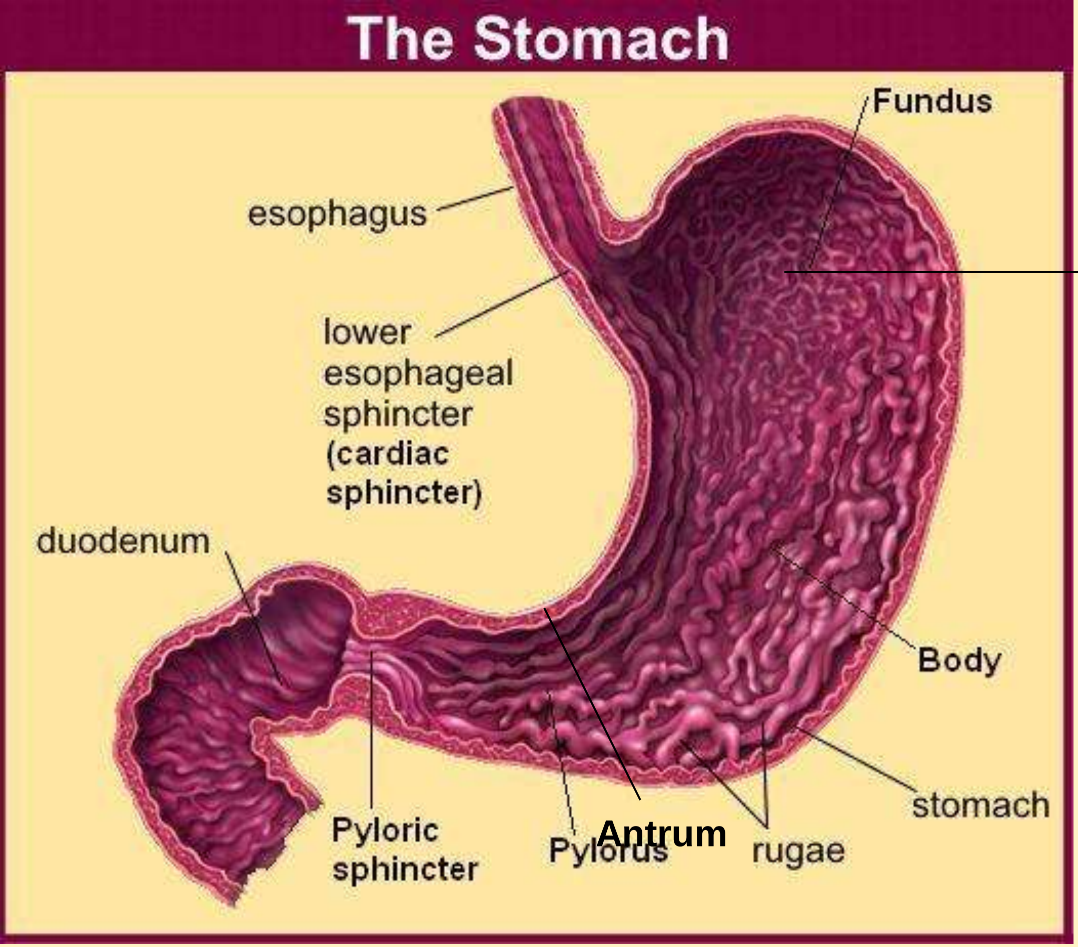
- Volume: 50ml to 4 liters of liquid
  - Chemical digestion by enzyme activity
  - Mechanical digestion by the mixing in the stomach

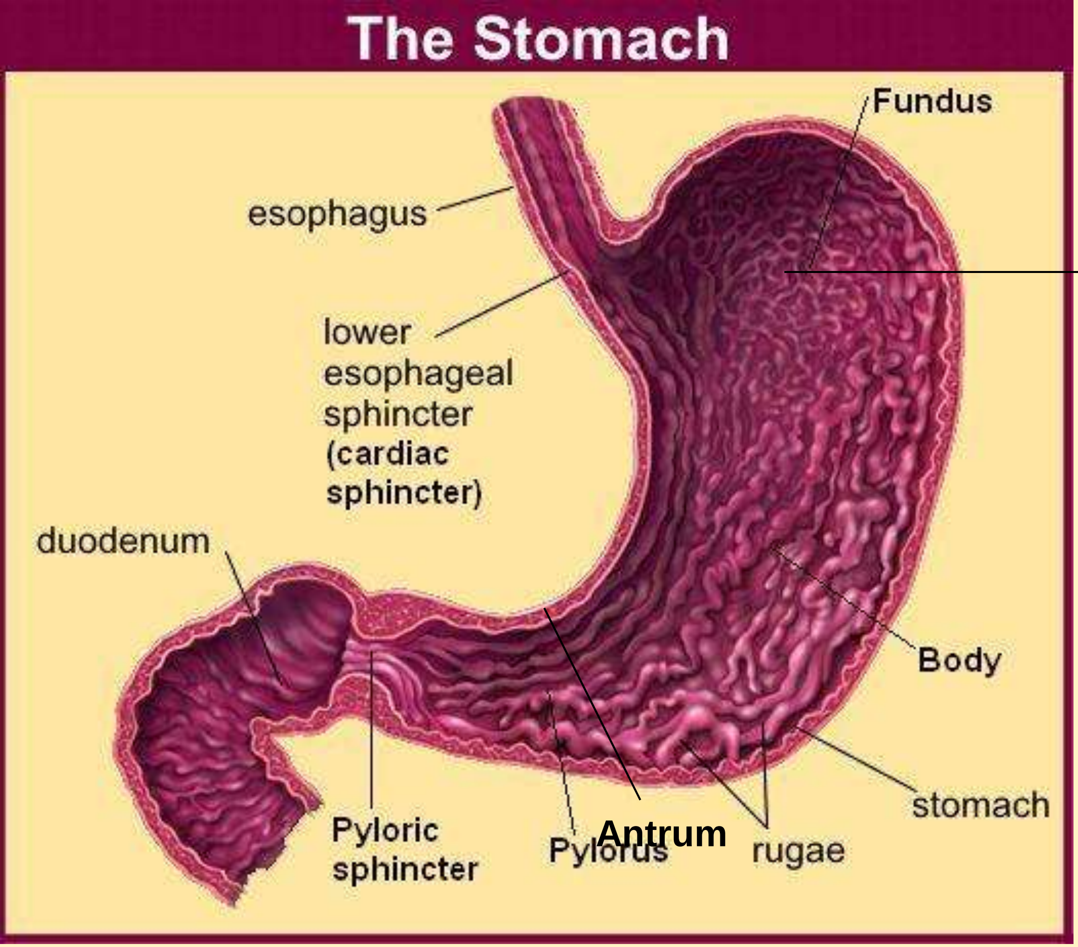


Stomach

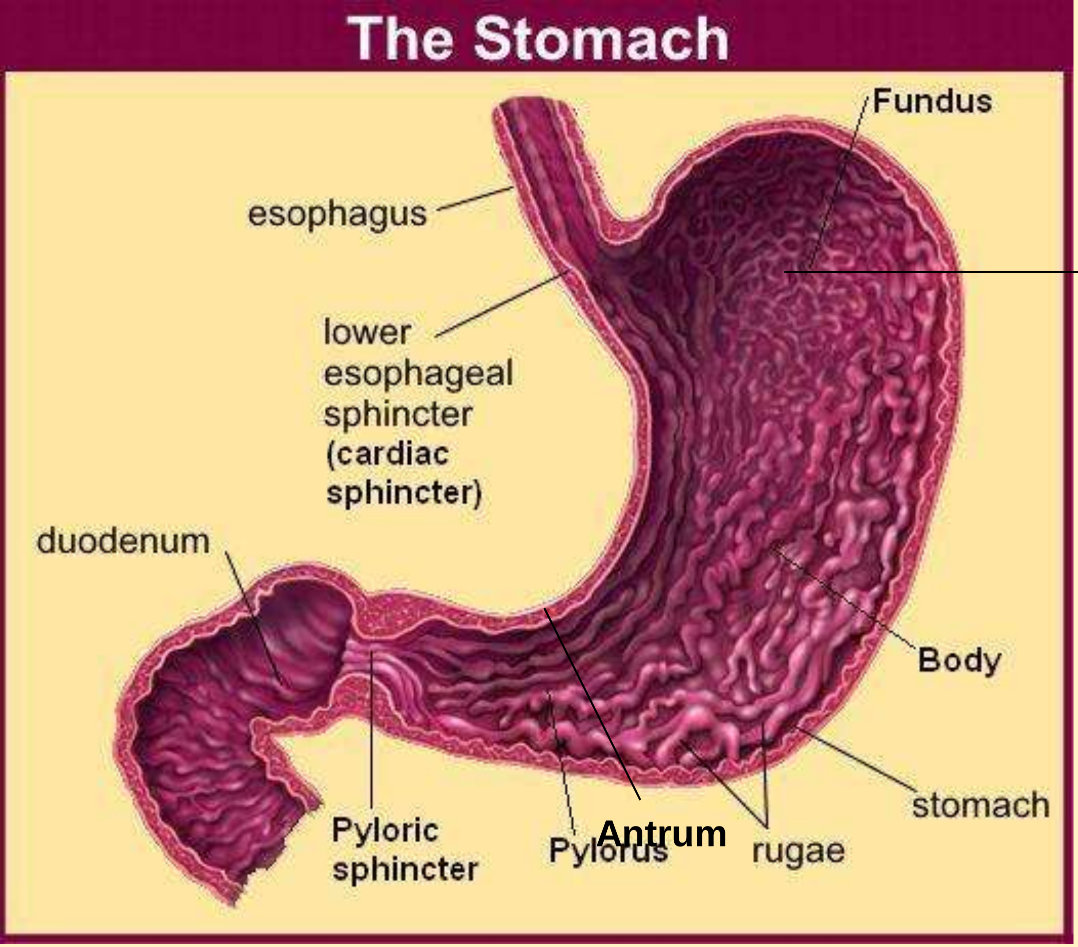


- Volume: 50ml to 4 liters of liquid
  - Chemical digestion by enzyme activity
  - Mechanical digestion by the mixing in the stomach
- Gastric juice: Colorless fluid
  - 1.5 L secreted/day
  - Hydrochloric acid
    - breaks the food apart and kills most of the bacteria that you swallow
  - Mucus (~1.5 g/L)
    - forms a gelatinous coating over the mucosal surface.
  - Pepsin (~ 1 g/L)
    - proteins broken down into smaller polypeptide chains
  - Salt, Gastric Lipase
    - fat digestion begins here

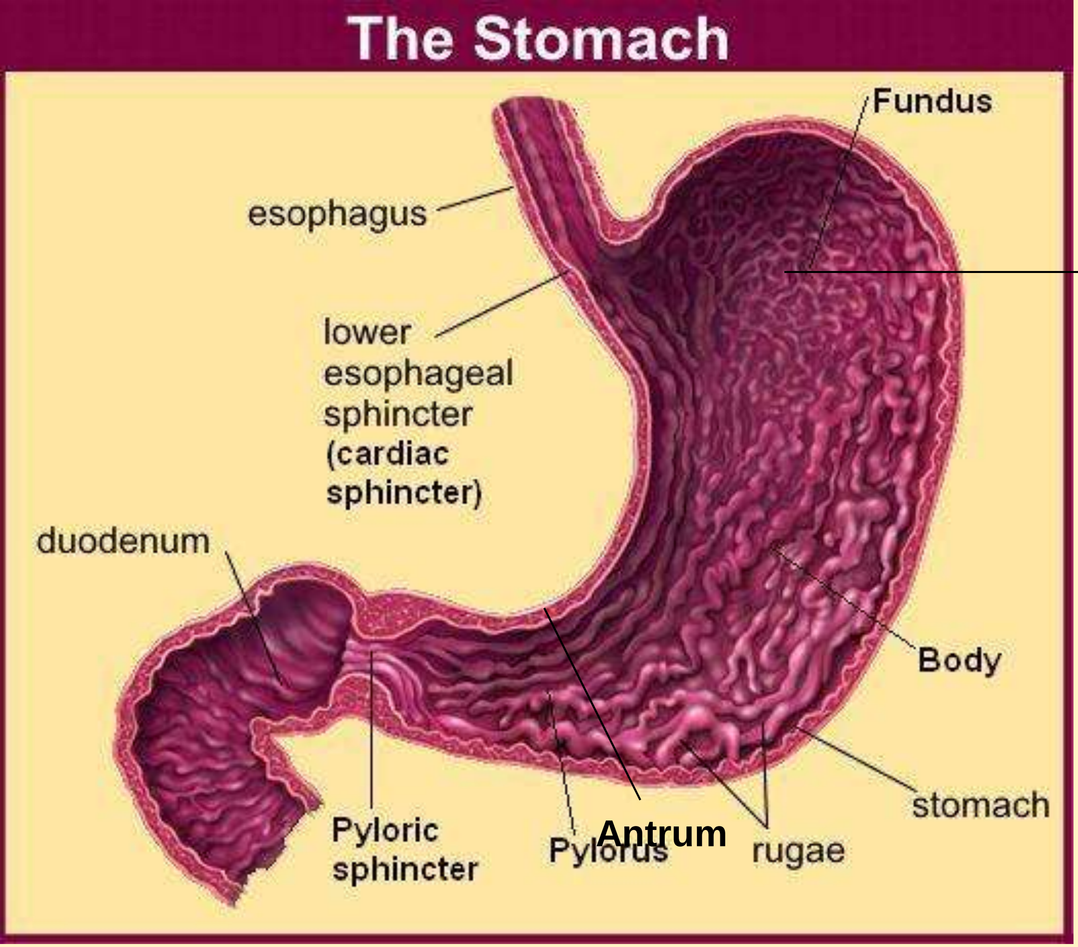

The Stomach
Fundus
esophagus
lower esophageal sphincter (cardiac sphincter)
duodenum
Body
stomach
Pyloric sphincter
Pylorus
Antrum
rugae



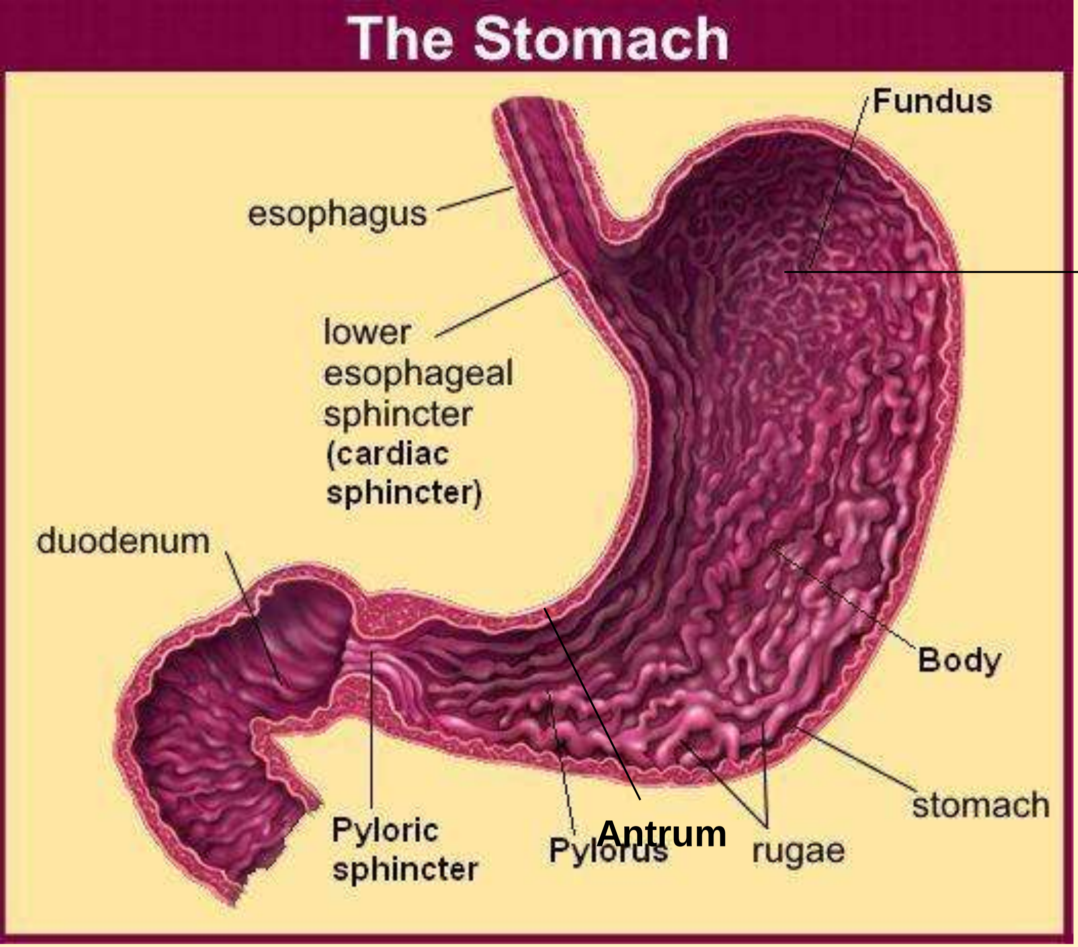
- Fundus: begins digestion of proteins and mixes together stomach contents.



- Fundus: begins digestion of proteins and mixes together stomach contents.
- Body: digests proteins and blends materials in stomach and reduced to a paste



- Fundus: begins digestion of proteins and mixes together stomach contents.
- Body: digests proteins and blends materials in stomach and reduced to a paste
- Antrum: Breaks down large food material into small particles



- Fundus: begins digestion of proteins and mixes together stomach contents.
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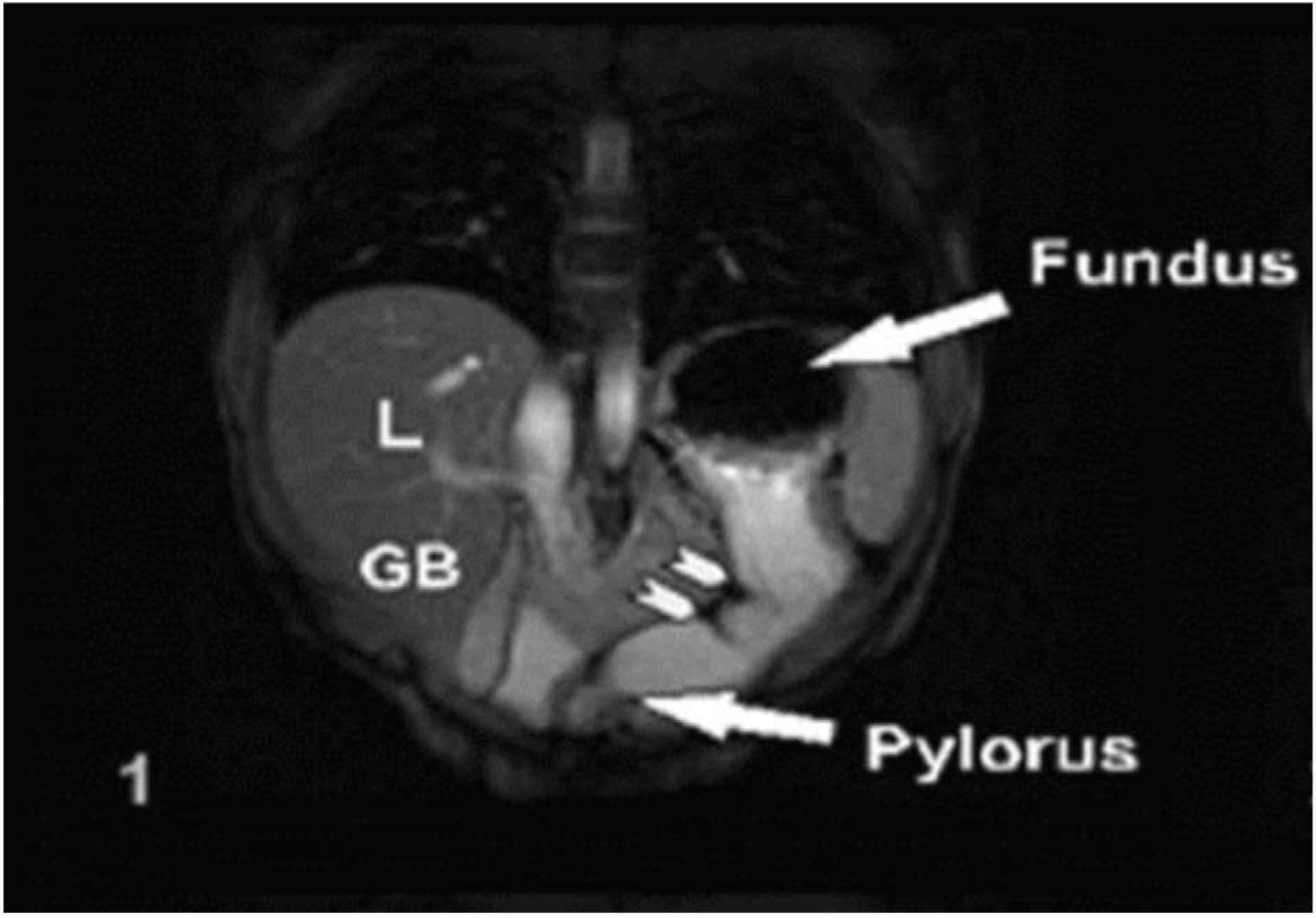
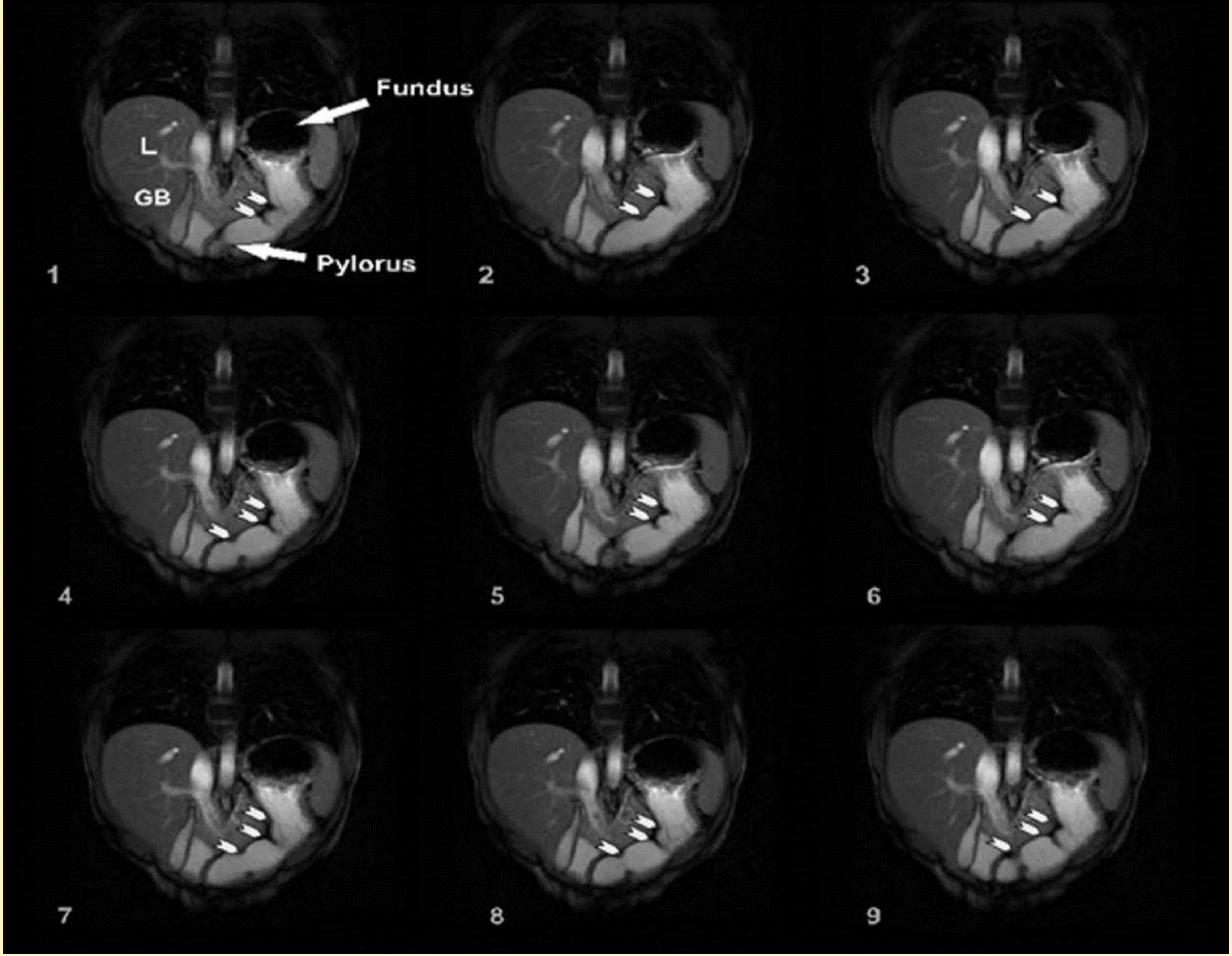
- Pyloric sphincter: a specialized valve that selectively empties the small particles and retains the large

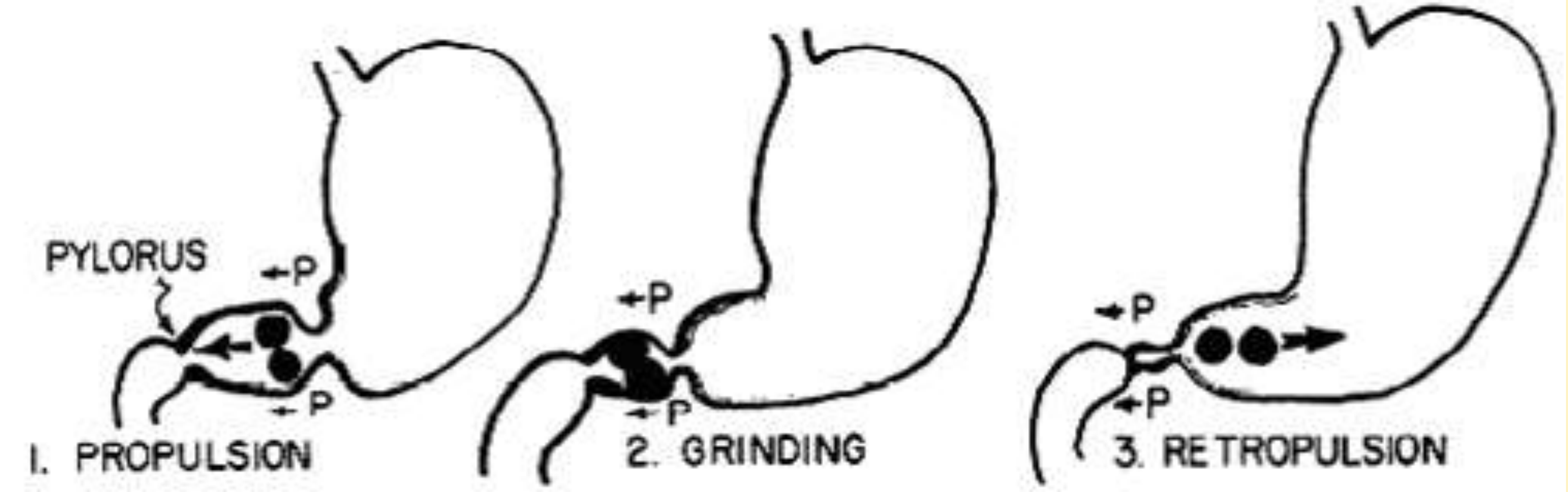


Fundus
L
GB
Pylorus
1



Dynamic MRI image series showing propagating antral contraction waves (small arrows) displayed in time intervals of 10 s. (Schwizer and others 2006)

Antral contraction of stomach



Propulsion, grinding, and **retropulsion** of solids by peristaltic contractions of distal stomach (Kelly 1980)

- From an engineering perspective, the human stomach is a receptacle, a grinder, a mixer and a pump that controls the digestion process.

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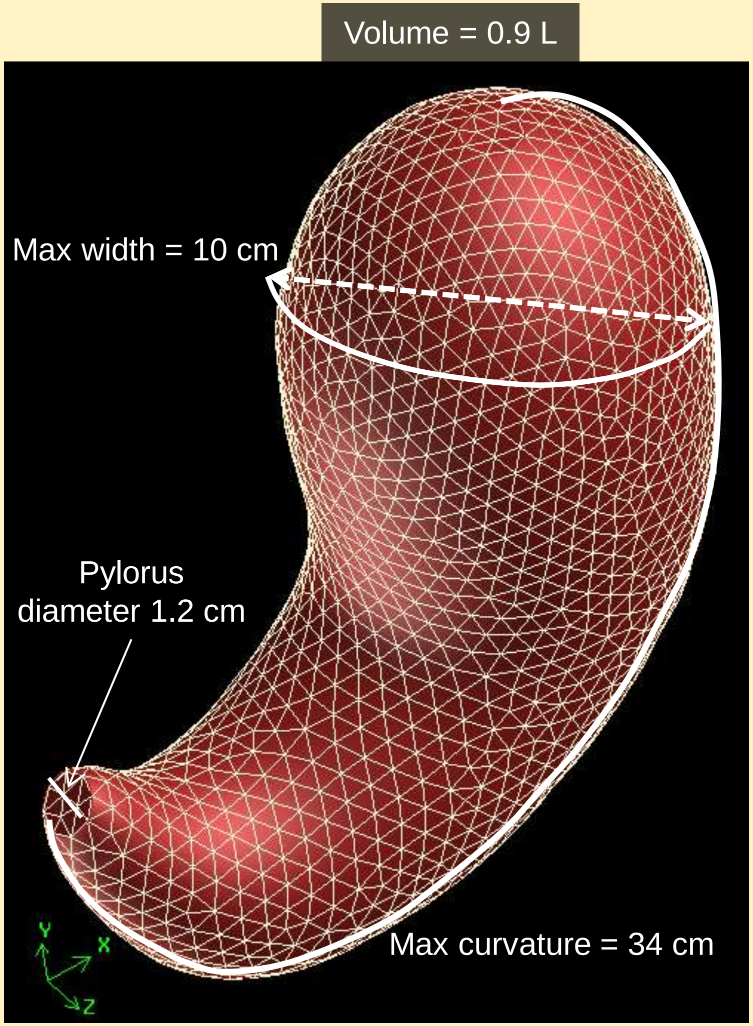
- Consider stomach to be a flexible wall reactor, with peristaltic wall motility.

- From an engineering perspective, the human stomach is a receptacle, a grinder, a mixer and a pump that controls the digestion process.
- Food enters the stomach through the oesophagus as a bolus
- Bolus disintegration ?
- Solid particulate disintegration ?

Develop a realistic computer-aided model of the human stomach and study flow characteristics and solid disintegration

3D MODEL-AVERAGE SIZED HUMAN STOMACH

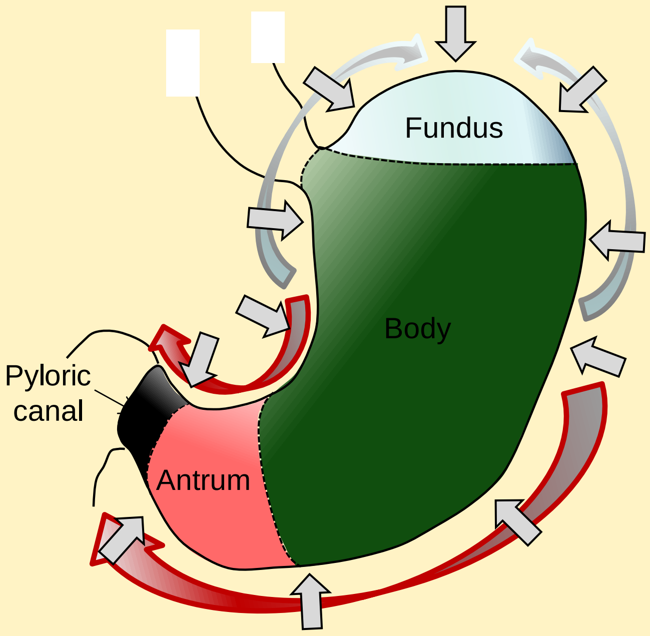
- Average dimensions*
  - Greater curvature ≈ 31 cm long.
  - 15 cm wide (at its widest point).
  - Pylorus’ diameter is ≈ 1 cm.
  - Stomach’s capacity is about 0.94 L.



* Keet, 1993; Schulze, 2006.

GASTRIC MOTILITY

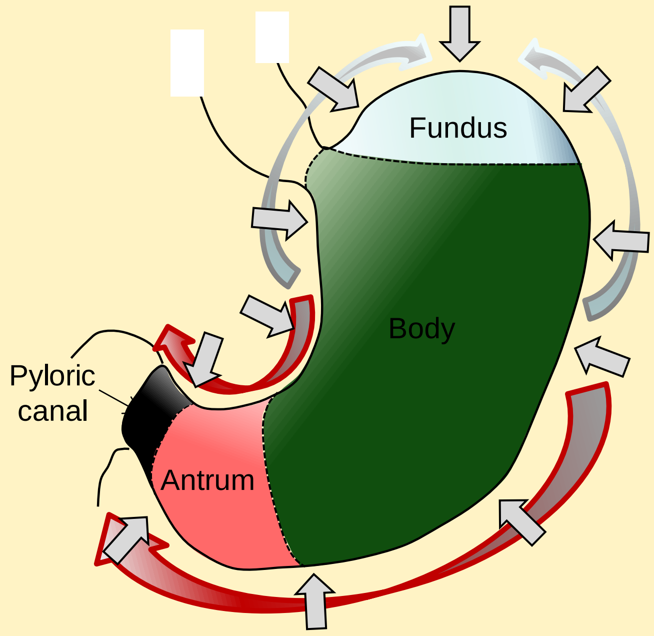
- The motility of the stomach wall can be characterized by three types of muscle contractions.
  - Slow and weak contractions that originate and develop in the upper part of the stomach.
  - A series of regular-peristaltic contraction waves (ACWs) that originate in the middle of the stomach, and propagate towards the pylorus.
  - A tonic contraction of the entire gastric wall that allows the stomach to accommodate itself to varying volumes.



GASTRIC MOTILITY

- Despite recent advances in imaging technologies, the motility pattern of the gastric wall is still poorly characterized.

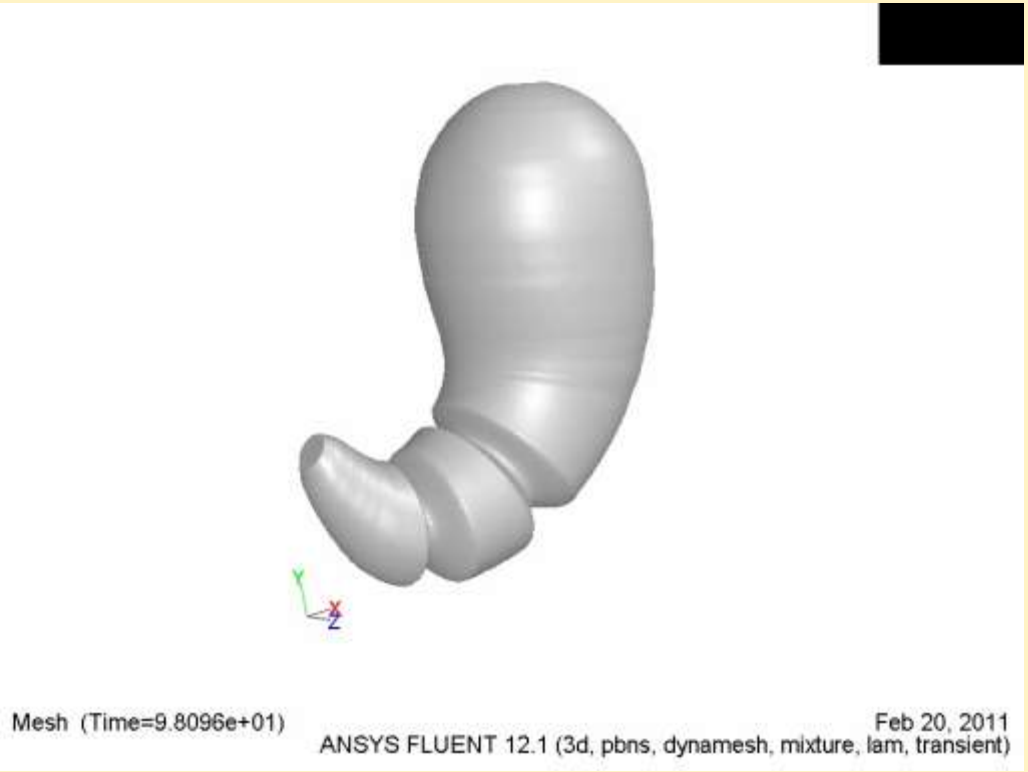
- The dynamics of ACWs is the only motor activity experimentally characterized.
  - By using MRI techniques, the motility of ACWs was tracked during 20 minutes after the ingestion of 500ml of a 10% glucose solution (Pal et al., 2007).

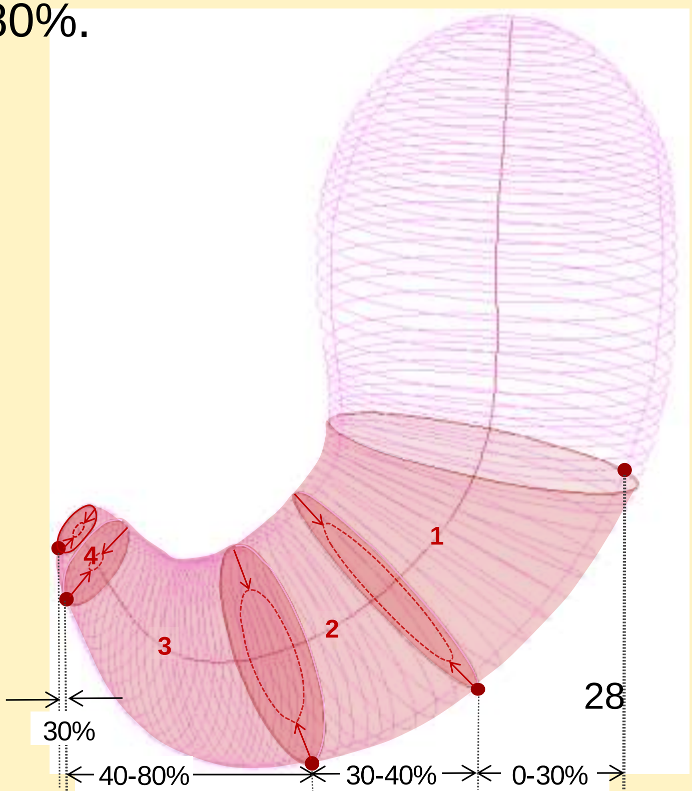


GASTRIC MOTILITY DURING DIGESTION

ACW dynamics:

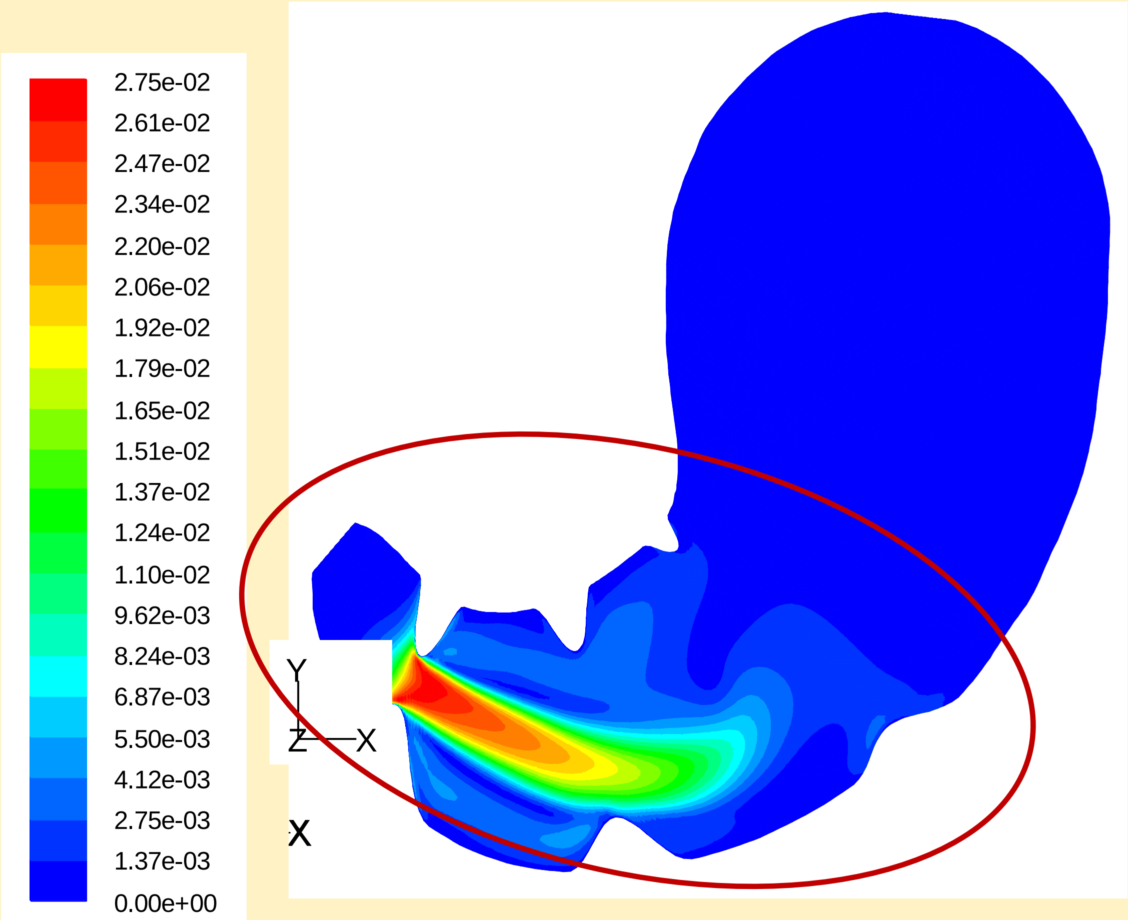
- Initiated every 20s at 15cm from the pylorus.
- Relative occlusion of ACWs: from 0 to 80%.





FLUID MOTIONS IN THE STOMACH

- The strongest fluid motions were predicted within the lower part of the stomach model.
- The rheological properties of gastric contents has a significant effect on the behavior of the antropyloric flow.



Velocity Magnitude (m/s)

RHEOLOGICAL PROPERTIES OF GASTRIC CONTENTS

- Fluid-dynamics of three different liquid meals were investigated.

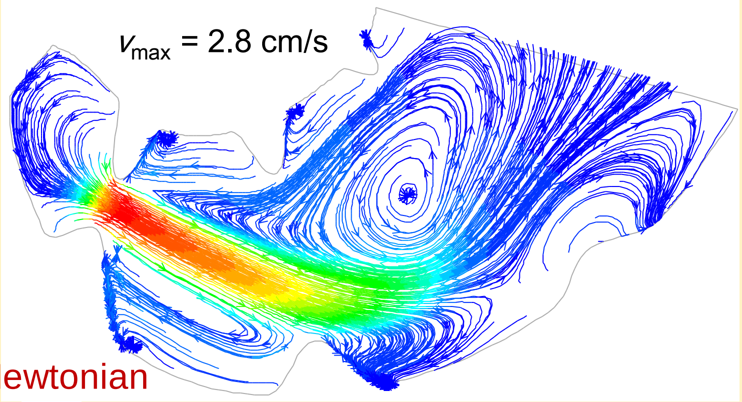
  – Newtonian fluid ($\tau = \mu \gamma$).
    - Water: μ =1 cP.

  – Newtonian fluid ($\tau = \mu \gamma$).
    - Honey: μ =1000 cP.

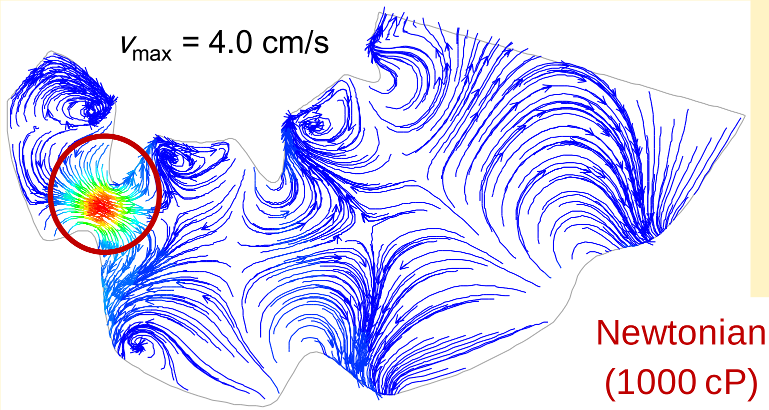
  – Non-Newtonian ($\tau = K \gamma n$).
    - Tomato juice (5.8 %):
      $K = 0.223\ Pa.s^n$
      $n = 0.59$.

ANTROPYLORIC FLOW MOTION

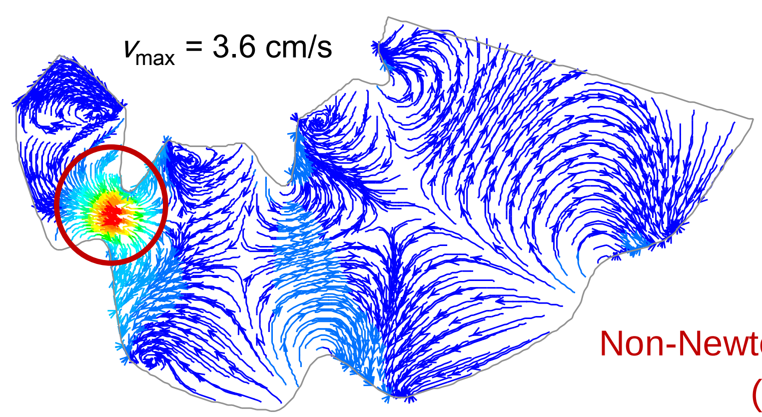
- Effect of viscosity on the formation of the retropulsive jet-like structure.



Newtonian
(1 cP)



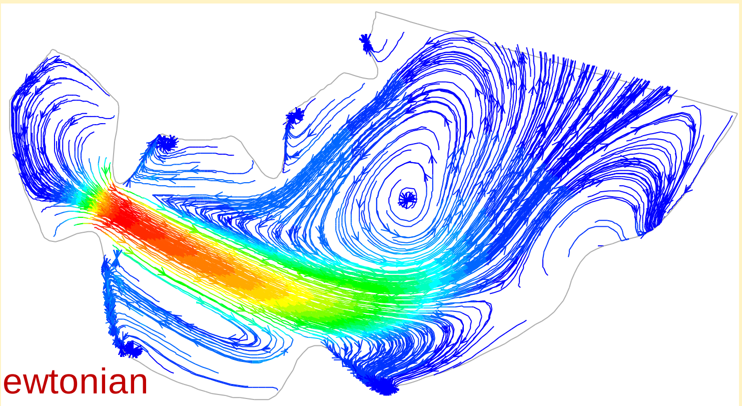
Newtonian
(1000 cP)



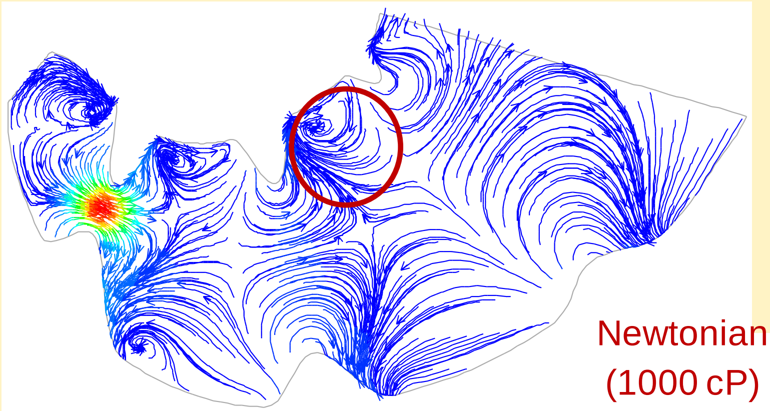
Non-Newtonian-shear thinning
(40-570 cP)

- No retropulsive jet-like structure developed.
- Higher and more localized retropulsive velocities were predicted at the peak of the ACW.

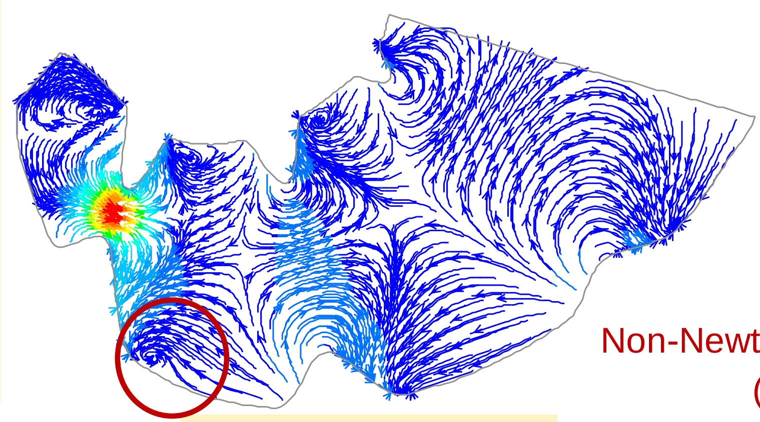
- Effect of viscosity on the formation of eddy structures.



Newtonian
(1 cP)



Newtonian
(1000 cP)

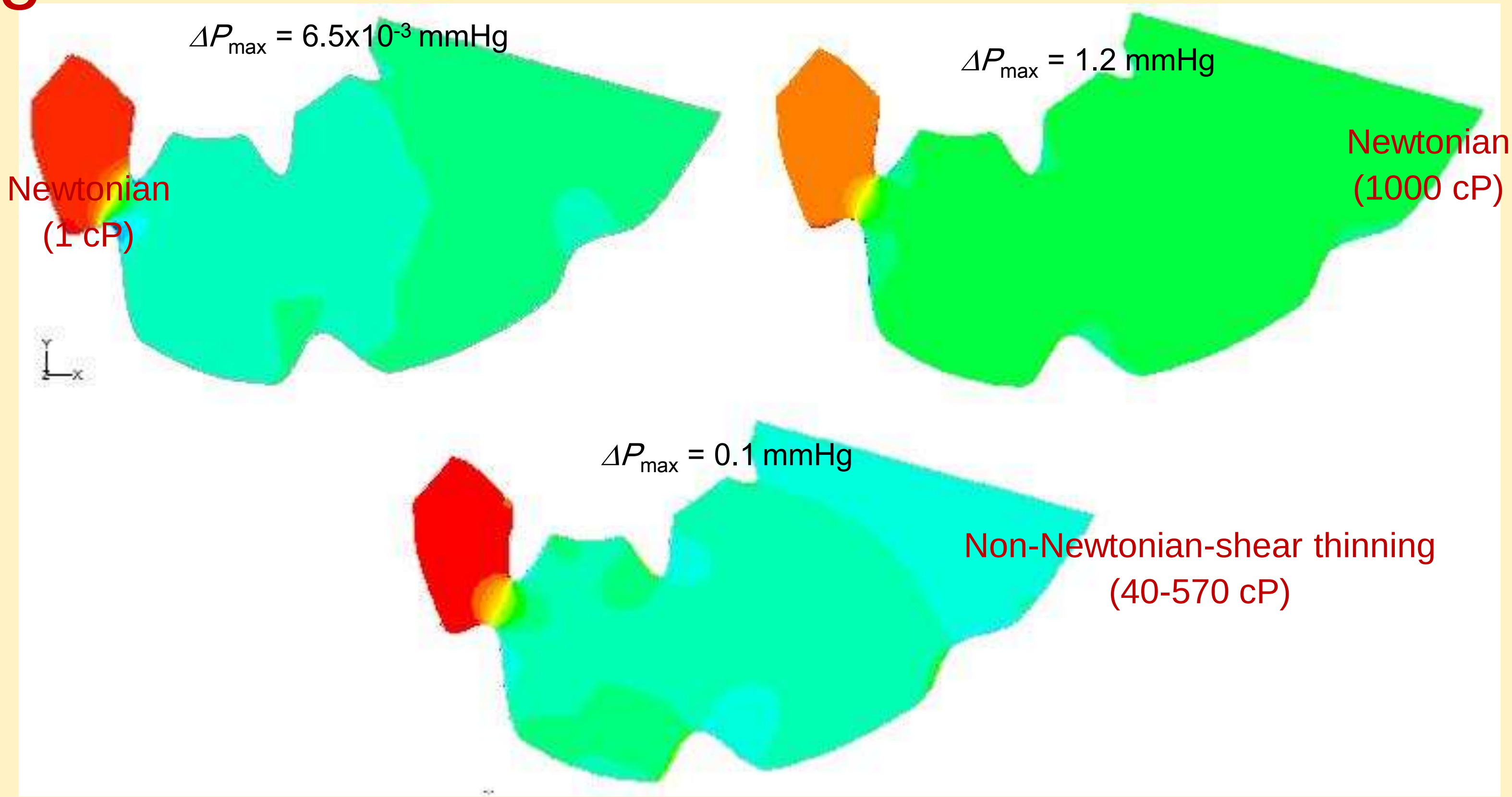


Non-Newtonian-shear thinning
(40-570 cP)

- Eddy structures are confined to smaller regions closer to the gastric walls.

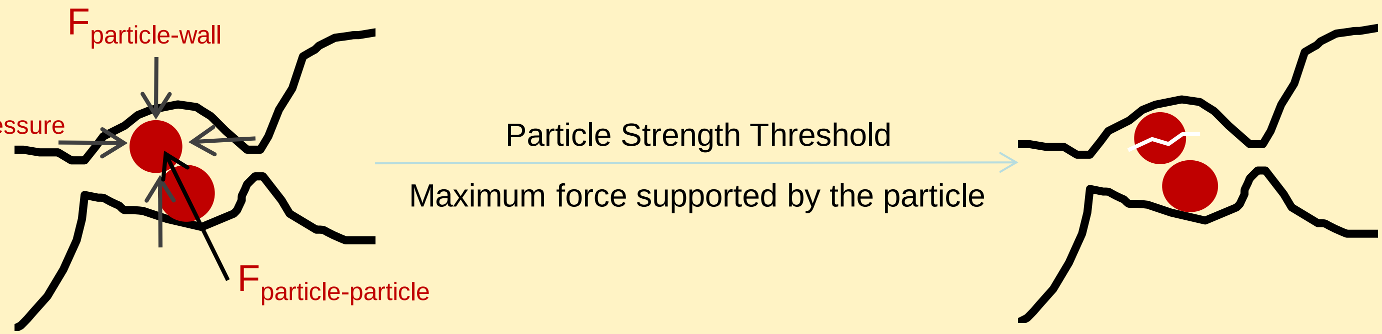
RESULTS: VISCOSITY AND LUMINAL PRESSURE

- Effect of viscosity on the pressure gradients within the stomach.



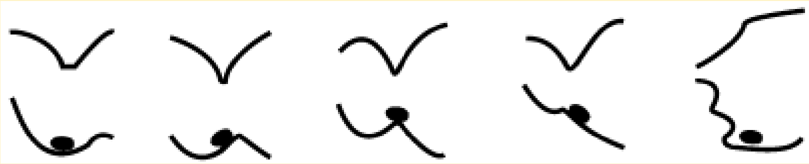
VISCOSITY AND LUMINAL PRESSURE

- The higher pressures that develop within the stomach, may improve the mechanical digestion of solid meals by:
  - Improving the mechanical breakdown of food particles.
  - Increasing the distension of the antral wall (i.e. by modifying the motility pattern of the stomach wall).



PARTICLE MOTION - NEWTONIAN 1cP

- These results are in good agreement with experimental data obtained using real-time ultrasonography.
  - Brown et al. (1993) tracked the motion of solid particles associated with the ingestion of 500 mL of clear chicken broth with five 5 garbanzo beans cut in half.



Shuttling of particles by antral contractions (Review article)- Schulze, 2006.

"…immediately after ingestion of the test meal, the beans, which were heavier than the surrounding liquid, were retained in the dependent portion of the stomach."

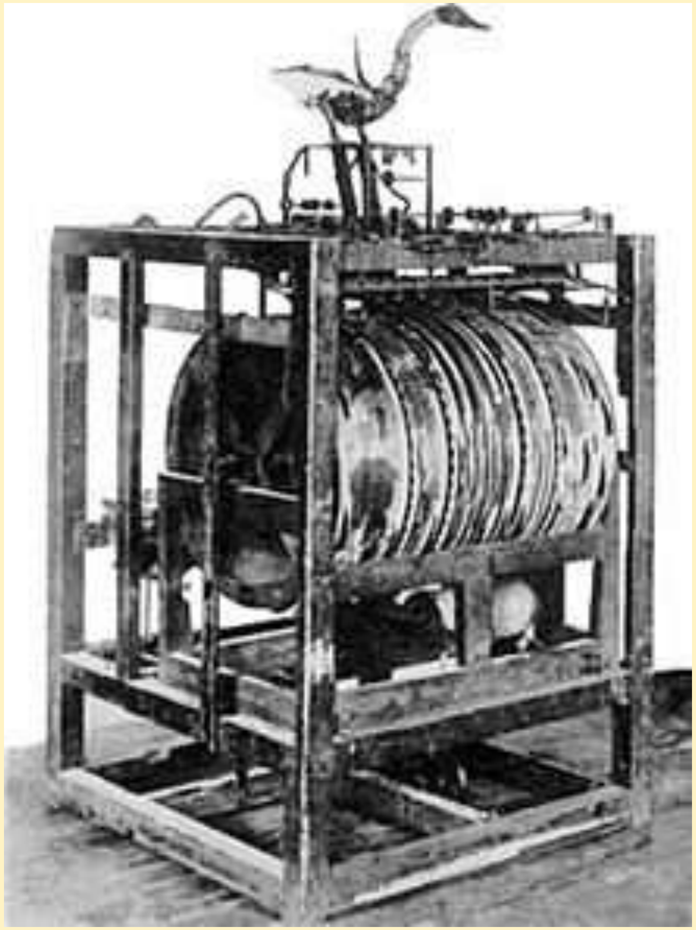
"…liquid passed over the beans which, for the most part, were retained along the gastric greater curve in the gastric sinus."

Brown et al., 1993.

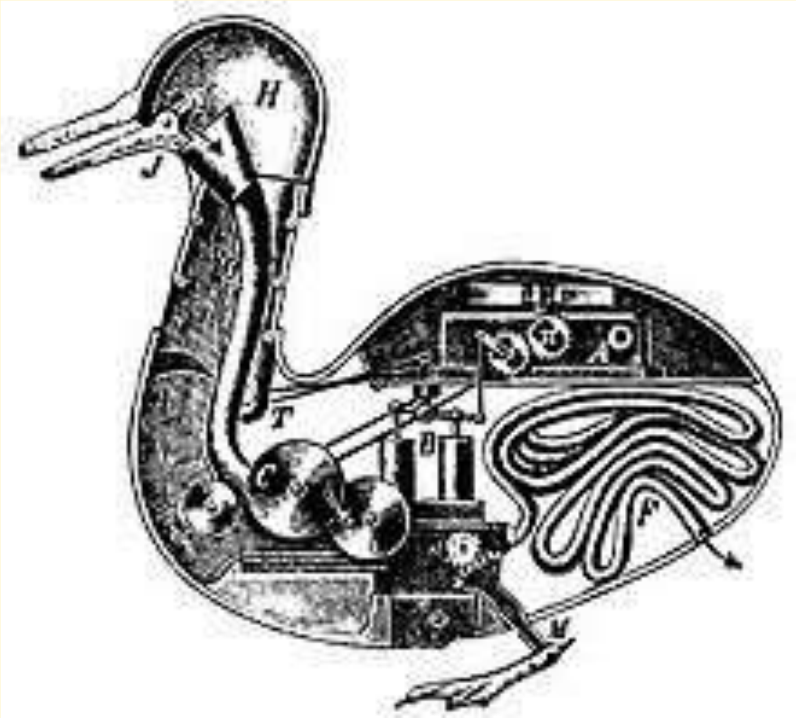
In vitro Systems

- To study food disintegration and digestion

Canard Digerateur
Jacques de Vaucanson, 1739



The Digesting Duck

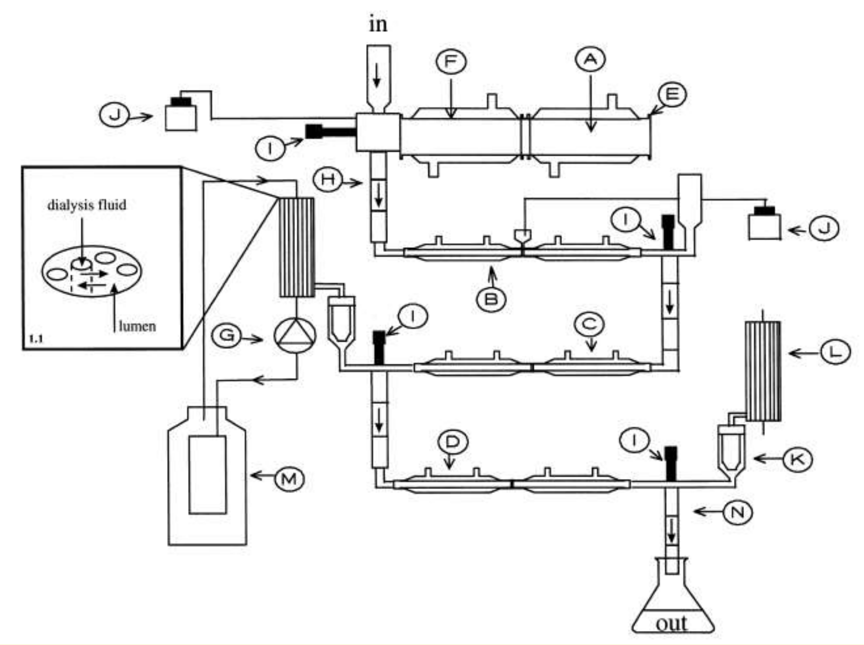


Voltaire wrote that "without...the duck of Vaucanson, you will have nothing to remind you of the glory of France."
(*"Sans...le canard de Vaucanson vous n'auriez rien qui fit ressouvenir de la gloire de la France."*)

TNO intestinal model (TIM)

Stomach

pH electrode

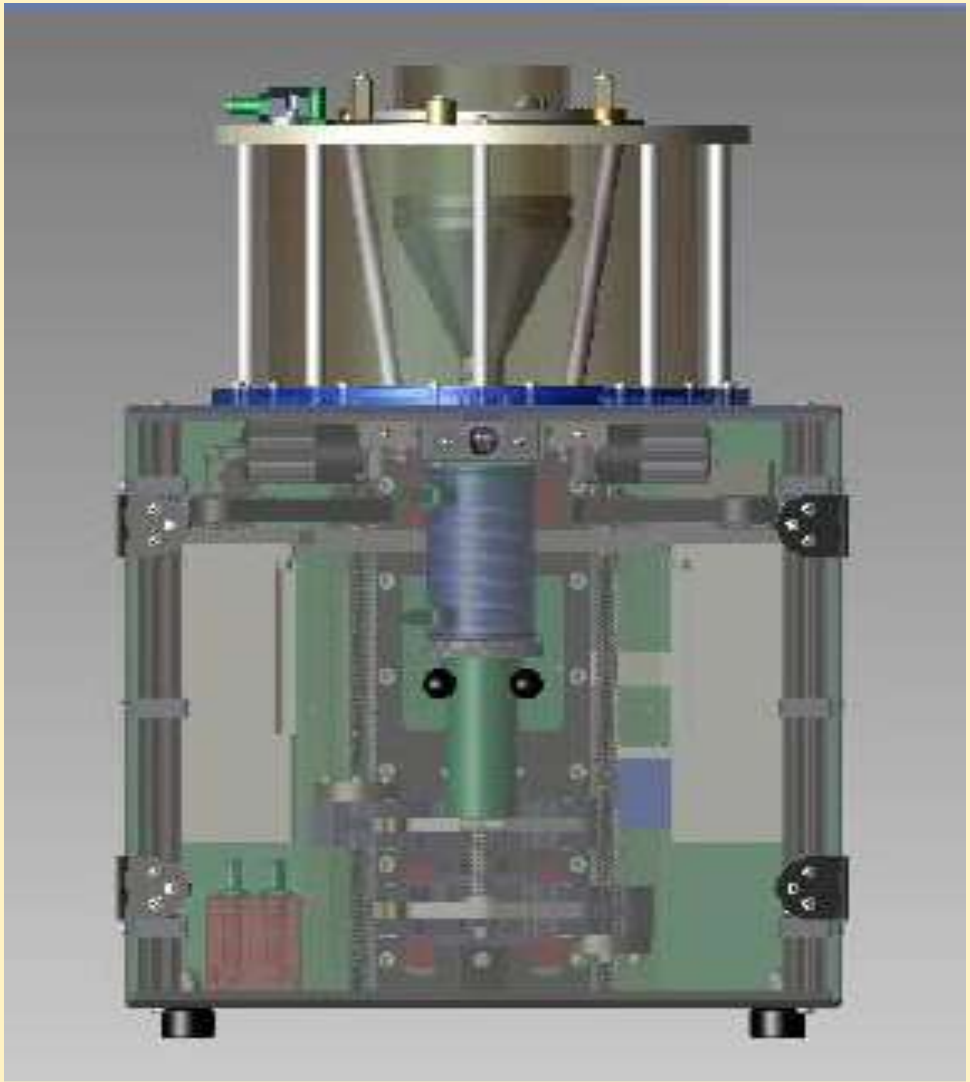


Hollow fiber membranes simulating the absorption

Intestine

TNO Nutrition and Food Research (Zeist, The Netherlands)

The model gut



Institute of Food Research,
Norwich Research Park, Colney,
Norwich NR4 7UA, UK

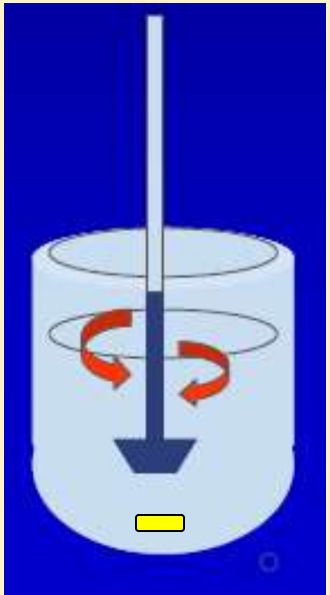
Needs in Pharmaceutical research

- "... *mechanical functions of stomach and duodenum are well defined in terms of viscoelastic properties, movement patterns of their walls….flow phenomenon to digestion remains to be established…contribution of pressure forces, shear stresses, flow reversals and vortical flow remains to be quantified*."

Schulze (2006)

In Vitro Dissolution Testing of Oral Dosage Forms: USP apparatus

- Apparatus 1 - Basket (37º)
- Apparatus 2 - Paddle (37º)
- Apparatus 3 - Reciprocating Cylinder (37º)
- Apparatus 4 - Flow-Through Cell (37º)
- 500 ml –1000 ml (900 ml)
- Agitation speed: 50-100 rpm for basket method, and 25-75 rpm for paddle method.
- Aqueous dissolution medium composed of 0.1 N HCl (or pH 1.2)



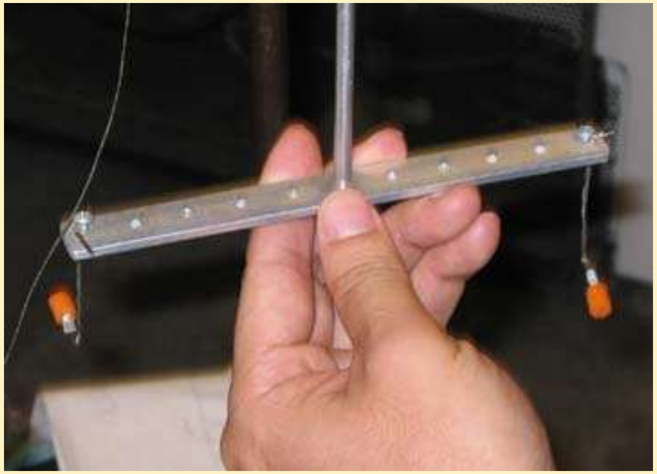
Food Disintegration System

- Food Disintegration system
  - Custom-built turntable
  - Glass chamber
  - Stainless steel annular container
  - Force measuring apparatus
- Useful in studying dissolution and disintegration kinetics of individual food particulates

Food Disintegration System

GP-22 ABS plastic
beads (~3 mm dia)

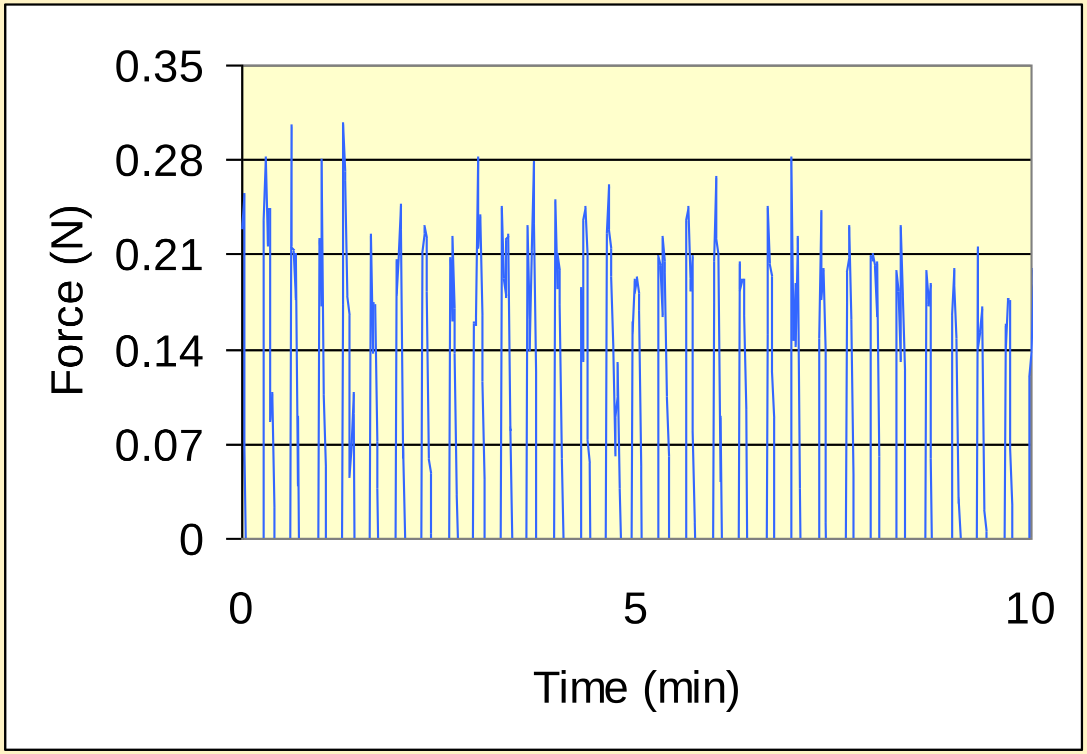
- Custom-built turntable
- Jacketed glass chamber
- On-line Force measuring apparatus



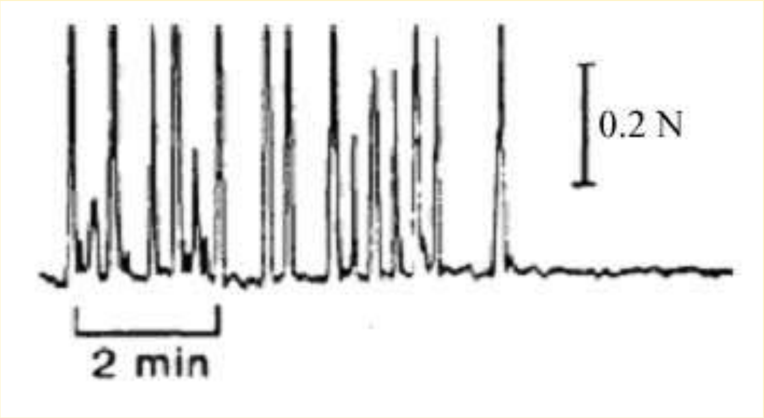
Sample holder

Kong and Singh (2008) *J Food Sci*

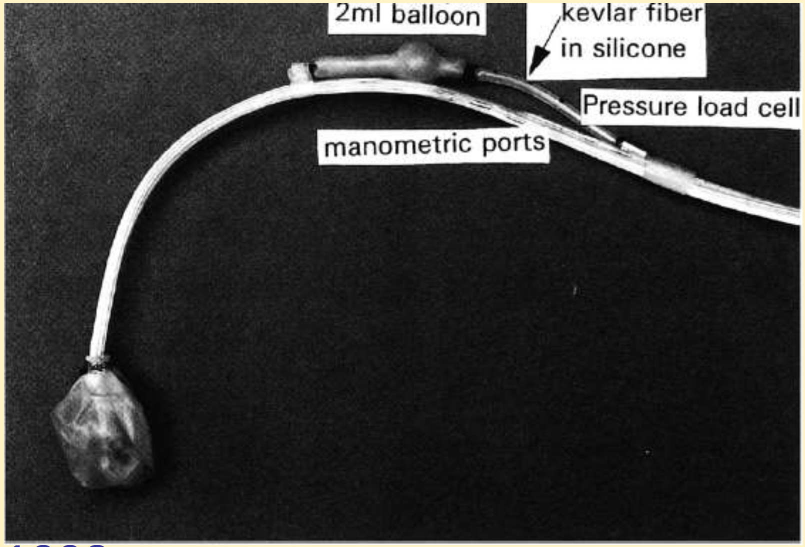
Profile of periodic force



In vitro

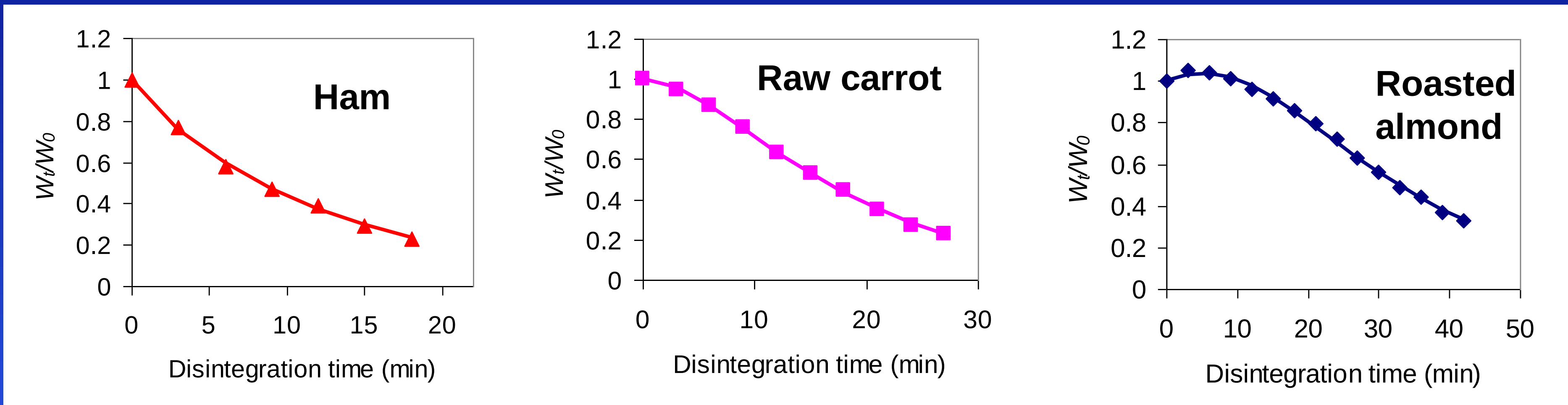


In vivo

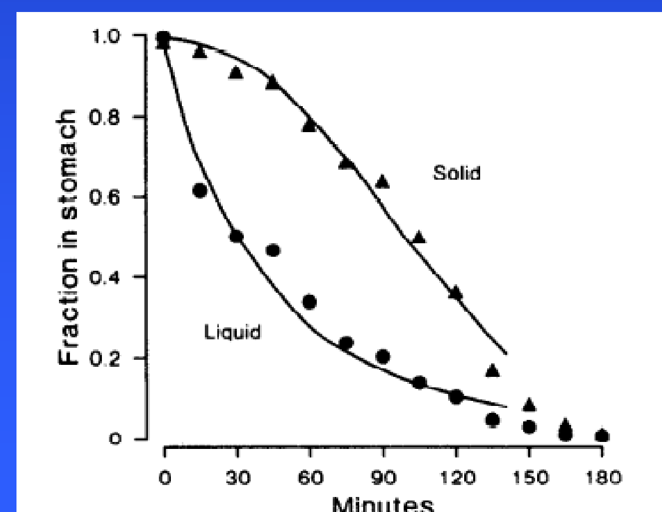


Vassallo MJ, et al. 1992.

Typical disintegration profiles



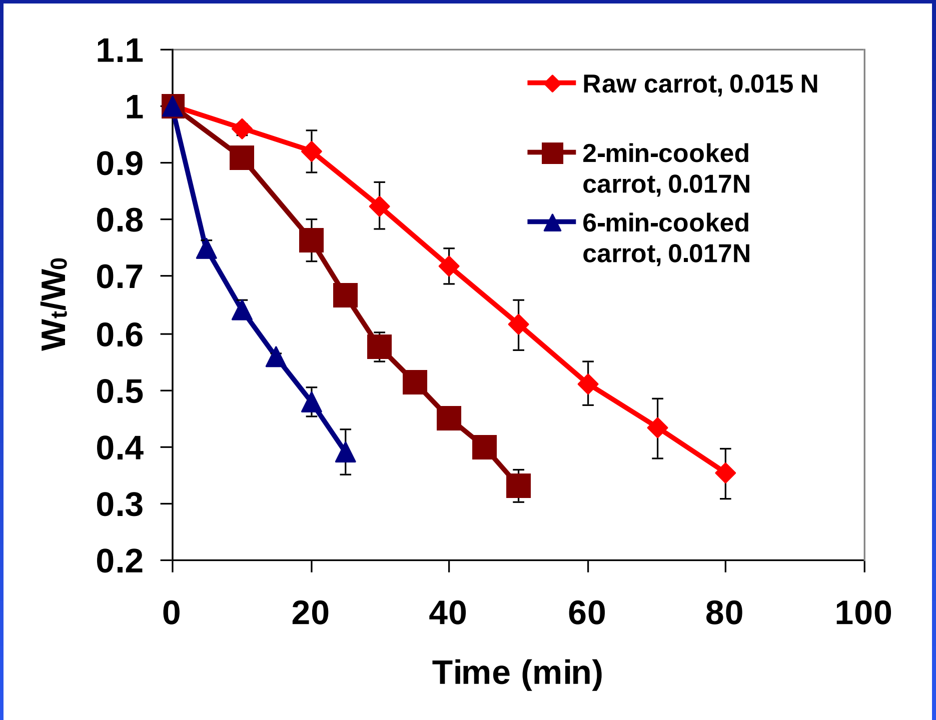
- Exponential: canned kidney beans, ham, Gummy bear candy, apple bar
- Sigmoidal: fruits such as raw carrots
- Delayed sigmoidal: dry foods such as peanuts, almonds, fried dough products



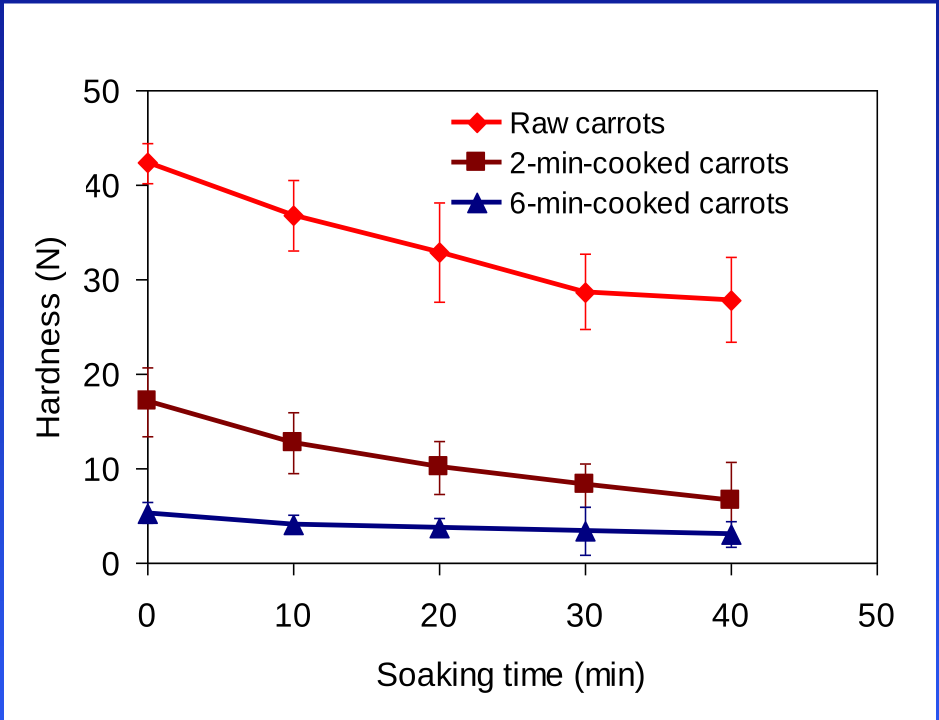
In vivo stomach emptying curves from scintigraphy data

(Camilleri et al. Am J Physiol 249: G580–G585.)

Carrot disintegration



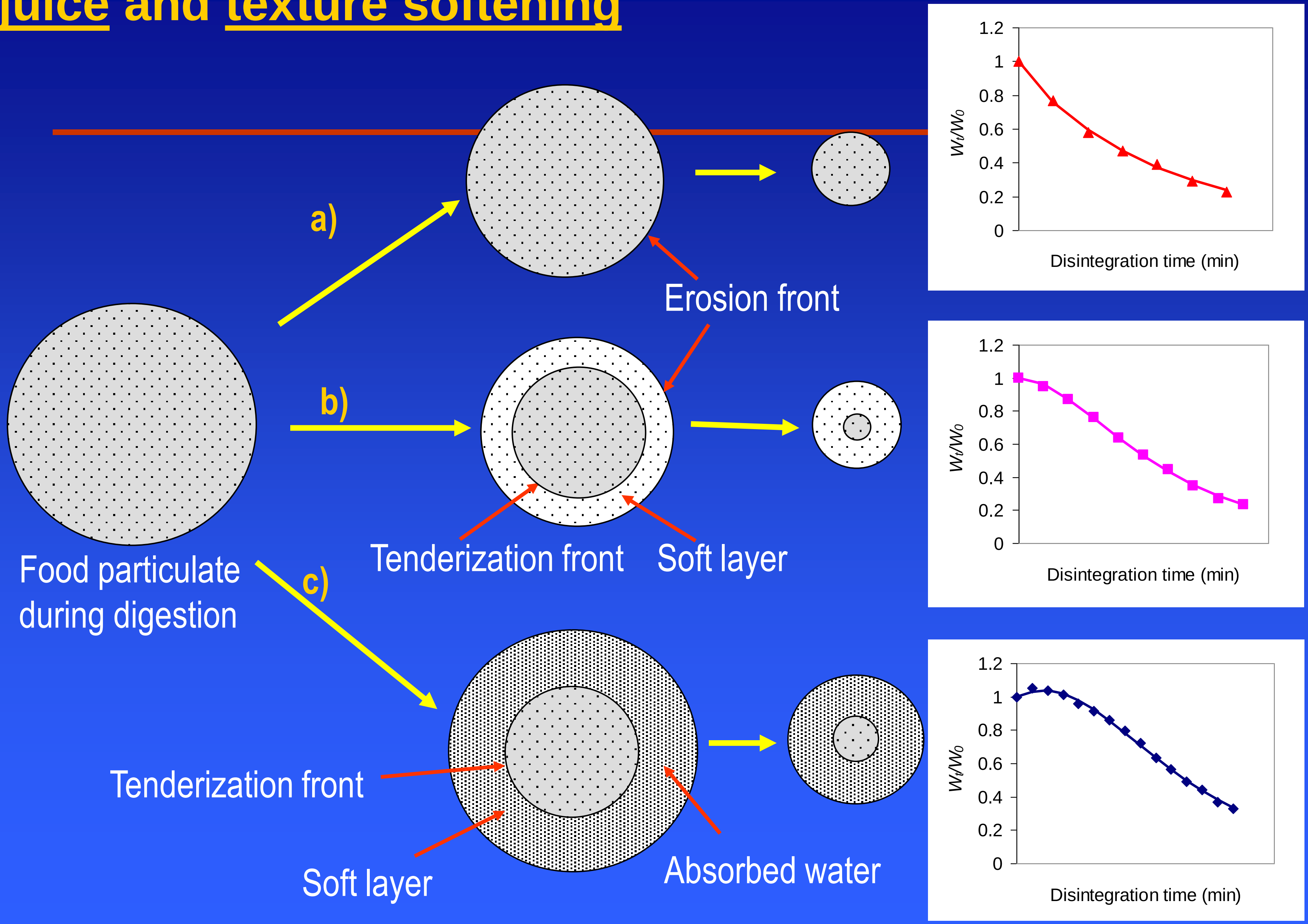
Disintegration profiles of carrot (n=6)



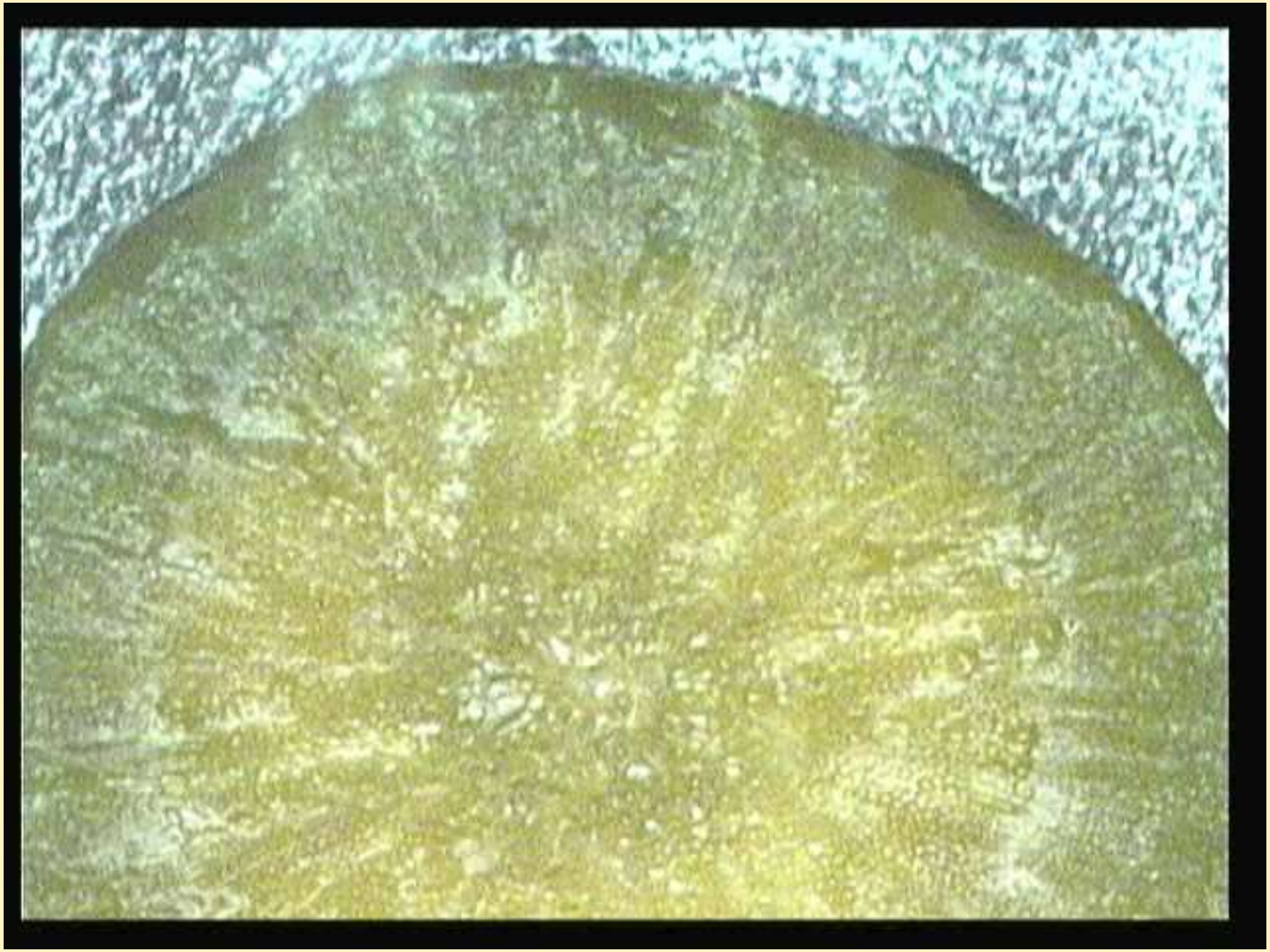
Hardness of carrot in gastric juice (n=8)

- The different profiles are a result of competition among surface erosion, texture softening and absorption of gastric juice

Simultaneous surface erosion, absorption of gastric juice and texture softening

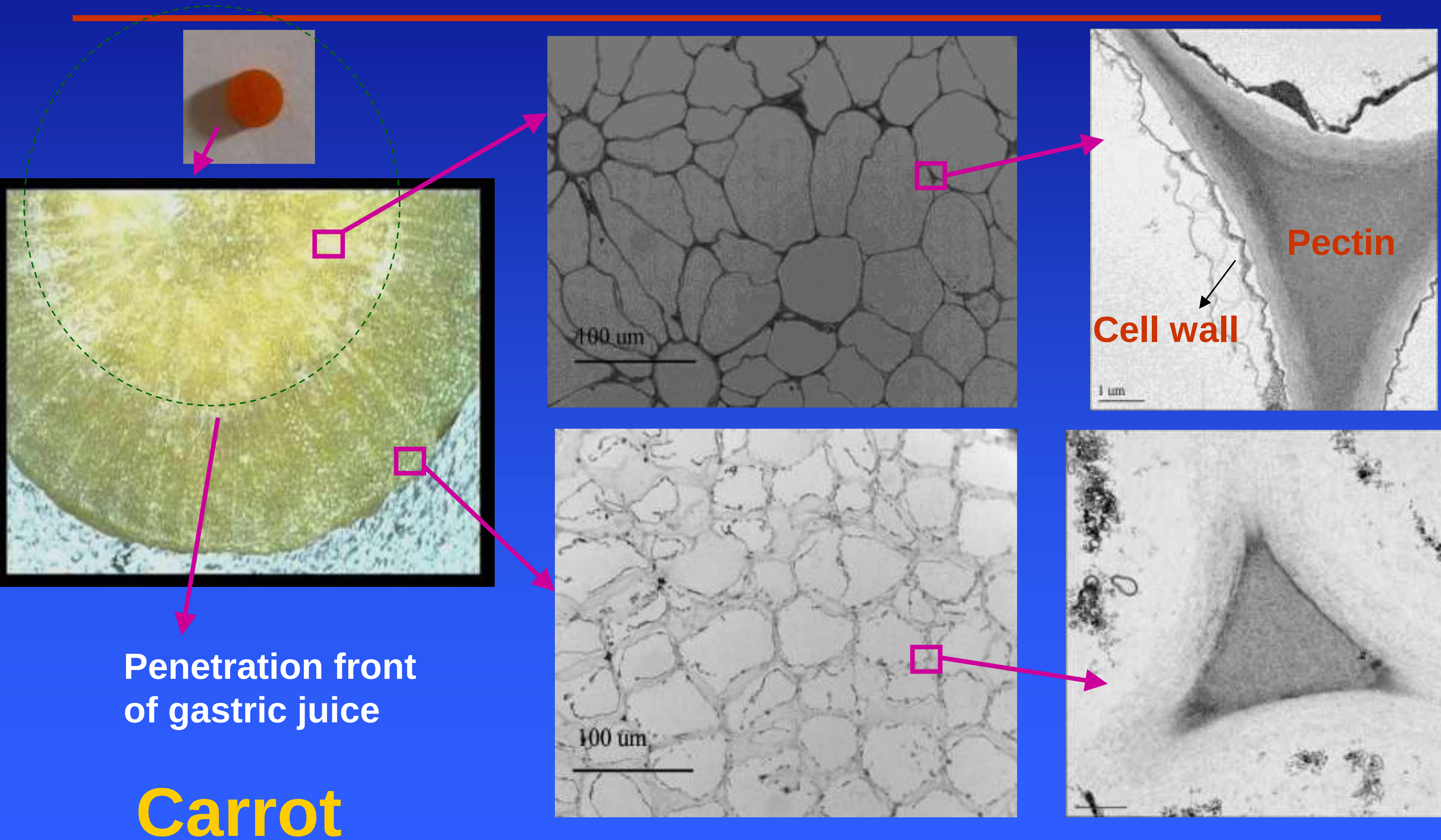


Penetration front



Carrot (Methylene blue)

Penetration front of gastric juice in carrot



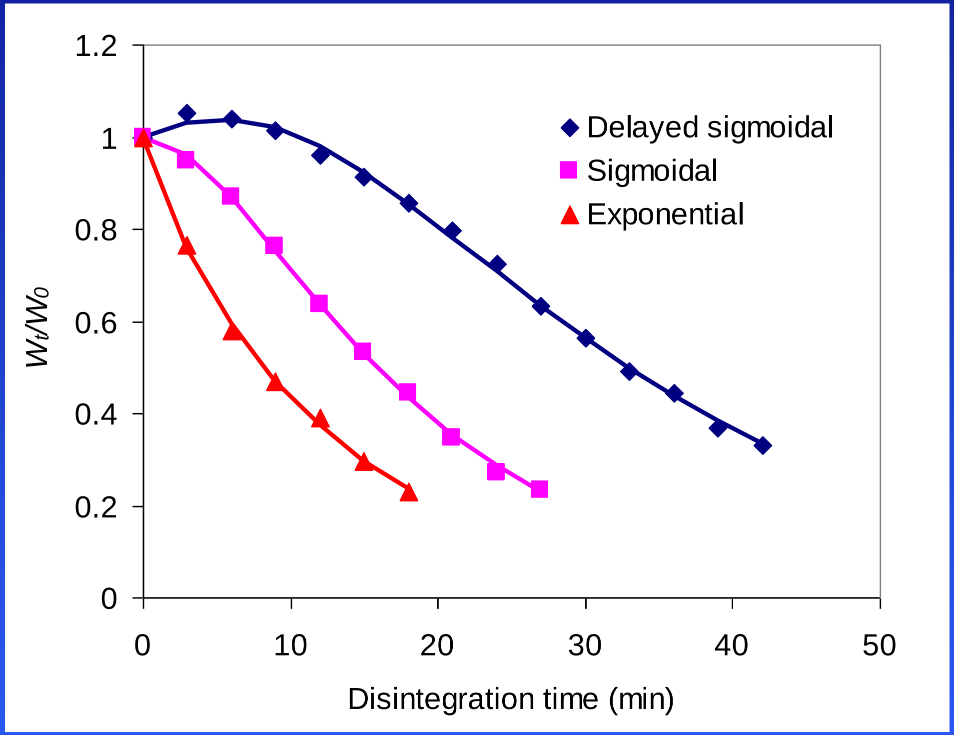
Categorize foods based on their structural breakdown in gastric environment?

- Linear-exponential equation:

$$y(t) = (1 + k \cdot \beta \cdot t) \cdot e^{-\beta \cdot t}$$

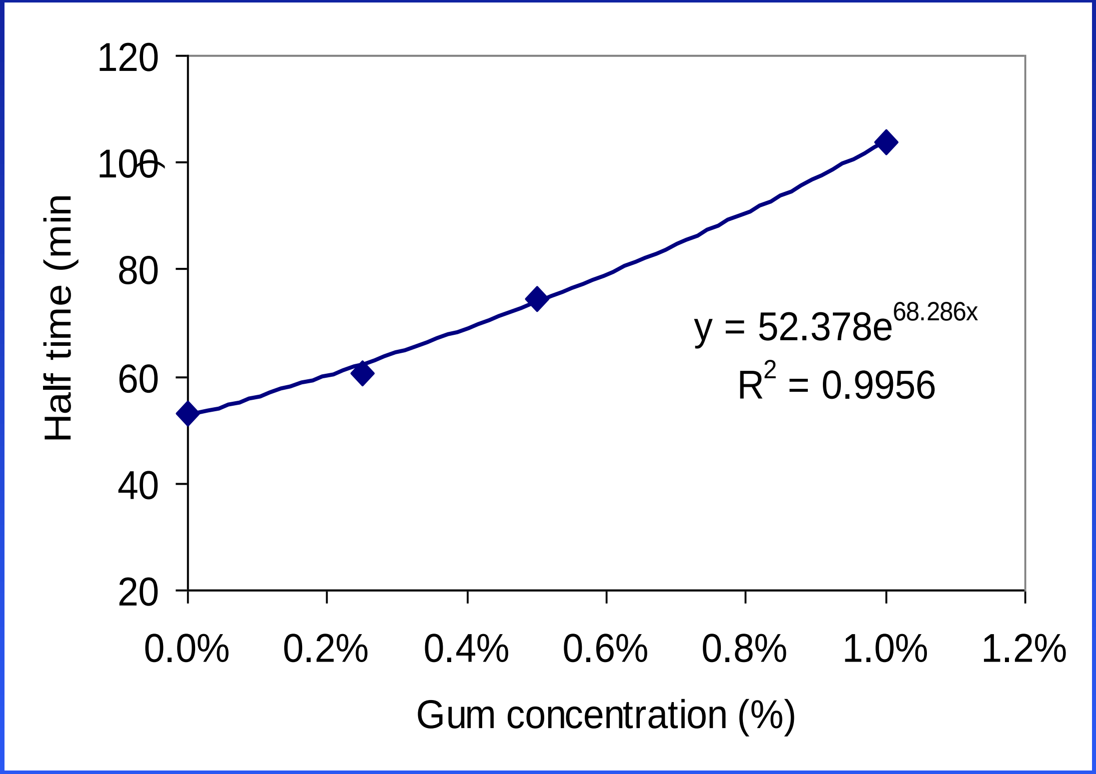
  - *k*: increase in weight with time t (min)
  - *β*: the concavity of the time-weight retention relationship (β >0)

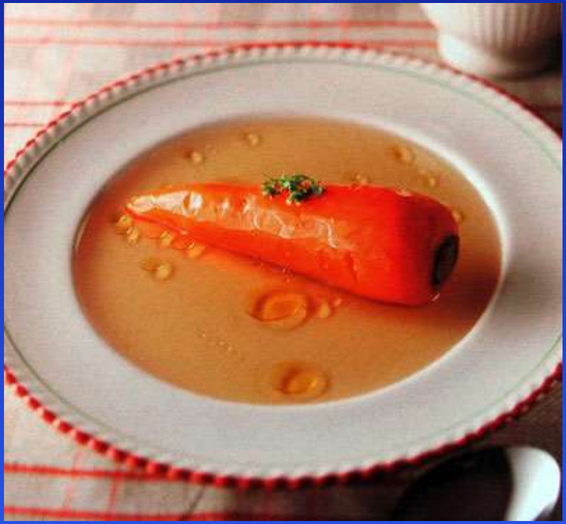
Candy, apple bar, Canned kidney beans	<5 min
Ham, breakfast pretzels, fried dough (no yeast)	5-10 min
Apple, raw carrots	10-20 min
Raw almond and peanut	>10 hours



- Half time($t_{1/2}$)
  - Can be derived by regression
  - Express as disintegration rates

Effect of viscosity



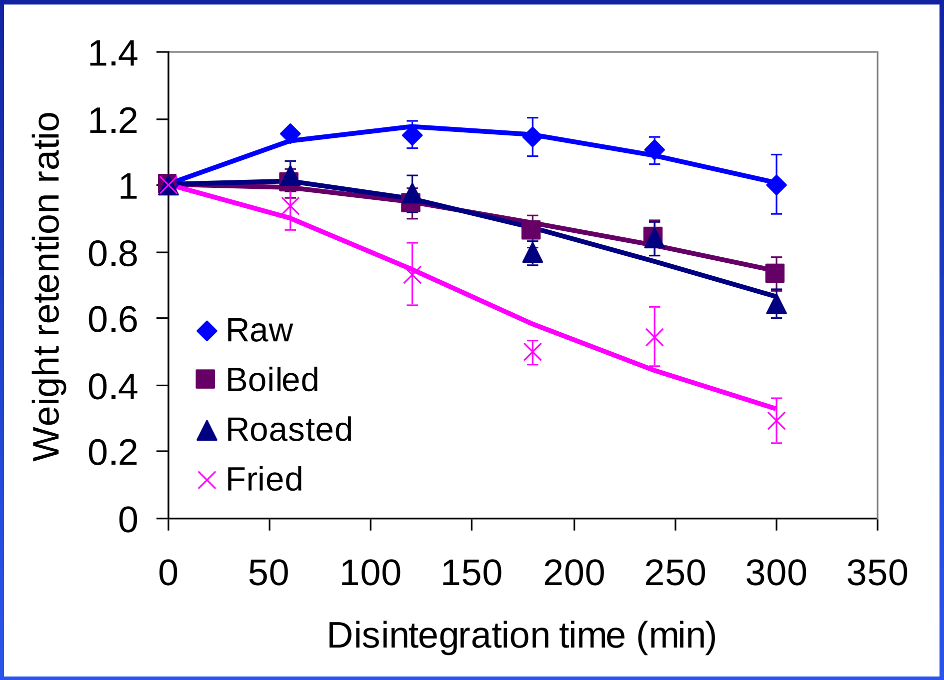


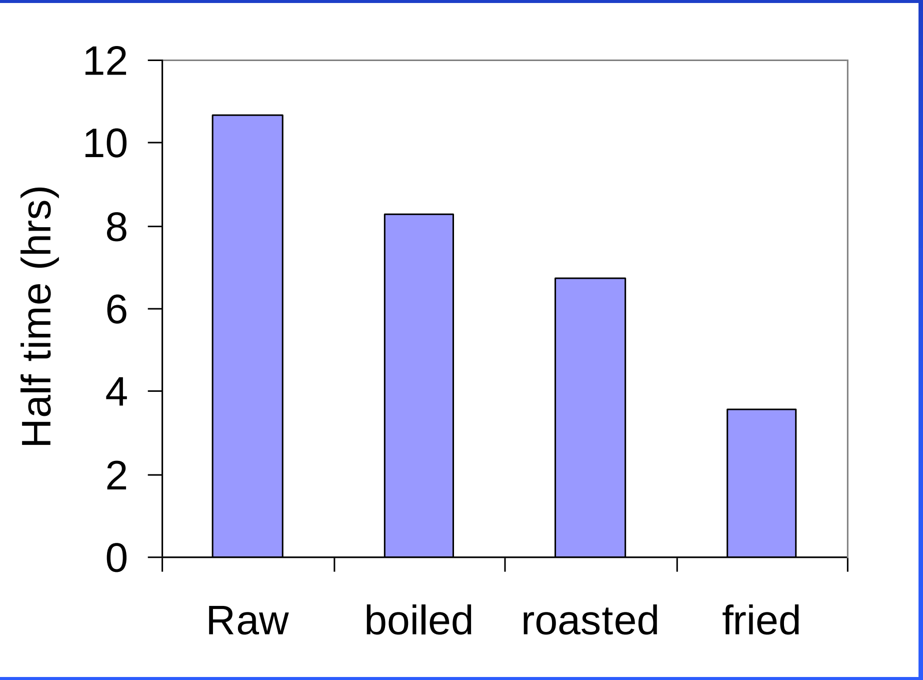
Effect of gastric viscosity on carrot disintegration

- Increase in the viscosity of gastric content delays food disintegration

Peanut digestion

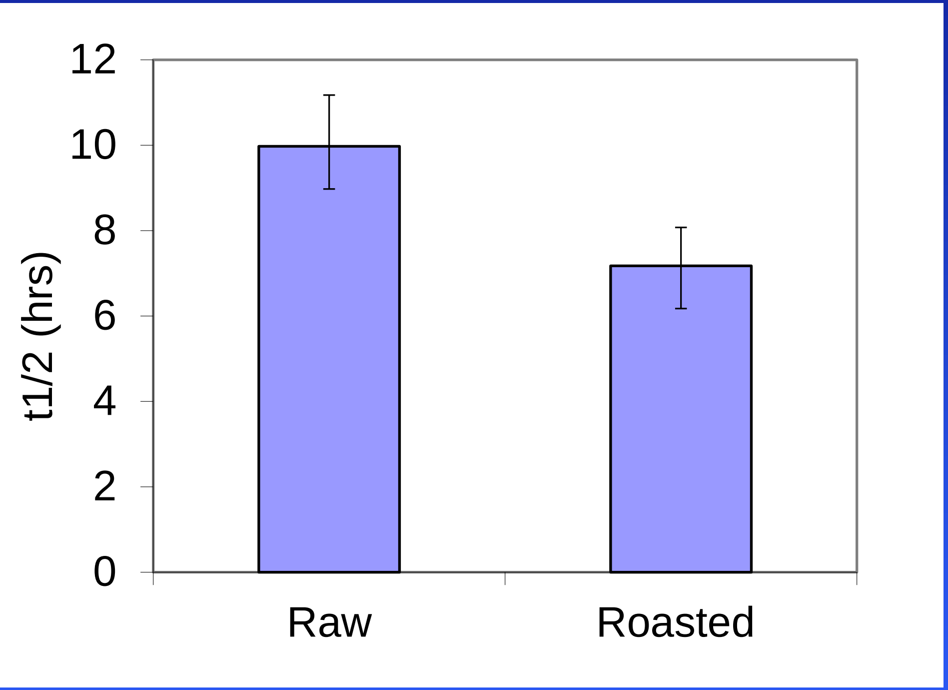
$$y(t) = (1 + k \cdot \beta \cdot t) \cdot e^{-\beta \cdot t}$$





Almond digestion

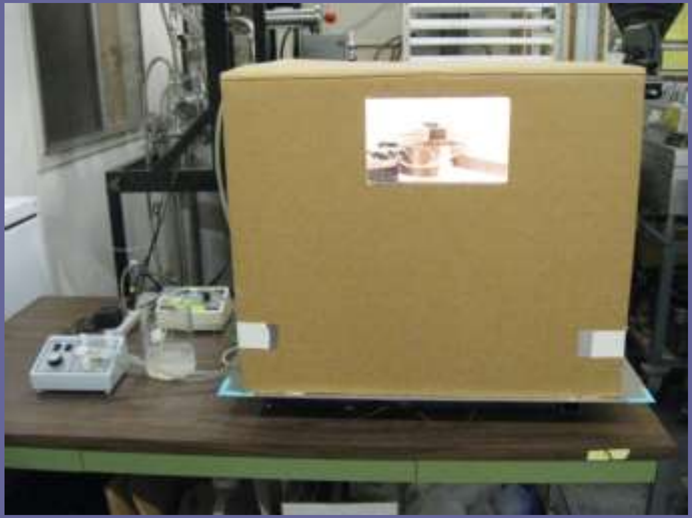
- Satiety properties of almonds?

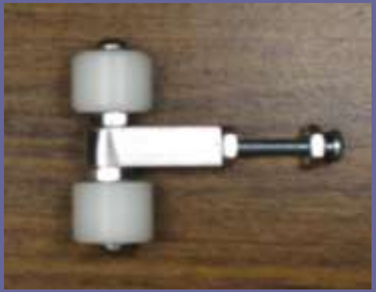


- Slow disintegration and swelling in the stomach contribute to satiety feeling

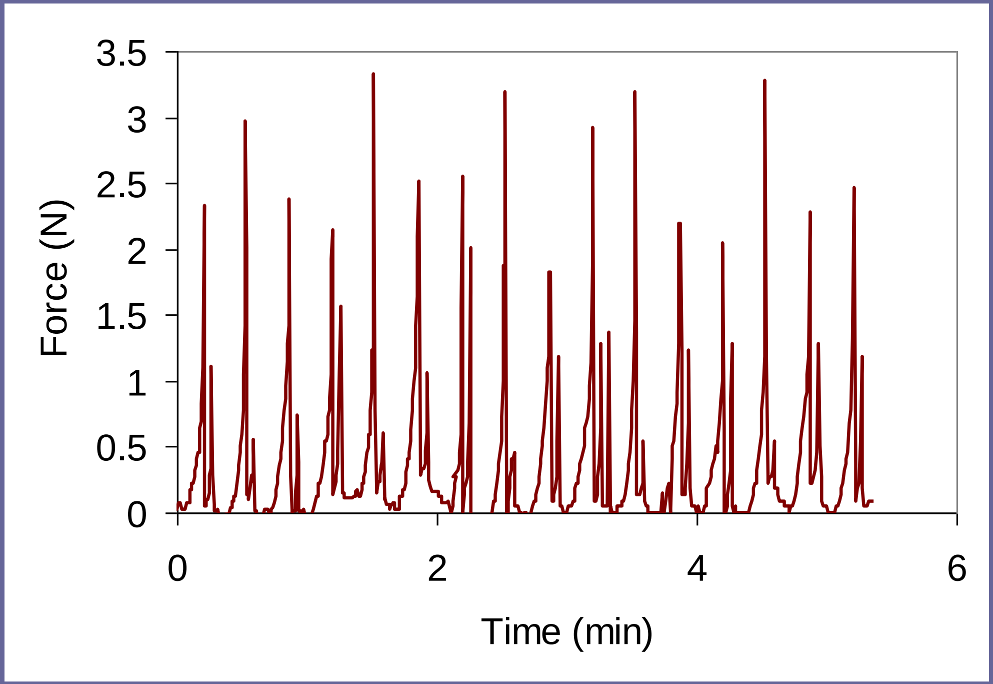
Human Gastric Simulator (HGS)

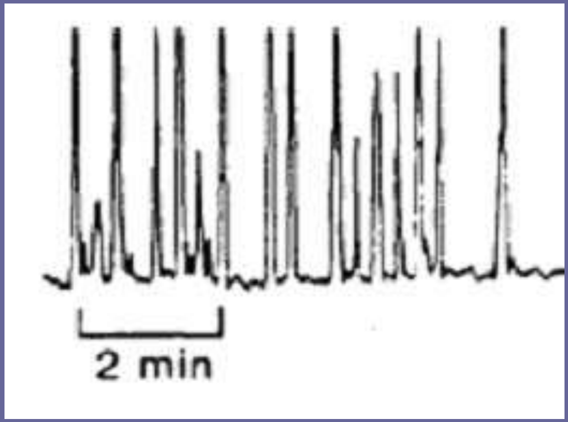
- Create peristaltic movement of walls
- Simulate gastric secretion (enzyme and acid) and stomach emptying
- Study size distribution of food particulates in digesta, nutrient release, and rheological properties
- Study physiological effects (pH, emptying, contraction) on digestion





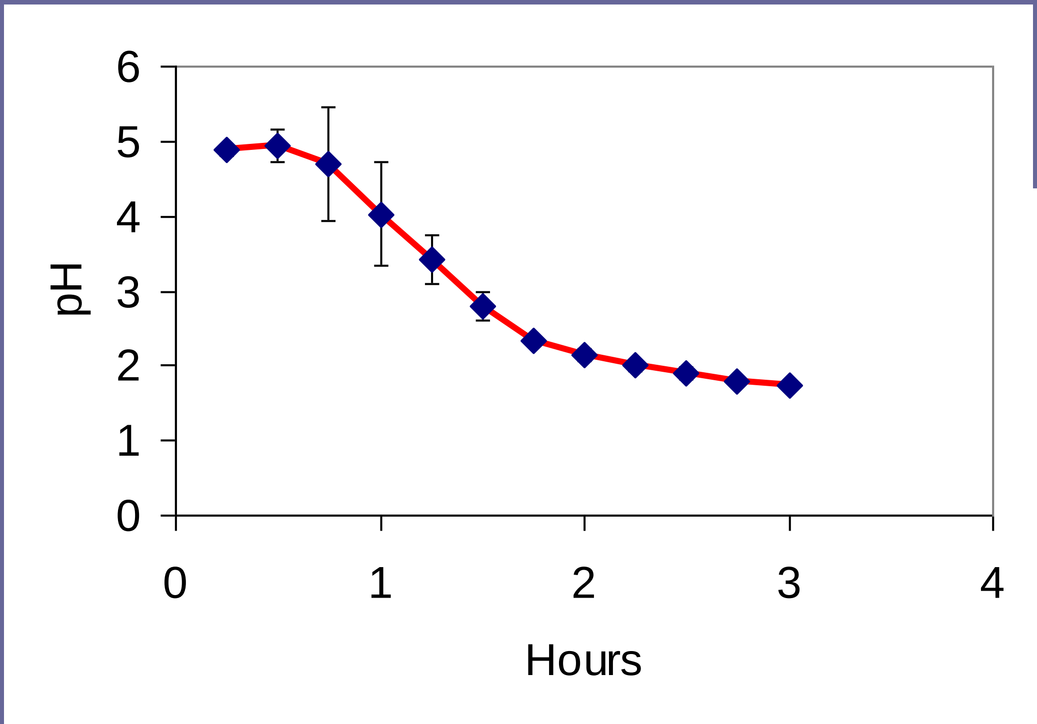
Comparison of stomach forces between *in vitro* and *in vivo*

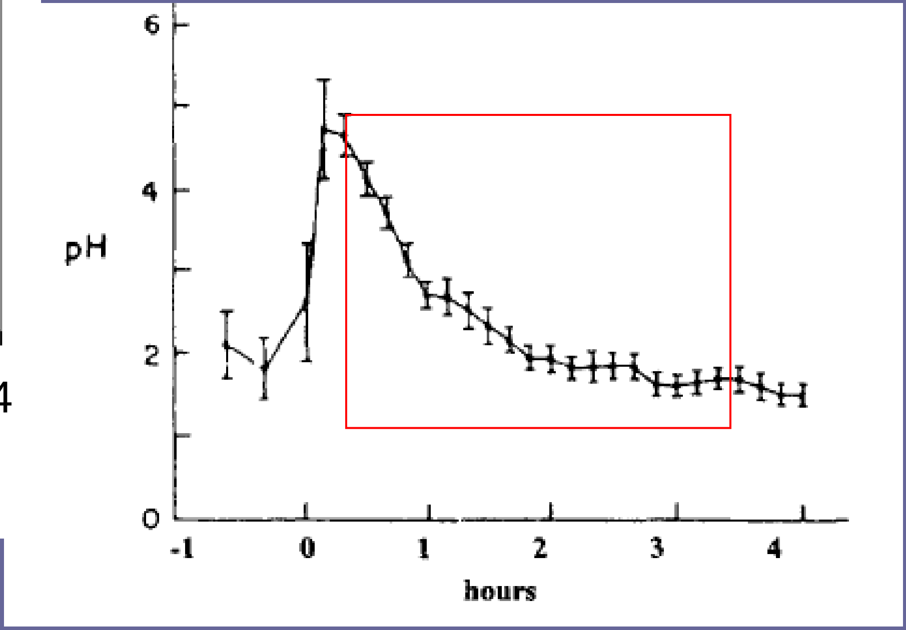




Profile of contraction force. Left: *in vitro* force created in the bottom of HGS simulating antral force in human stomach; right: *in vivo* force profile obtained from stomach proximate to antrum (Vassallo et al. 1992. Am J Physiol Gastrointest Liver Physiol 263: G230–9.)

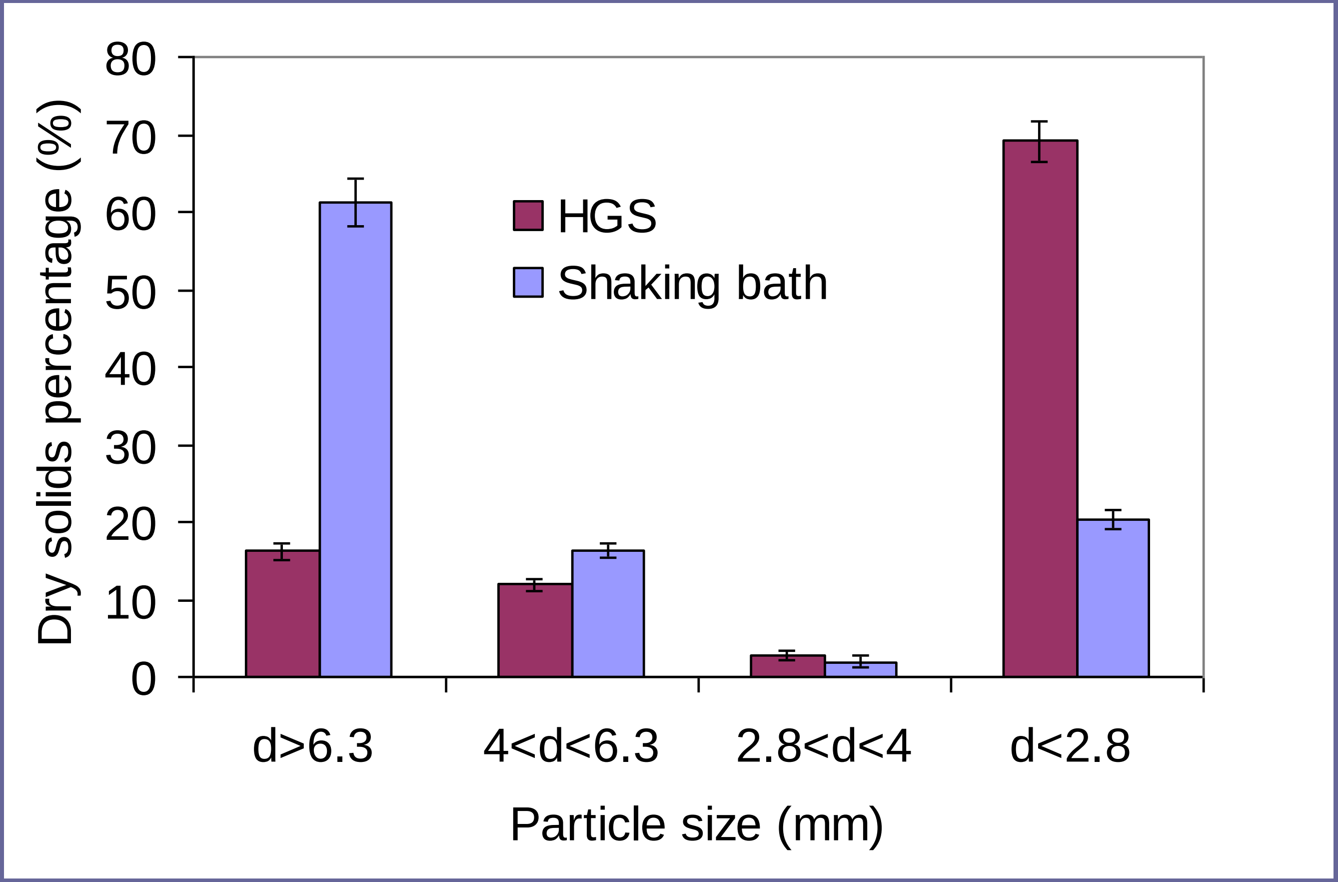
Comparison of gastric pH between *in vitro/in vivo*





Profiles of pH. Left: pH of the emptied fluid of HGS; right: *in vivo* gastric pH; red rectangle area indicates the pH after food intake (Malagelada et al. 1976. Gastroenterol 70: 203-10)

Comparison of disintegration efficiency between HGS and shaking bath



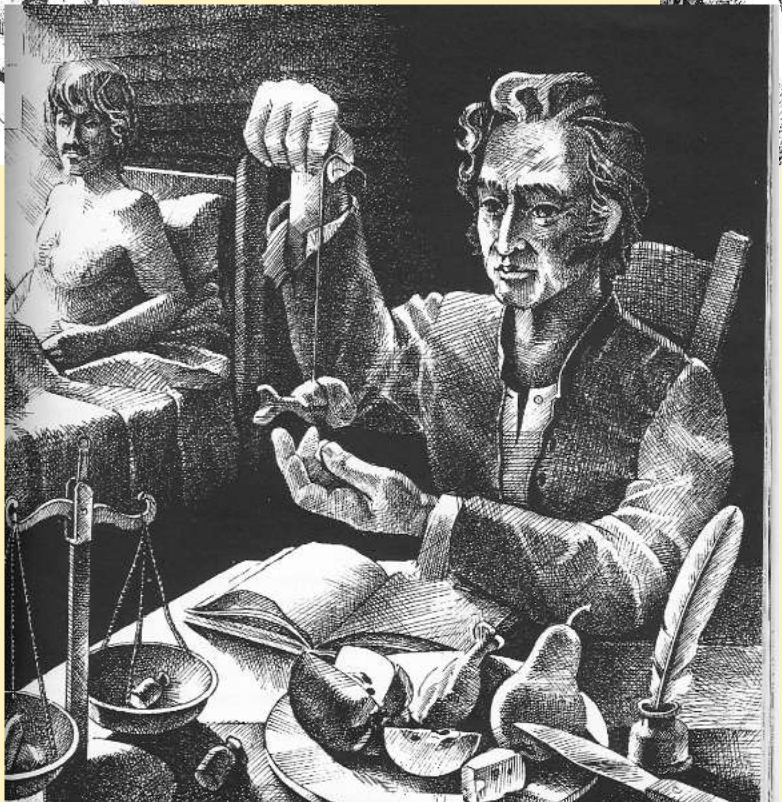
Comparison between particle size distribution of apple after digestion in HGS and shaking bath (mean of three trials)

In vivo trials

- Human trials

June 6, 1822
Mackinac Island
Michigan

Alexis St. Martin



Experiments and observations on the gastric juice and the physiology of digestion

By
William Beaumont,

Experiment 2.

Sept. 18. At 2 o'clock, P. M., he dined on six ounces of *boiled, fresh, salmon trout*, three ounces of *bread*, and a *potato*, and drank half a pint of *water*. Continued at work, sawing and splitting wood. He had eaten nothing from the time he took his breakfast; had been hard at work all the time; looked, and said he felt quite fatigued.

At 3 o'clock, 40 mins., stomach about half full of a nearly homogeneous semi-fluid, of a rich milk or cream colour, and about the consistence of fine corn meal gruel—a few small particles of the fish, and some of the potato, could be distinguished. 4 o'clock, 15 mins., stomach empty and clean.

Experiment 3.

Sept. 20. At 1 o'clock, 15 mins., P. M., he dined on three ounces *fat pork*, and one pint of *corn* and *beans*, (green,) two ounces of *bread*, and half a pint of *water;* and kept exercising. Digested in three hours and three quarters.

Experiment 4.

Sept. 21. At 8 o'clock, A. M., he breakfasted on eight ounces of *beef's liver, broiled*, two ounces of *bread*, and drank half a pint of *water*. Continued usual exercise. 9 o'clock 30 mins., stomach full of partially chymified food, considerable oil, (melted butter,) floating on the surface; black pepper mingled with it, and emitting a strong aromatic odour of the spice. 10 o'clock, 30 mins., stomach empty and clean. Extracted two drachms of gastric juice.

Experiments and observations on the gastric juice and the physiology of digestion

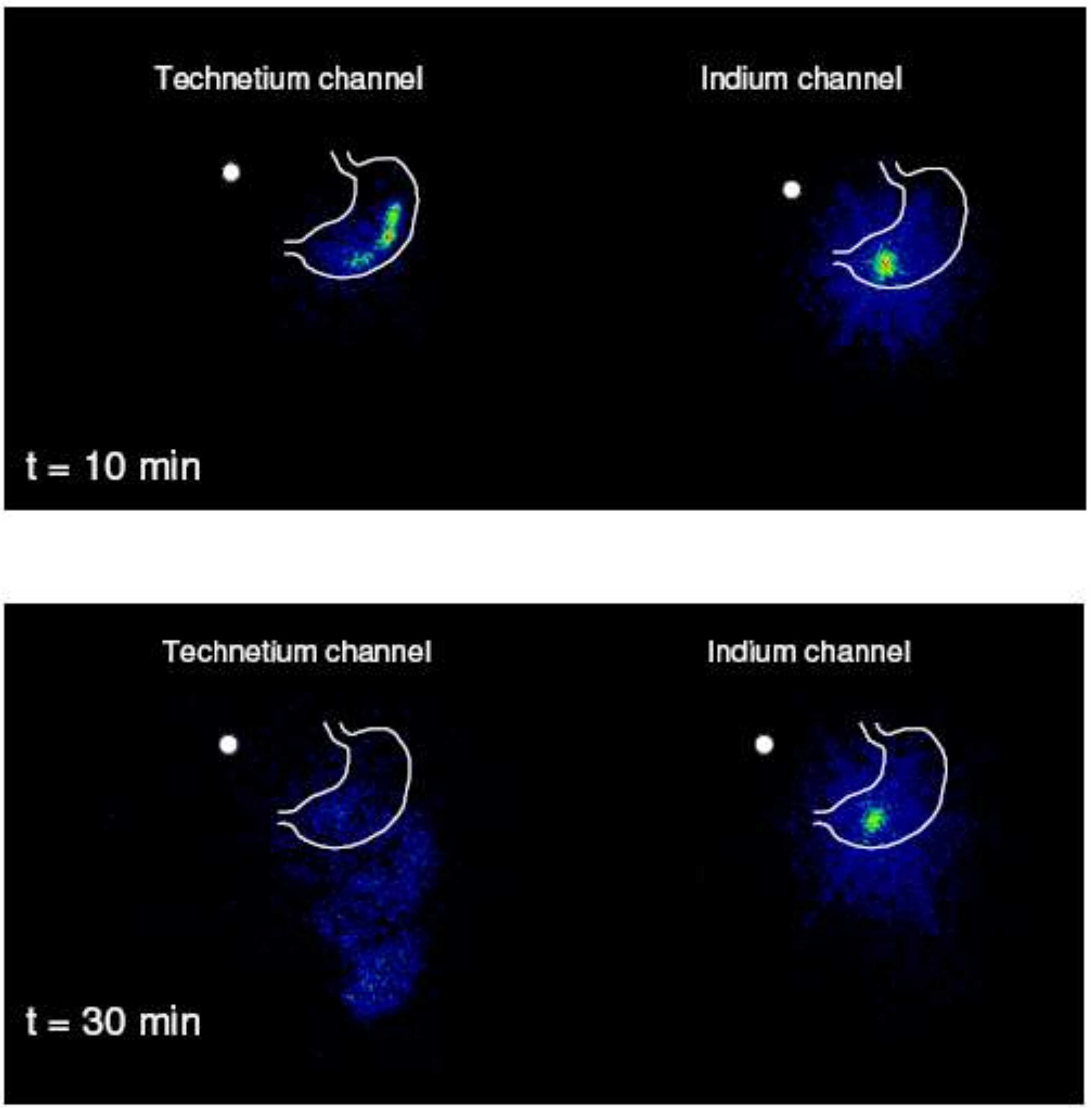
By
William Beaumont,

In vivo methods to assess gastric disintegration and emptying rate

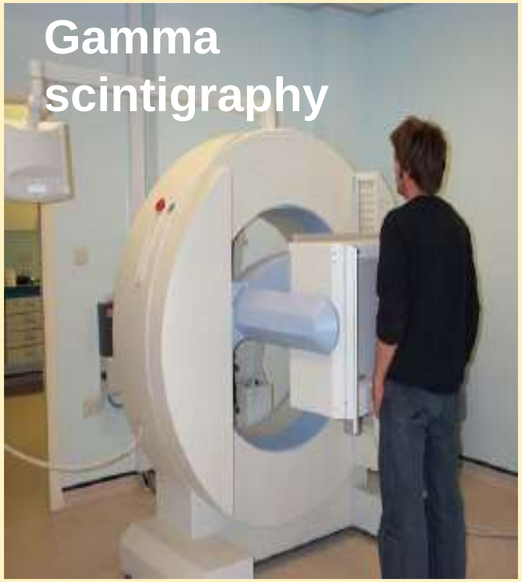
- Feeding study
  - acquiring the digesta samples using **naso-gastric tube**
- Intubation techniques: gastric barostat and intraluminal manometry
  - "gold standard" for assessing motility of the stomach

In vivo methods to assess gastric disintegration and emptying rate

- **Feeding study**
  - acquiring the digesta samples using **naso-gastric tube**
- **Intubation techniques**: gastric barostat and intraluminal manometry
  - "gold standard" for assessing motility of the stomach
- **Scintigraphic imaging**: liquid barium sulphate, radioopaque spheres
  - standard method to measure gastric emptying
- **Ultrasonograph**y measures gastric volume or antral cross-section. The information is used to estimate the rate of emptying and evaluate antral motility.
- **Magnetic resonance imaging** (MRI)
- Indirect methods such as blood test and **breath test**

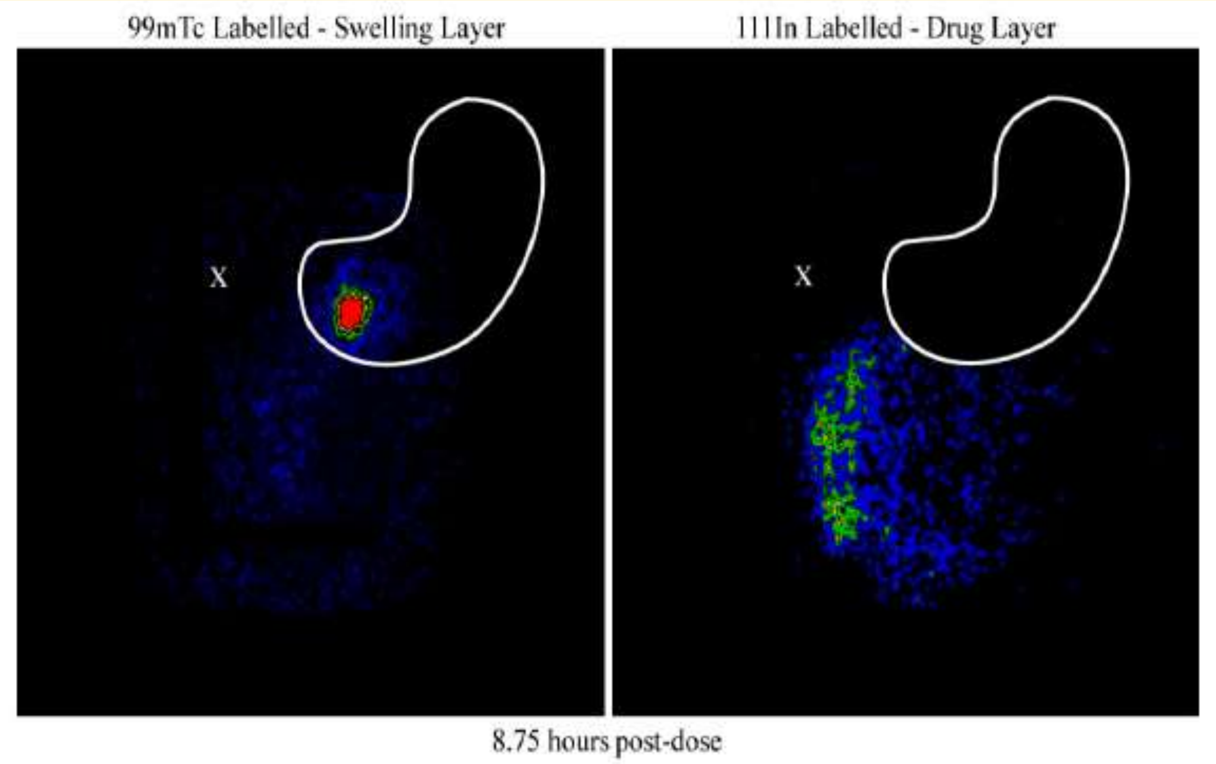


Scintigraphic images shows capsule disintegration and gastric emptying of its contents)



www.bio-images.co.uk/AAPS2002.pdf

MRI images showing disintegration and gastric emptying of drug tablet



www.pharmprofiles.co.uk/UserFiles/File/pdf/DepomedPresentation.pdf

In vivo trials

- Animal trials
  - Rats
  - Pigs
    - Canulated
    - Euthanized

Canulated Cow

http://t1.gstatic.com/

In vivo trials

Pigs Arrive at Housing Facility

Massey University New Zealand

Meal Preparation

Feeding Trials using Pigs

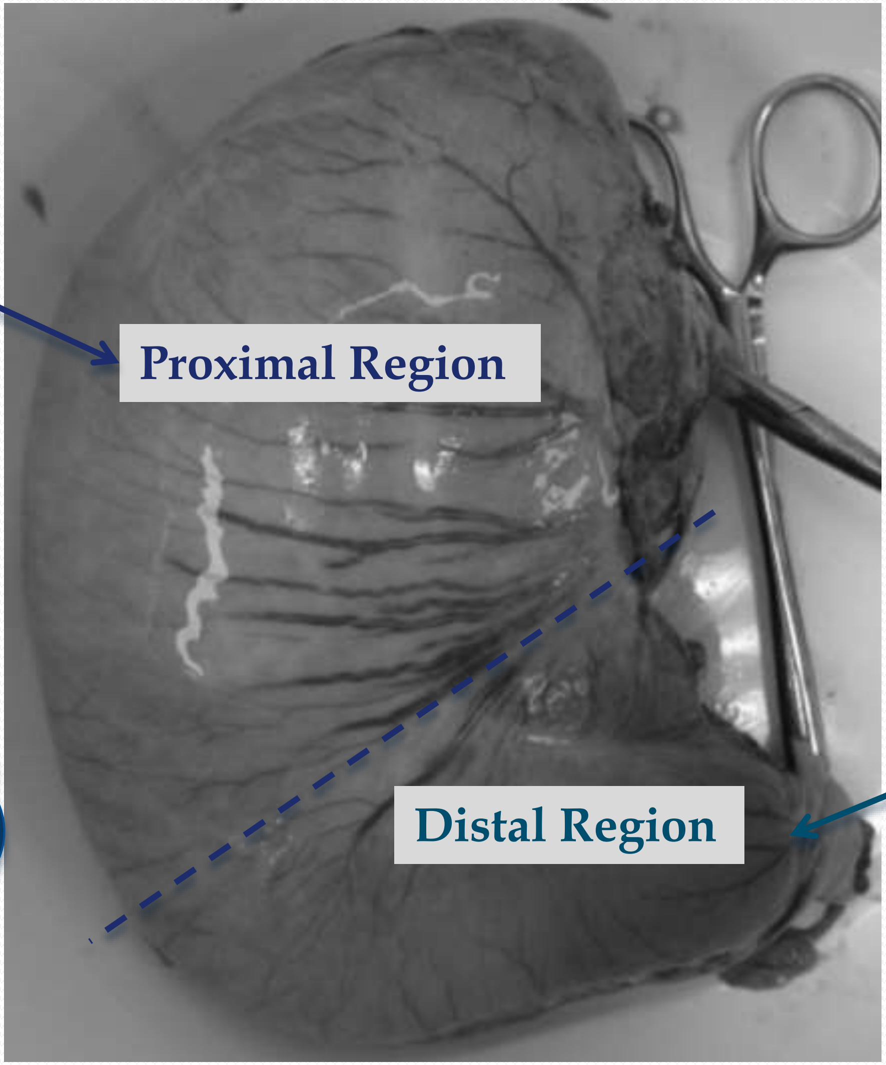
- Obtain *in vivo* data examining impact of various conditions on food digestion -- 96 pigs
  - **Processing**
    - White rice (cooked)
    - Brown rice (cooked)
  - **Digestion time**
    - 20 min
    - 60 min
    - 120 min, 180 min, 300 min
  - **Location in stomach**
    - Fundus/body
    - Antrum

Approved by the Massey University Ethics Committee

Sampling

- Pigs euthanized at 0, 60, 120, 180, or 300 min after eating brown or white rice meal

Food Reservoir?



Main location for breakdown?

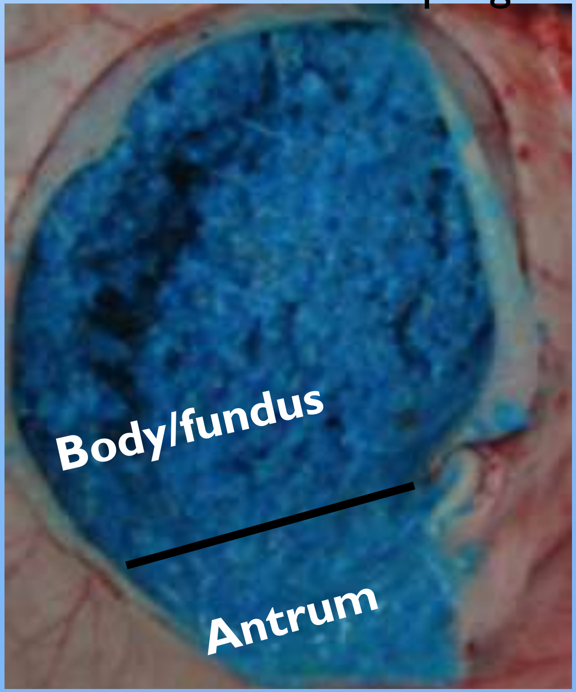
Mixing between regions??

Methods

- Samples taken from body/fundus & antral regions

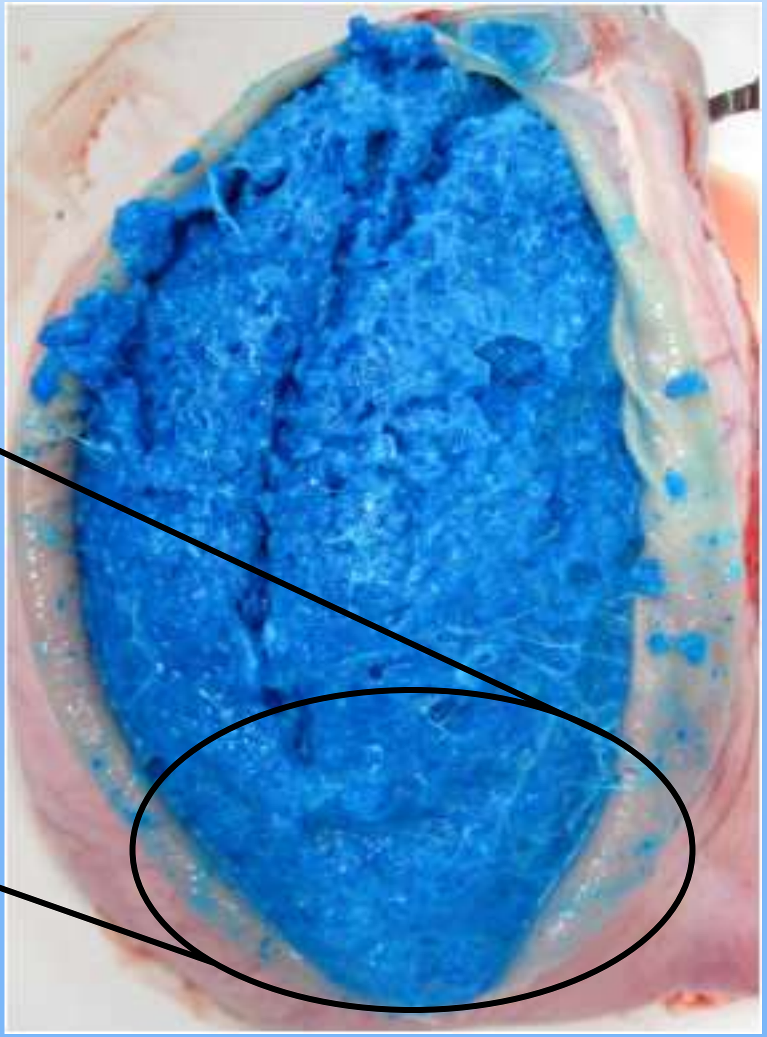
- Key Measurements
  - Texture
  - Rheological properties
  - pH
  - Moisture content
  - Particle size distribution

esophagus



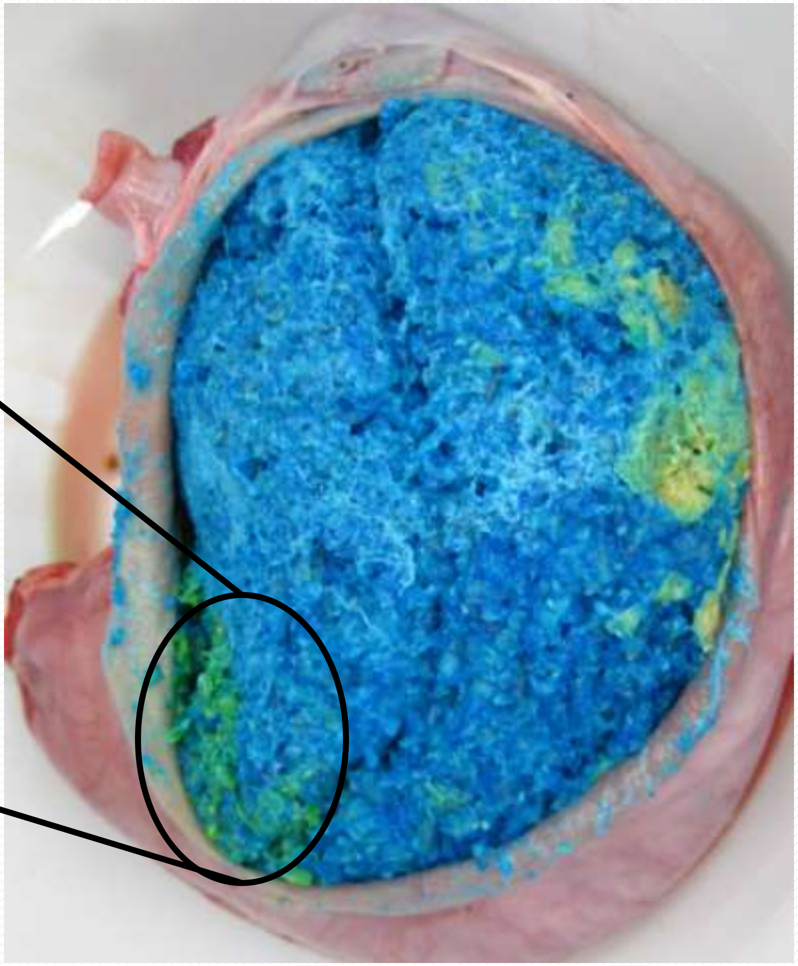
Pyloric sphincter

Results:
20 min white rice



More “liquid-like” portion in antrum

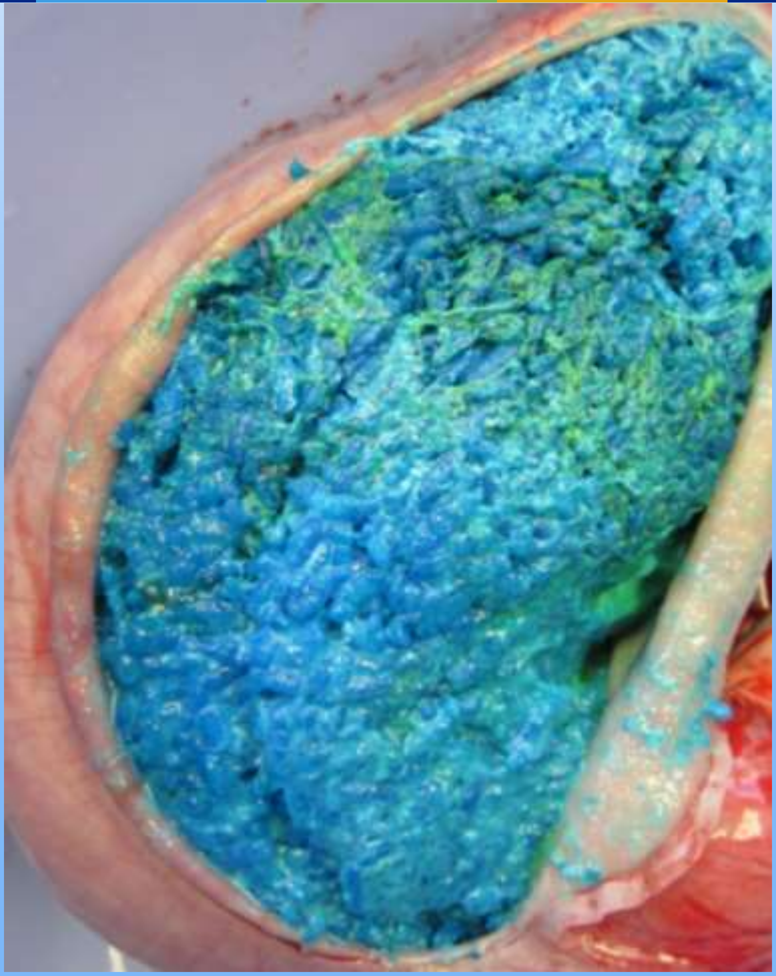
Results: 20 min brown rice



Evidence of "antral grinding" → outer bran layer broken off of inner endosperm layer

Rice Gastric Digestion: 20 mins

Brown Rice

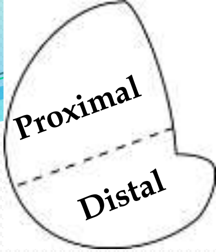


White Rice

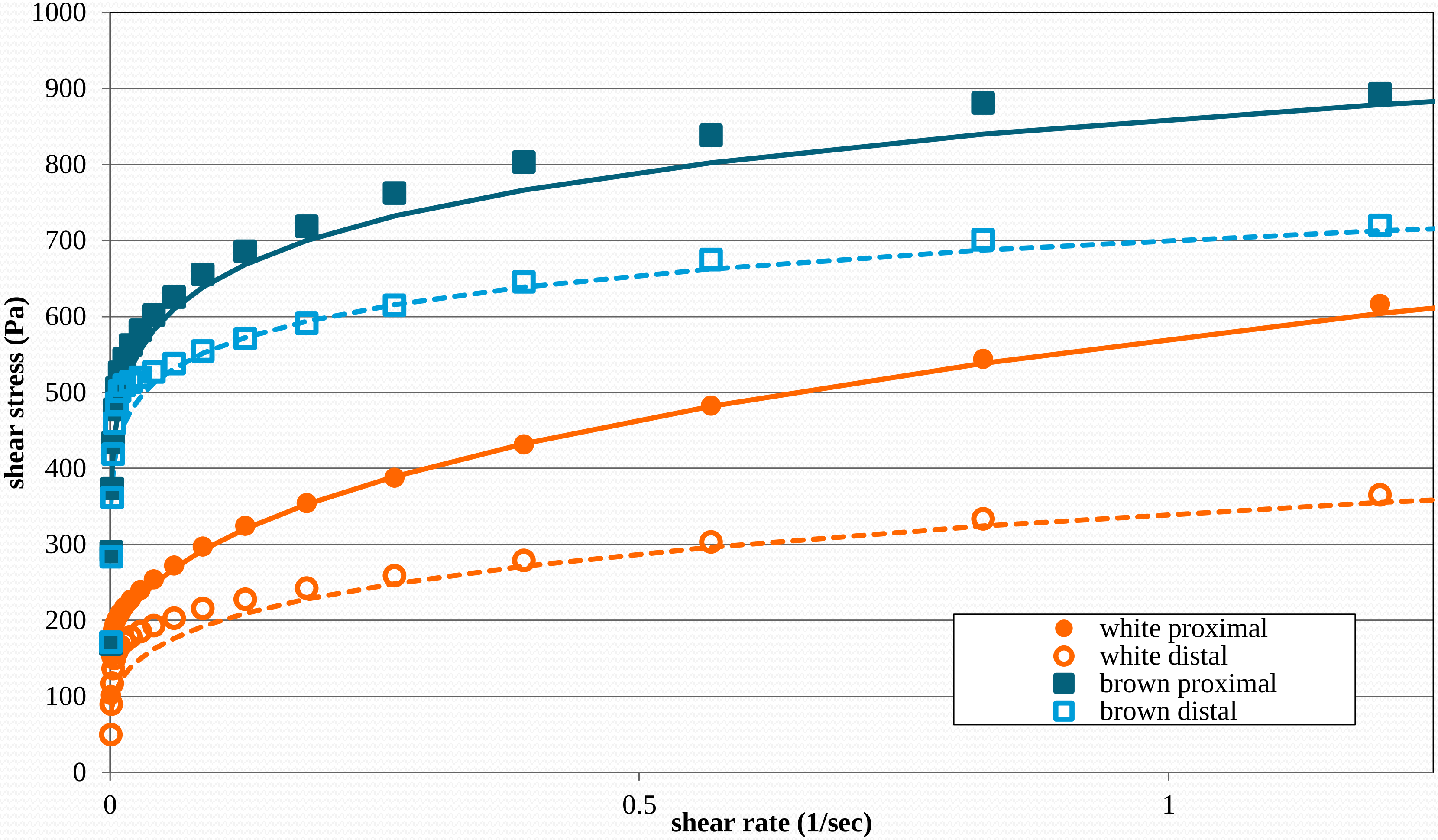
300 min digestion

Brown rice -- antrum

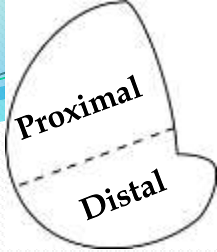
White rice -- antrum



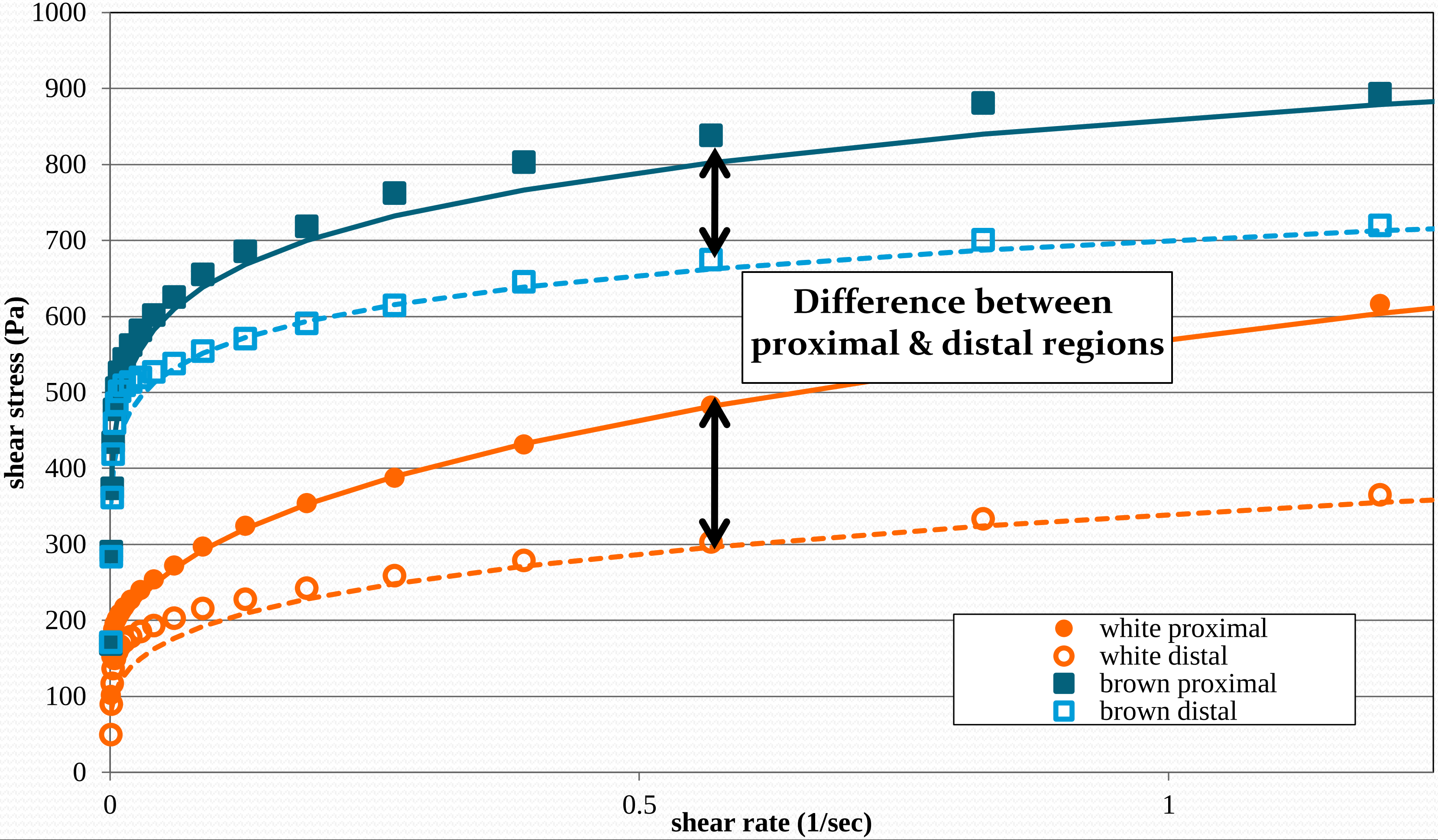
20 min digestion



Data points are experimentally measured values. Lines represent Hershel-Bulkely model predictions.

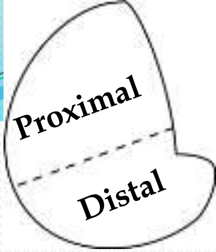


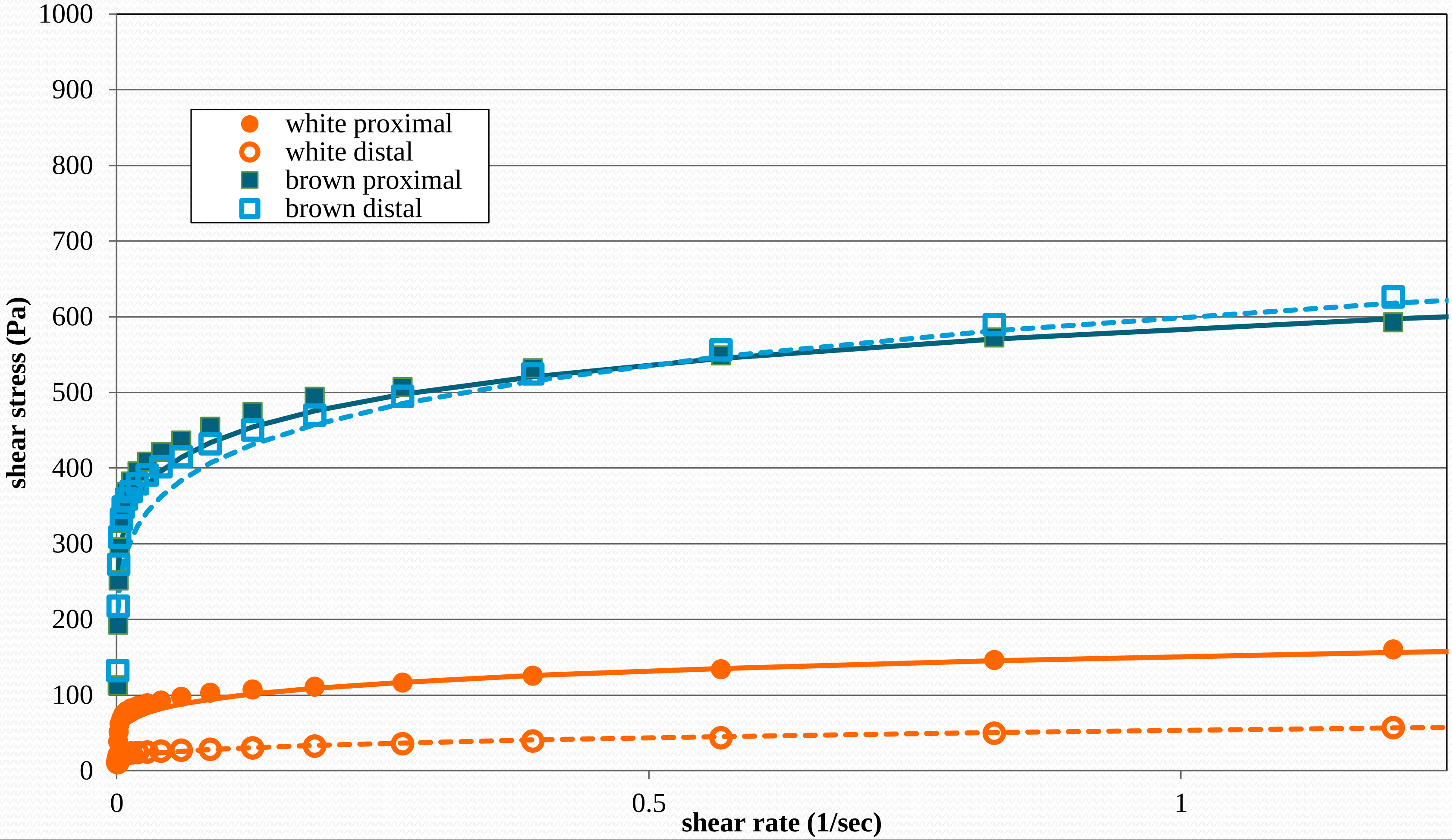
20 min digestion



Data points are experimentally measured values. Lines represent Hershel-Bulkely model predictions.

120 min digestion





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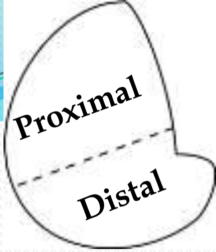
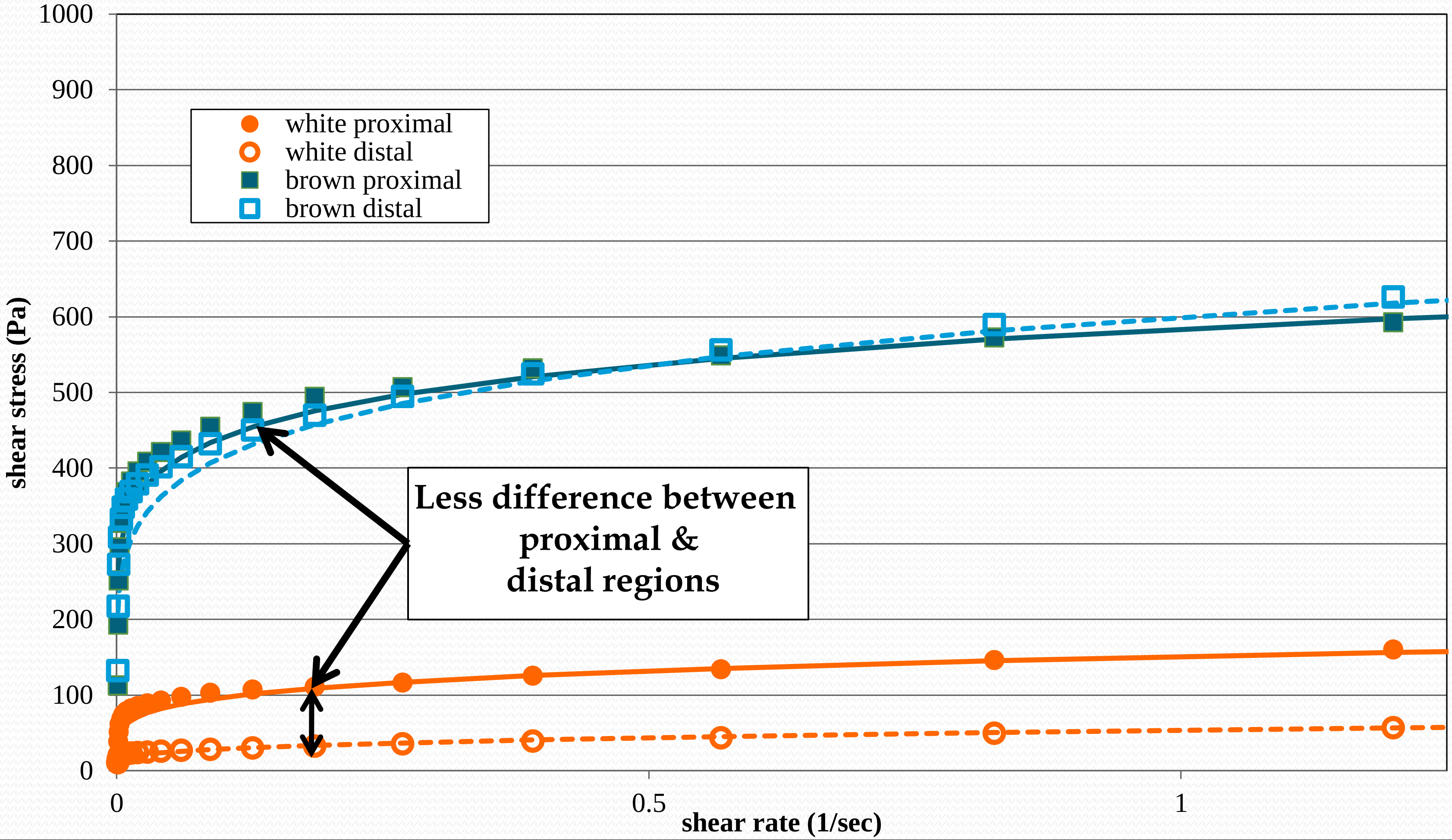
120 min digestion





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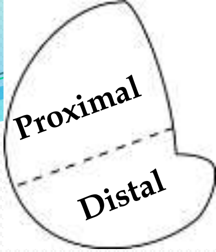
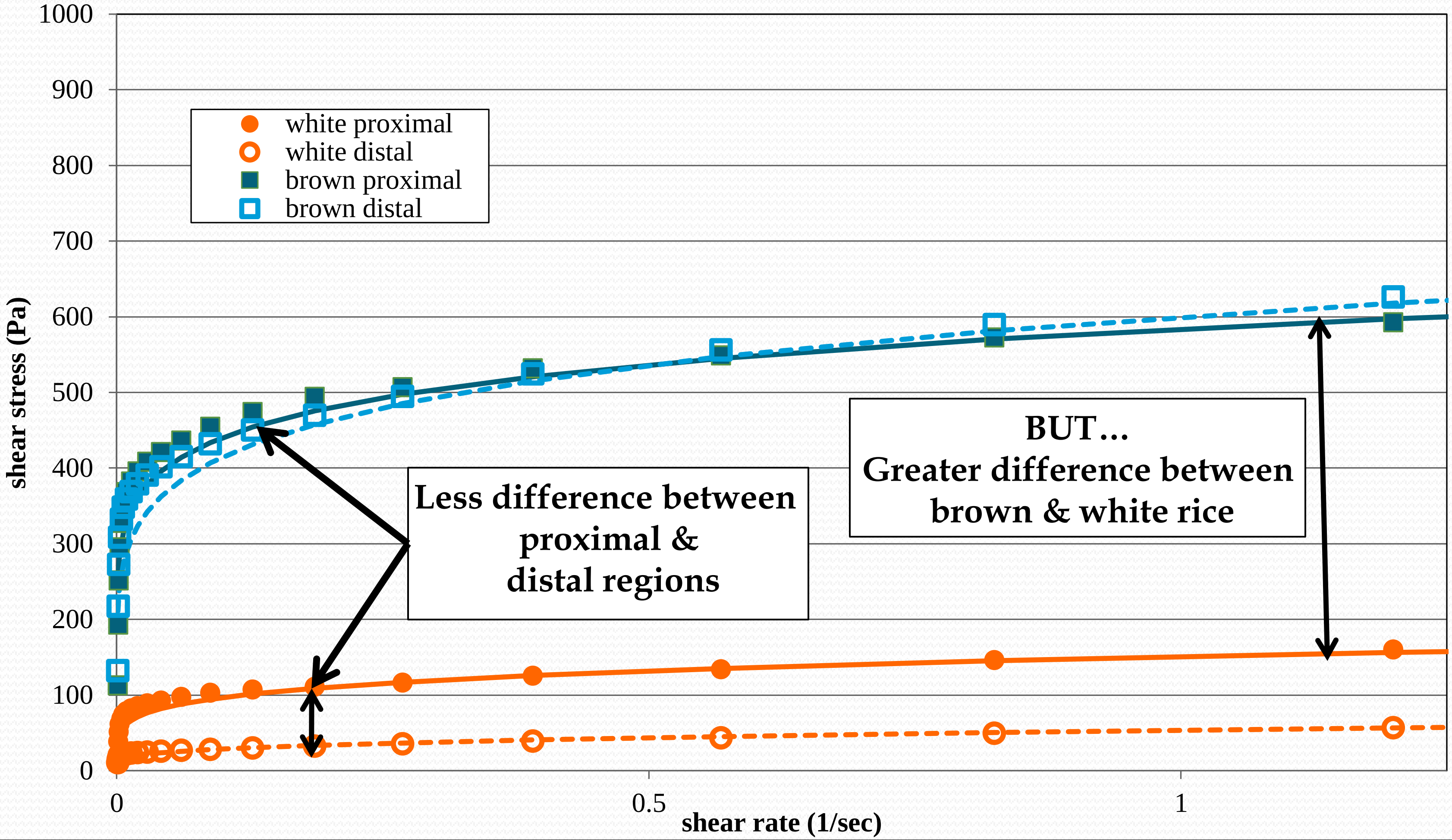


120 min digestion



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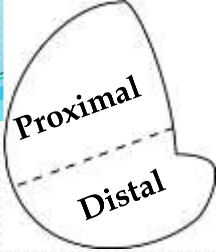
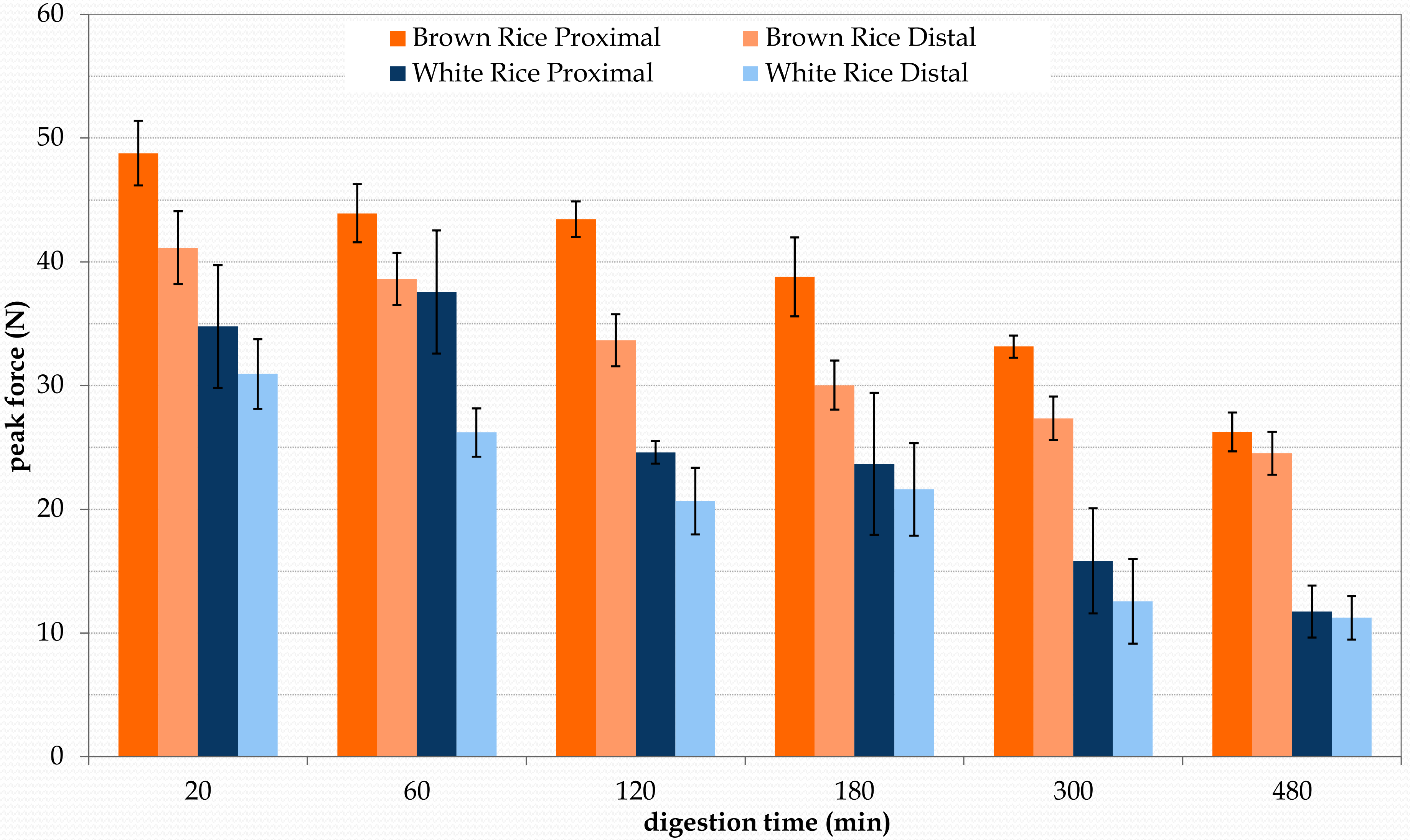
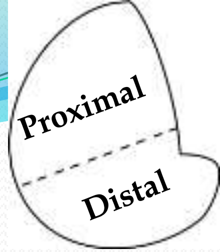
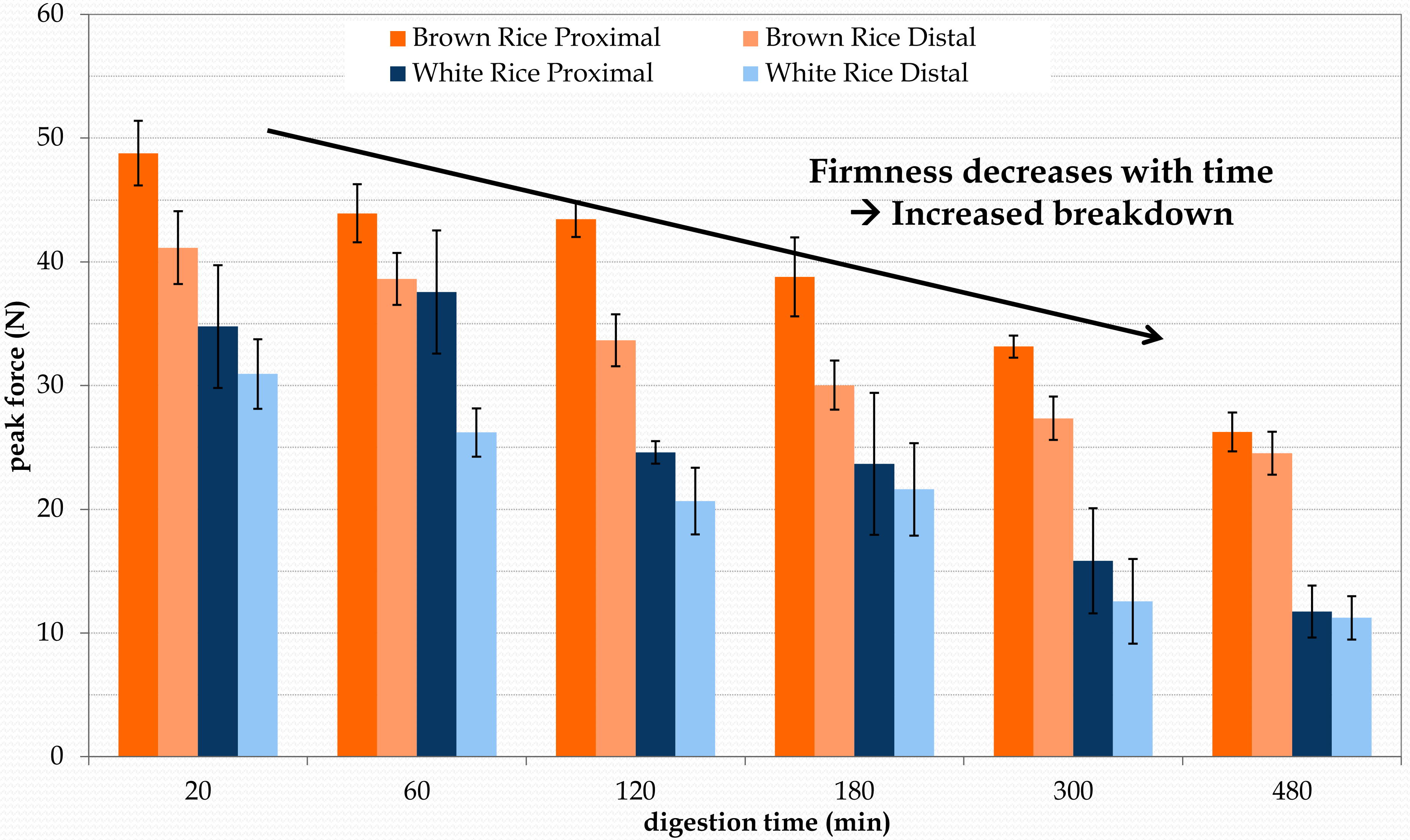
Rice Grain Compression



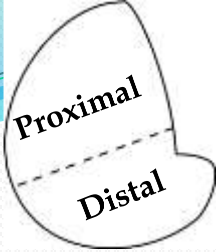


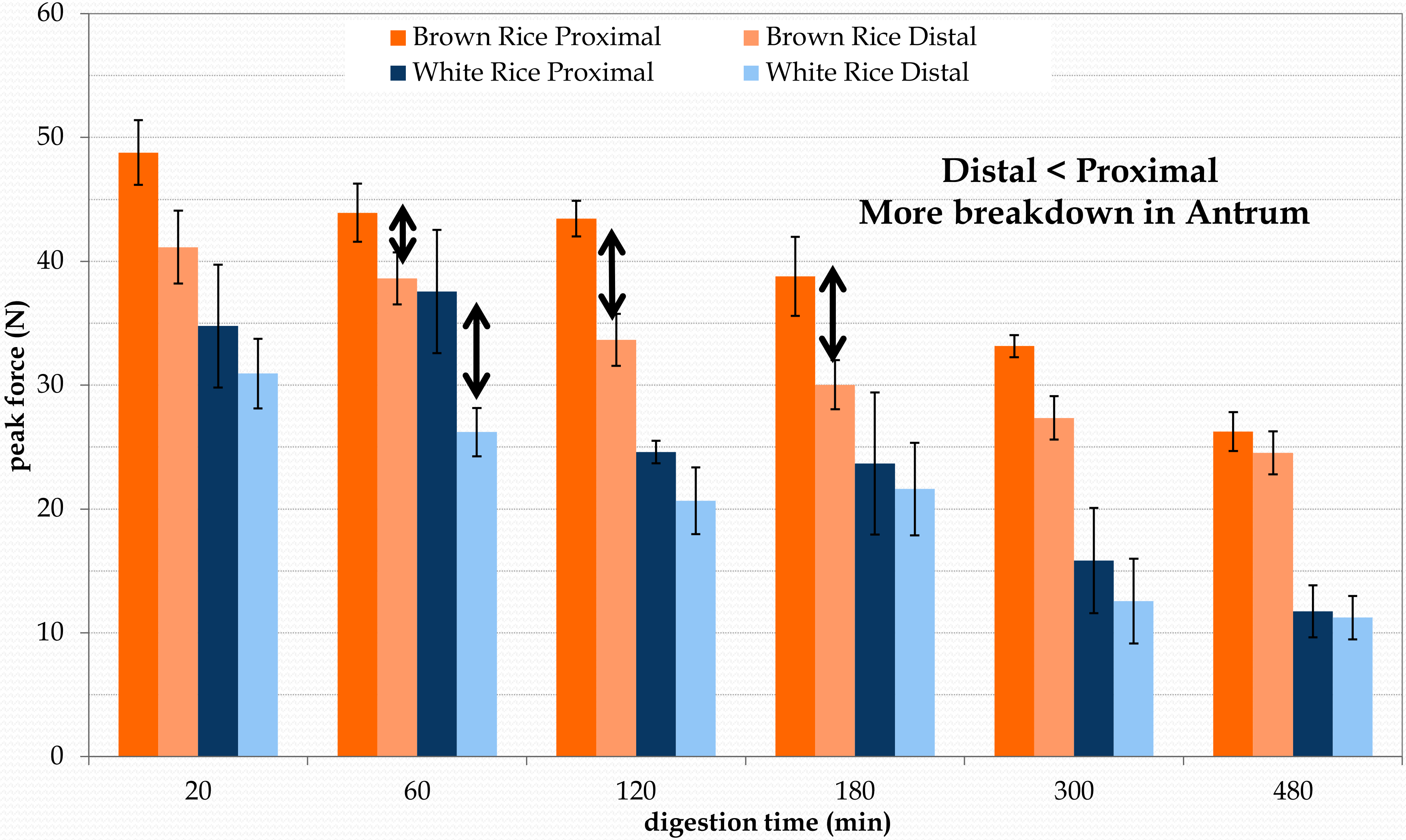
Rice Grain Compression





Rice Grain Compression

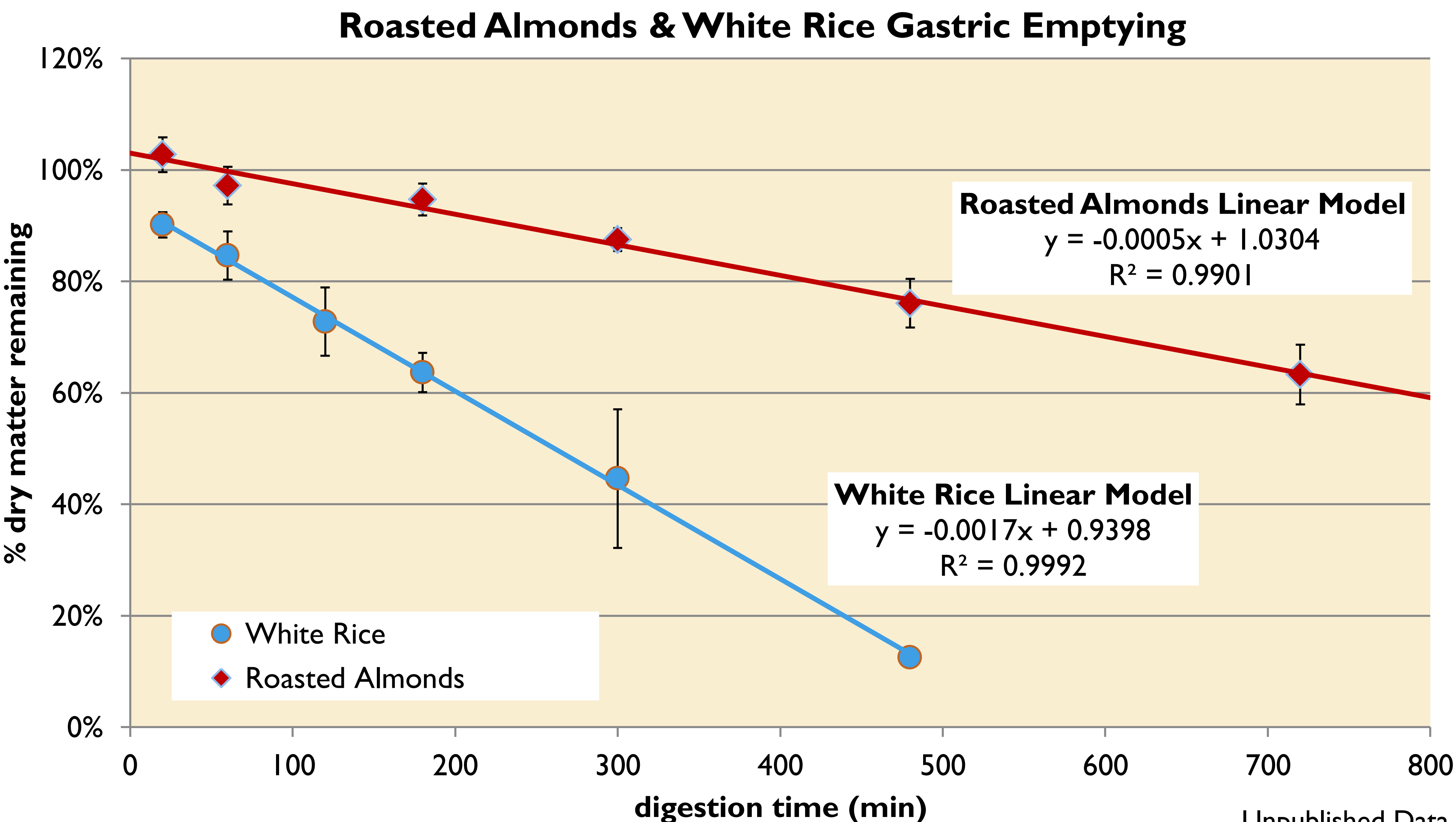




In Vivo Trial with Raw and Roasted Almonds

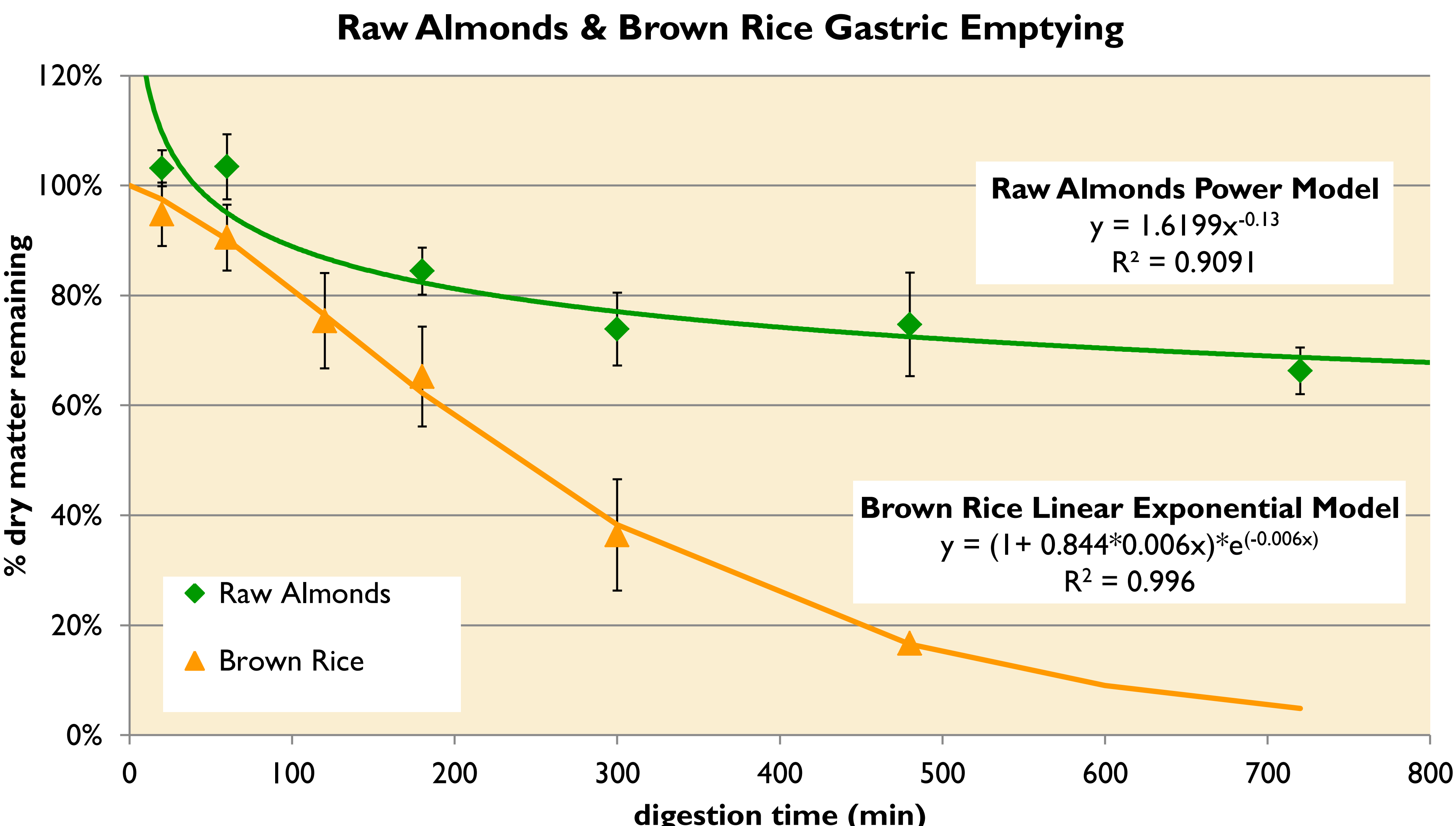
- **Animal Housing**
  - 72 male pigs (23 ± 1.5 kg)
  - Housed in metabolic cages
  - 7 day acclimation period
- **Diet Preparation**
  - Raw & roasted, medium diced almonds
  - Individual meals prepared 2x daily
- **Final meal**
  - Prior to final meal 18 hr fast
  - 2 hr without water
  - Meal of *only* almonds

Gastric Emptying: Processed Foods



Unpublished Data

Gastric Emptying: Less Processed



Unpublished Data

Mixing of Digesta in Stomach

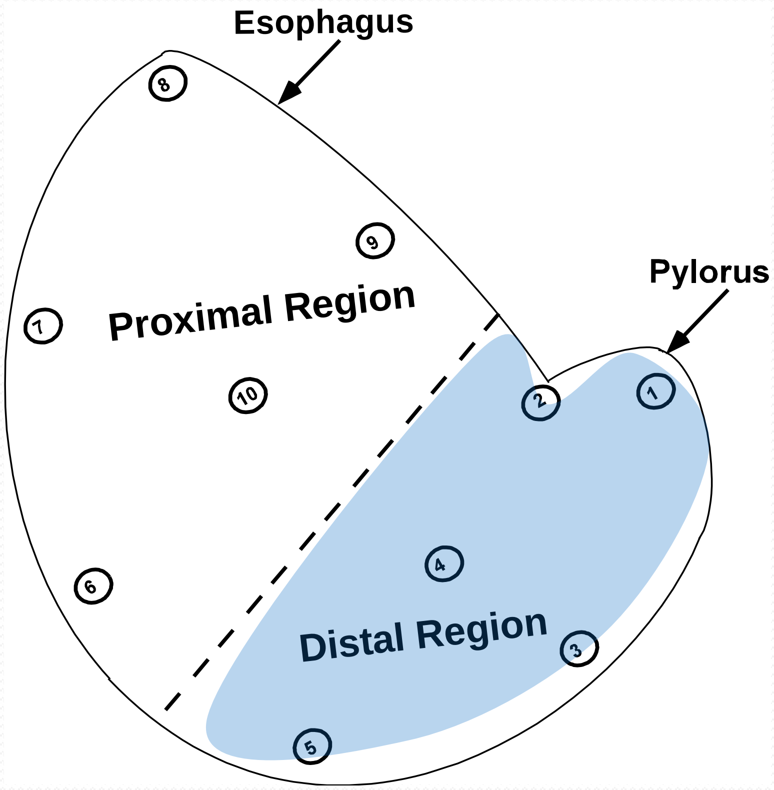
- 50% of daily dry matter requirement of almonds
- 25% water
- 0.3% indigestible marker evenly mixed with sample
  - Titanium dioxide (TiO_2)
  - Chromium oxide (Cr_2O_3)

Particle Mixing using Markers

- Each meal → divided into 2 portions

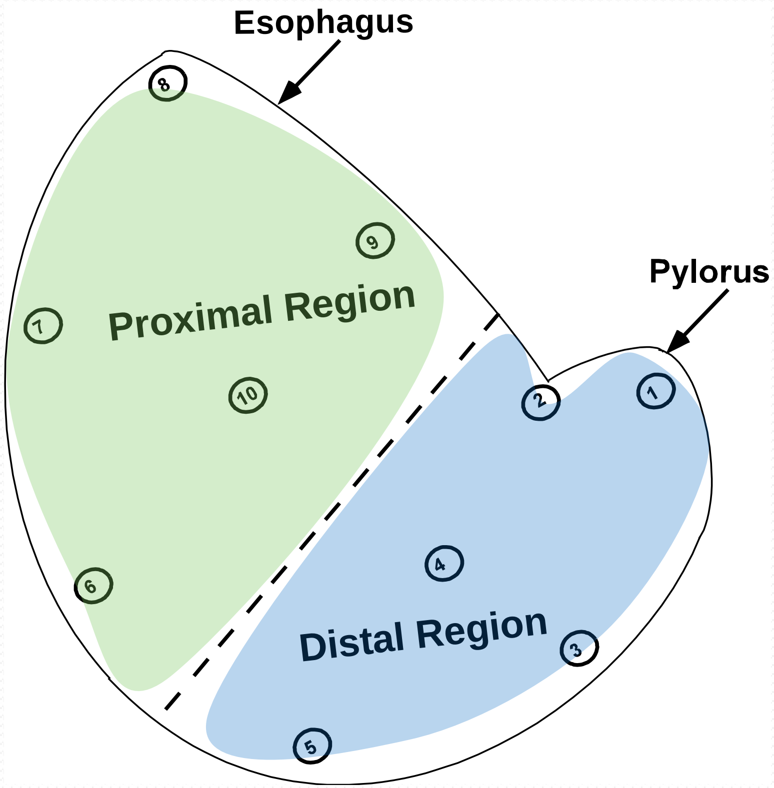
Particle Mixing using Markers

- Each meal → divided into 2 portions
  - Portion 1: **Titanium Dioxide (TiO_2)**



Particle Mixing using Markers

- Each meal → divided into 2 portions
  - Portion 1: **Titanium Dioxide (TiO_2)**
  - Portion 2: **Chromium Oxide (Cr_2O_3)**



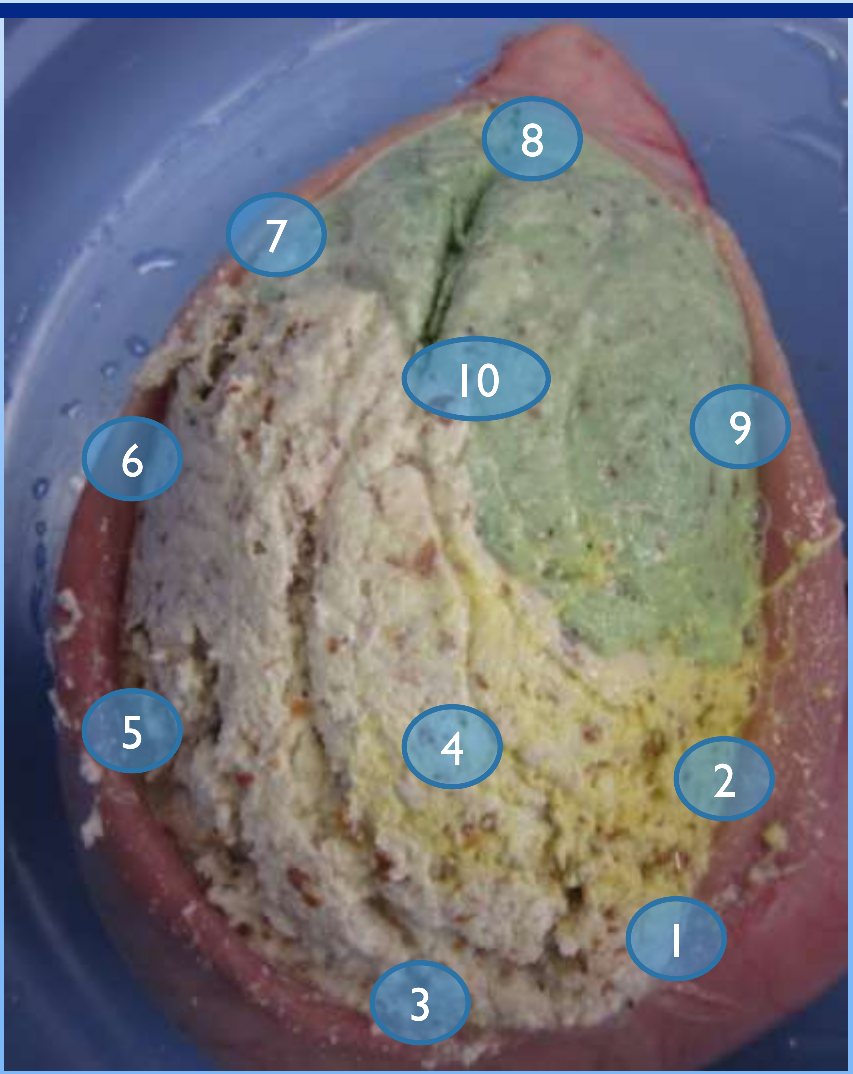
Raw Almond Digestion

Chromic oxide "portion"

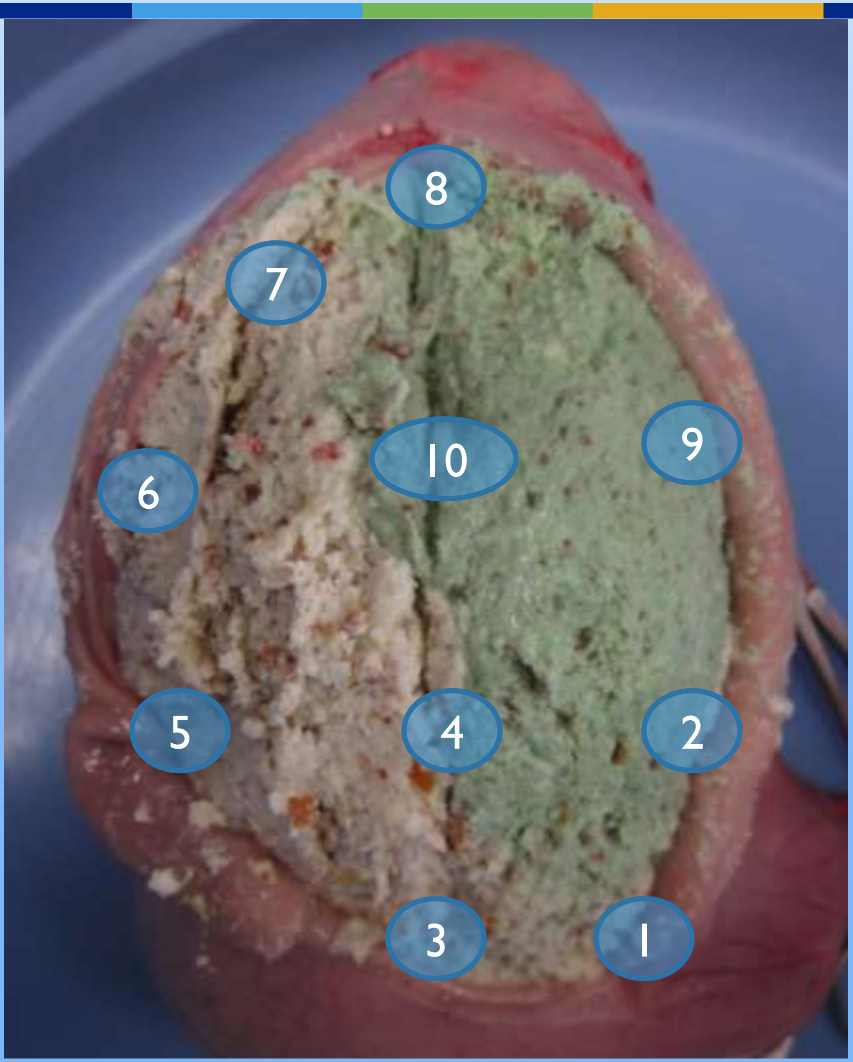
Titanium dioxide "portion"

20 min

Raw Almond Digestion



20 min



1 hour

Mixing Index Calculation

- **Difference between variance** (σ^2_t) and **equilibrium variance** (σ^2_∞) drives mixing
- **Mixing index**:
  - σ^2_t = variance at time t
  - σ^2_0 = long time variance
  - σ^2_0 = initial variance

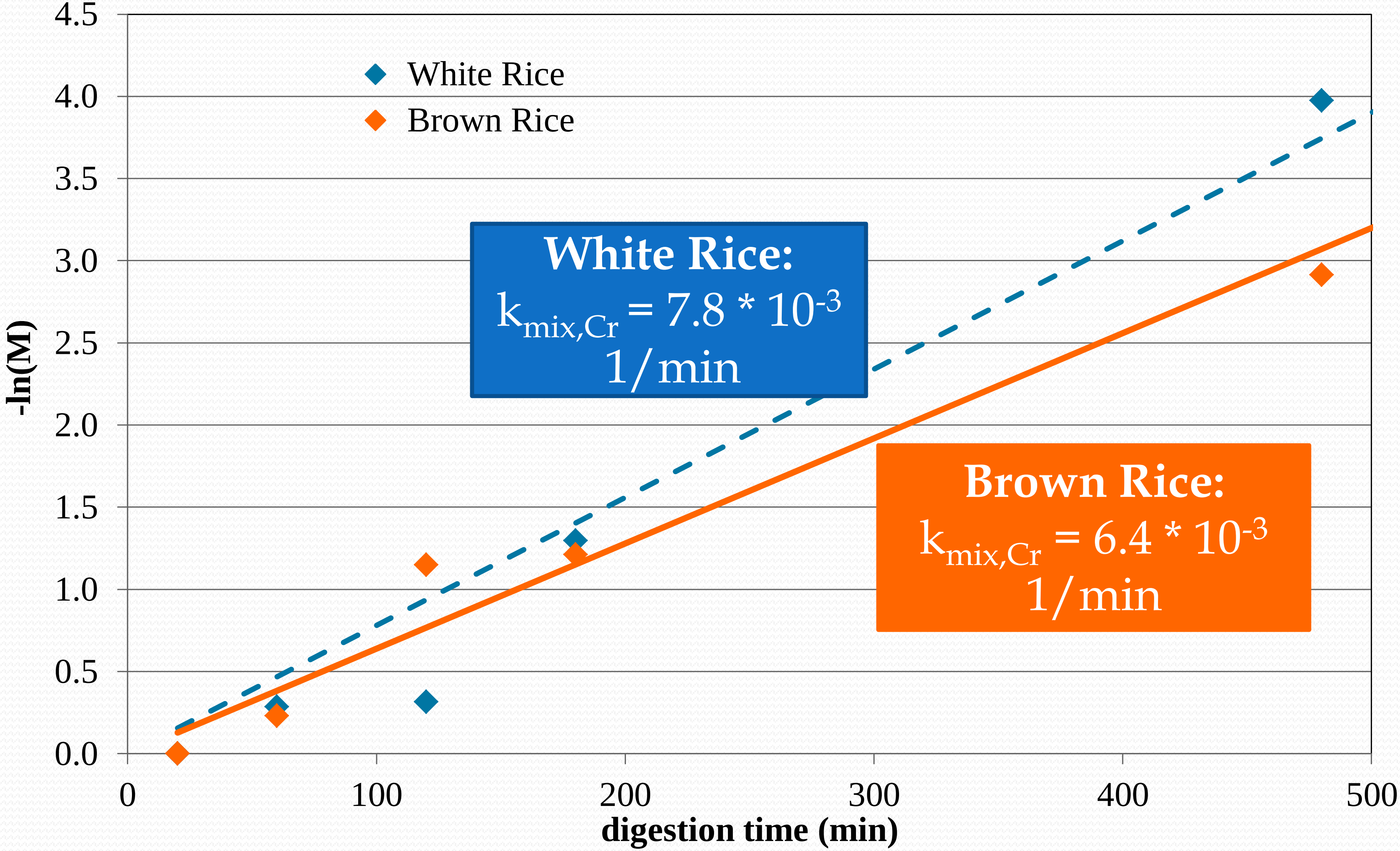
$$\boxed{M = \frac{\sigma_t^2 - \sigma_\infty^2}{\sigma_0^2 - \sigma_\infty^2}}$$

- Evolution of mixing indices over time to determine **rate of mixing**:
  - t = time elapsed
  - k_{mix} = mixing rate constant

$$\boxed{\ln(M) = -k_{mix} * t}$$

References: Smith, 2003; Schofield, 1976

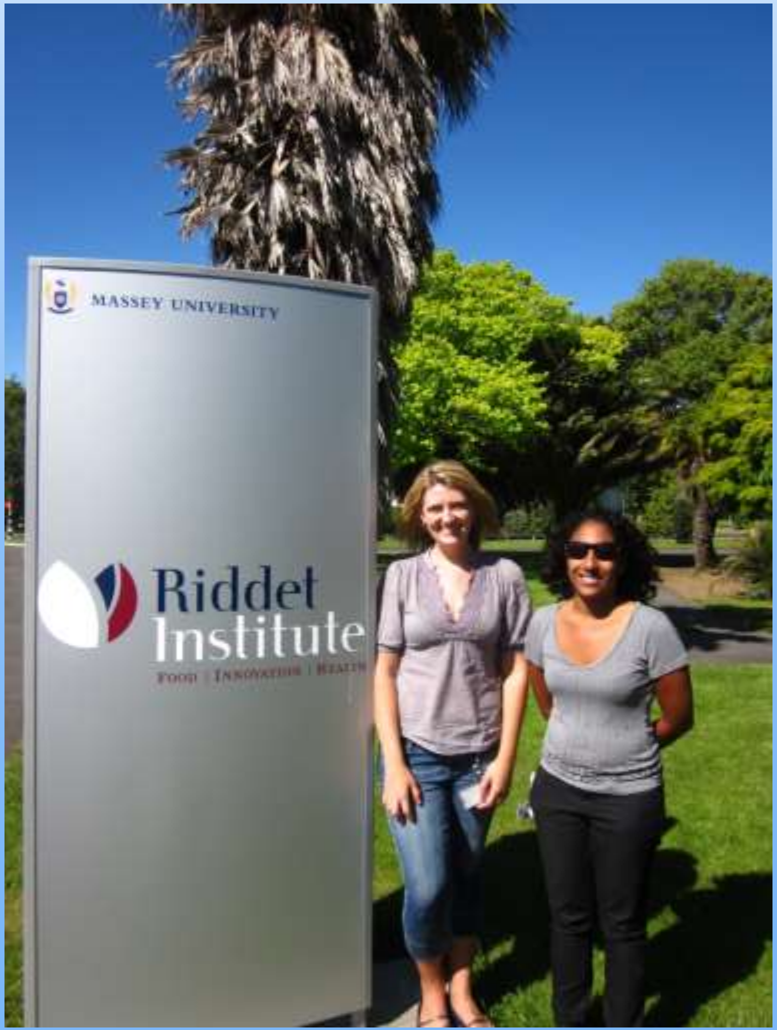
Mixing Index Calculation: Cr



Food Structure, textural properties and digestion

Summary

- Gastric digestion of foods remains a poorly understood process
- A quantitative understanding is required to develop next generation of foods for health
- Strong collaborations among food scientists and engineers and researchers from medical, nutrition, and pharmacology fields are necessary to advance science in this area.



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Massey University
New Zealand