A discrete population balance to simulate the particle size distribution in a bolus of chewed rice

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This is part of a larger body of work:

‘Model food breakdown and bolus formation during chewing’

> Looking at a number of different food systems:
  Cooked meat, pork
  Peanuts
  Gelatine
  Rice
Food breakdown

Food before the first bite

Mechanical size reduction and saliva addition

A loose aggregation of particles progressively becomes more cohesive

Excess liquid, small particles and dissolved solids are swallowed

Cohesive bolus formed comprising approx 50% of ingested solids

Processes that occur at the particle-liquid interface

Absorption

Dissolution / Leaching
Comminution Models

> Comminution is considered to be a composite of two processes
  - Particle Selection
  - Particle Breakage

> Have been adapted from industrial processes and used to simulate mastication (van der Bilt 1987, Lucas and Luke 1983b).
Rice comminution model

- Every particle in the system is individually accounted for

- A mechanistic selection function from the literature (van der Glas et al 1992)

- A cleave and paste breakage function developed in this work
Particle selection

Breakage site – tooth surface suitable for breaking particles of a particular size.
The first particle will occupy a fraction of the breakage sites, given by,

\[ O_1(X,1) = \frac{S_1(X,1)}{n_b(X)} \]

Where \( S_1(X,1) \) is the average chance of the first particle being selected.

\( O_1(X,1) \) depends on factors such as the particle manipulation of the tongue, it is the selection chance of a single particle per breakage site, by definition considered to be a measure of the particle affinity of the oral system for size \( X \).
Van der Glas et al (1992)

Theoretical number of particles requires to achieve the occupied fraction of the particle mixture

\[
n_s(X_i) = n_b(X_i)
\]

Total fraction of breakage sites occupied by the particle mixture

\[
1 - \prod_{j=1}^{k} (1 - O_1(X_j, 1))^{n_{X_j}}
\]

Number of breakage sites

\[
\sum_{j=1}^{k} (n_{X_j} \cdot \ln(1 - O_1(X_j, 1)))
\]

Number of selected particles

\[
n_x \cdot \ln(1 - O_1(X_i, 1))
\]
Selection function

Mixture of particles

Calculate the number of selected particles of each size class
Threshold particle size

> It is reasonable to consider a size threshold, below which particles are no longer fragmented as the result of a breakage event.

> Selection thresholds of 1.8 and 1.0 mm have been suggested for brittle foods. Such a threshold will need to be determined from the particle size data.

> The desire to continue chewing may be dictated by the proportion of particles above some size threshold.
There are many possibilities for particle fragmentation. Influenced by particle properties, orientation and the oral physiology.

\[ P_i = \left( \frac{V_t}{V_i} \right) \]
Assumptions

- Comminution only
- Volume is conserved
- Spherical particles
- Selection and breakage parameters are constant
Experimental

- Rice chewing – subject took a spoonful of rice and chewed naturally until instructed to expectorate after 8, 16, 24, 32 or 40 chews. The natural swallow point was 32 chews.

- We couldn’t measure the distribution before 8 chews because particles were still present that were too large for Mastersizer.

- Solids lost from the bolus were measured
Results - PSD in the rice bolus

Volume Fraction of particles in each bin

- Volume %
- log Bin Size (μm)

Threshold size

- 40 chews
- 32 chews
- 24 chews
- 16 chews
- 8 chews
Comparison between the PSD simulation and the Mastersizer data for particles in the large size range
Model Parameters

\[ n_s(X_i) = n_b(X_i) \left[ \frac{n_s \cdot \ln(1 - O_1(X_i,1))}{\sum_{j=1}^{k} \left( n_s \cdot \ln(1 - O_1(X_i,1)) \right)^{n_j}} \right] \left[ 1 - \prod_{j=1}^{k} \left( 1 - O_1(X_i,1) \right)^{n_j} \right] \]

**Breakage function**

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave no. daughter particles</td>
<td>1.6</td>
</tr>
</tbody>
</table>

\[ P_i = \left( \frac{V_t}{V_i} \right)^\alpha \]

<table>
<thead>
<tr>
<th>( X (\mu m) )</th>
<th>( n_b )</th>
<th>( O_1(x,1) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4714 - 4046</td>
<td>20</td>
<td>0.05012</td>
</tr>
<tr>
<td>4045 - 3473</td>
<td>27</td>
<td>0.03467</td>
</tr>
<tr>
<td>3472 - 2981</td>
<td>37</td>
<td>0.02089</td>
</tr>
<tr>
<td>2980 - 2559</td>
<td>50</td>
<td>0.01259</td>
</tr>
<tr>
<td>2558 - 2196</td>
<td>68</td>
<td>0.00759</td>
</tr>
<tr>
<td>2195 - 1885</td>
<td>91</td>
<td>0.00457</td>
</tr>
<tr>
<td>1884 - 1618</td>
<td>126</td>
<td>0.00275</td>
</tr>
<tr>
<td>1617 - 1389</td>
<td>170</td>
<td>0.00166</td>
</tr>
<tr>
<td>1388 - 1192</td>
<td>229</td>
<td>0.00100</td>
</tr>
<tr>
<td>1191 - 1023</td>
<td>316</td>
<td>0.00060</td>
</tr>
<tr>
<td>1022 - 878</td>
<td>427</td>
<td>0.00035</td>
</tr>
<tr>
<td>877 - 754</td>
<td>575</td>
<td>0.00021</td>
</tr>
<tr>
<td>753 - 647</td>
<td>776</td>
<td>0.00013</td>
</tr>
</tbody>
</table>
Discussion points

Discrepancy could be owing to

– Too many particles being selected in the later stages

– The volume of the bolus selected each chew was consistent throughout mastication

– Particle properties changing over time

– Attrition
Solids Lost from the bolus

What/why?

> Solids lost/displaced from the bolus were not considered in the model.

They are significant and should be incorporated to better represent bolus formation.

<table>
<thead>
<tr>
<th>No. chews</th>
<th>Mass loss (% dry solids)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>7.26 ± 0.75</td>
</tr>
<tr>
<td>16</td>
<td>7.84 ± 1.27</td>
</tr>
<tr>
<td>24</td>
<td>11.73 ± 0.85</td>
</tr>
<tr>
<td>32</td>
<td>13.28 ± 1.82</td>
</tr>
<tr>
<td>40</td>
<td>14.57 ± 2.83</td>
</tr>
</tbody>
</table>
Conclusions

> A number based simulation using mechanistic selection and breakage functions has been shown to produce a PSD for large particles similar to experimental data.

> The model presented here could be adapted to other foods and extended to incorporate mass transfer of moisture and solutes between the solid and liquid phases.

Future/Current work

> Single chew experiments for validation of the selection function parameters of breakage sites and particle affinity.


Thank You!

Questions?