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# Mechanistic model of *in vitro* salt release from model dairy gels based on standardized breakdown test simulating mastication

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## Abstract

The temporal dominance of sensations method showed that four model dairy products had different dynamic profiles in terms of salt and texture perception. We investigated the physical origins of these differences, by studying the breakdown of these products and its impact on salt release. An experimental device was used for monitoring the kinetics of salt release from the food products into water -simulating saliva- after a standardized compression -simulating mastication- independently of the inter and intra individual variability. A mechanistic model was developed to quantify product breakdown in terms of the area of contact between the product and the aqueous phase. Fat had a major influence on breakdown behaviour and the calculated contact area that could be accounted for by the microstructure of the product. These results provide insight into the possible origins of differences in sensory perceptions of foods. We also discussed the use of this mechanistic model for modeling salt release in the conditions of food consumption.

*Keywords:* cheese, dynamic, sensory, Temporal Dominance Sensation, texture, NaCl

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## 1. Introduction

Reducing the salt content of food has become a major concern for public health authorities worldwide. There is strong scientific evidence that dietary salt consumption is responsible for hypertension, which may result in cardiovascular disease, gastric cancer, osteoporosis, cataracts, kidney stones and diabetes (Organisation, 2007). The World Health Organisation therefore recommends limiting daily sodium chloride intake to 5 g. Salt consumption may, however, be two or three times higher than this recommended level in some developed countries.

Reducing the salt or fat content of food is a major challenge for food manufacturers, because it often leads to a loss of organoleptic qualities. Food structure and texture affect aroma and taste perception (Phan et al., 2008; Saint-Eve et al., 2009; Koliandris et al., 2010; Panouillé et al., 2010),

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19 so one promising possibility is the tailoring of the food matrix to decrease salt content without  
20 decreasing the perception of saltiness. For example, liquid model cheeses were perceived as being  
21 more salty than gelled model cheeses (Panouillé et al., 2010). For gelled model cheeses, the degree  
22 of saltiness perceived depends on fat content (Panouillé et al., 2010). In this context, mechanistic  
23 models describing stimuli release during food consumption are of great interest, because they may  
24 make it possible to identify the most important physicochemical and physiological parameters  
25 responsible for this release (Harrison et al., 1998; Wright et al., 2003; Wright and Hills, 2003;  
26 Tréléa et al., 2008). Harrison et al. (1998) and Wright and Hills (2003) developed the first  
27 models of flavour release (i.e. the release of aroma compounds) from the chewed bolus. They  
28 demonstrated the importance of having detailed knowledge of the mastication process for the  
29 prediction of particle size distribution and of the contact areas between the product and the  
30 saliva and between the product and air. Food fragmentation can be modelled from empirical  
31 laws fitted to experimental data obtained in spit-out experiments (Kobayashi et al., 2006, 2010) or  
32 by statistical models considering mastication as a selection and breakdown process (van der Bilt  
33 et al., 1987; Baragar et al., 1996; Harrison et al., 1998; Wright et al., 2003). From the distribution  
34 of chewing and swallowing time intervals measured by electromyography, Wright et al. (2003)  
35 simulated individual mastication patterns for use in flavour release calculations. However, to  
36 our knowledge, no model has yet been developed that takes into account the properties of the  
37 product for the prediction of particle size distribution and salt release in the mouth.

38 The objective of this study was so to quantify the breakdown of model dairy products in  
39 terms of contact areas independently of the individual variability of consumers.

40 Four model dairy products of different composition were chosen for study because they had  
41 already been extensively characterised, not only in terms of rheology and texture, but also in  
42 term of bolus formation (Panouillé et al., 2010; Drago et al., 2010). We first undertook a sensory  
43 characterisation of these dairy products. We characterised the dynamics of saltiness and texture  
44 perception, by generating temporal dominance of sensation (TDS) profiles for the four products.  
45 We then used an experimental device similar to those used in previous studies by Koliandris et al.  
46 (2008) and Mills et al. (2011), to measure salt release from product to water after breakdown  
47 in controlled conditions. A mechanistic model was developed for calculation of the contact area  
48 between the water and the product generated by compression. Finally, the results were discussed  
49 in terms of composition, structure and perception. We also discussed the use of this mechanistic  
50 model and methodology to model salt release in conditions of food consumption.

## 2. Materials & Methods

### 2.1. Samples preparation

Model cheeses were prepared as previously described by Saint-Eve et al. (2009): PL60 ultrafiltered skim milk retentate powder (Triballat, Noyal-sur-Vilaine, France), anhydrous milk fat (Corman, Goé, Belgium) and sodium chloride (Prolabo, France) were mixed. The pH was adjusted to 6.2 by adding glucono-delta-lactone (Sigma – Aldrich, Steinheim, Germany), rennet was added and the mixture was poured into containers and allowed to coagulate for 3 h at 30°C. We used ultrafiltered skim milk retentate powder because the mineral composition of this product is similar to that of cow’s milk, making it possible to avoid syneresis. Model cheeses were stored at 4°C overnight and experiments were carried out on the day after their preparation. We studied four model cheeses differing only in their fat content (0 or 40% w/w, dry basis) and retentate powder concentration (150 or 250 g/kg). The other components remained constant: salt content (1% w/w) and pH-value (6.2). Hereafter, we referred to the products as follows: PL60 concentration (g/kg) (150 or 250) / fat content (% dry basis, 0 or 40). Table 1 summarizes the various compositions and notations for the four products.

### 2.2. Sensory analysis

The temporal perception of the four model cheeses was studied using the temporal dominance of sensation (TDS) method. Each panelist scored, over the course of time, the intensity of the descriptor perceived as dominant. TDS has been processed by 16 trained panelists, volunteer and motivated. For TDS measurement, seven attributes (moistness, softness, firmness, crumbliness, stickiness, fattiness and saltiness) were chosen, following the profile performed on the same products (Panouillé et al., 2010). We used the same terms and definitions as in the previous study. All the attributes were presented simultaneously on a screen with a button. The panellists had to click on “start” when they placed a sample of the model cheese in the mouth and, during the evaluation, they were asked to select the attribute they considered to be dominant. If the dominant attribute change during the course of the trial, the subjects were asked to click on the new dominant attribute. For each panellist, we collected the following data during the consumption of each product: the time at which as attribute was identified as dominant and the name of the attribute concerned. During each run, the subjects were free to chew the sample as they wished. Samples were coded with three-digit random numbers and served in transparent plastic cups. Sample size was standardised at 5 g. The four samples were assessed in duplicate, in random order, over two evaluation sessions. Data were acquired with Fizz software

83 (Biosystèmes, 1990), in individual sensory booths under white light. TDS analysis was performed  
84 with Fizz Data Treatment. The dominance proportions were used to draw TDS curves over time,  
85 providing information about the descriptors considered dominant during the consumption period.  
86 Dominance proportions for an attribute  $d^a$  were calculated by dividing the number of citations of  
87 this attribute  $n_c^a$  by the number of judges  $n_j$  and the number of replicate  $n_r$ , i.e  $d_a = n_c^a / (n_j n_r)$ .  
88 The sensory perceptions between panellists are close when the dominance rate is high. For each  
89 sample of model cheese, the dominance curves of all the descriptors are displayed on the same  
90 graph. Two other curves are also displayed to facilitate interpretation. The first, labelled as  
91 “chance” indicates the dominance proportion that an attribute would be expected to obtain by  
92 chance alone (1/number of attributes). The second curve, labelled “significance”, indicates the  
93 smallest value of the proportion significantly higher than that expected by chance alone, in a  
94 binomial test. TDS curves above the significance level may be considered to be consistent across  
95 the panel (Pineau et al., 2009).

### 96 *2.3. Conductivity measurements*

97 Conductivity was measured with a conductivity probe (Heito, France). In addition to NaCl,  
98 the model cheese contained other solutes such as potassium, calcium, phosphates, citrates and  
99 lactates (Lauverjat et al., 2009; Flourey et al., 2009). All these species contribute to the conduc-  
100 tivity signal. With similar products, Lauverjat et al. (2009) showed that NaCl had mass transfer  
101 properties (diffusion and partition coefficients) similar to those of the other solutes. There is  
102 therefore no need to distinguish between the different solutes in this study. We use the term  
103 “salt” in this context to describe all the species contributing to the conductivity signal. The  
104 conductivity probe was thus calibrated at 37°C, with aqueous NaCl solutions prepared with  
105 deionised water, and concentrations are given in g/L NaCl equivalent.

### 106 *2.4. Experimental set-up for product breakdown and salt release measurement*

107 A schematic diagram of the experimental set-up is shown in Figure 1. It consisted of a  
108 conductivity probe (Heito, France), a texturometer (TAXT2, Stable Microsystems) equipped  
109 with a Teflon probe 35 mm in diameter, a beaker of deionised water at 37°C (400 mL), and a  
110 magnetic stirrer. On-line measurements of changes in conductivity began at time  $t=0$ . At  $t=60$  s,  
111 a calibrated cylinder of product (12 mm height and 20 mm diameter,  $\sim 3$  g of product) was placed  
112 in the beaker. At  $t=150$  s, the product was compressed one or several times to a deformation  
113 level of 80 % of the initial height. This compression took only 1 s in an overall experiment time  
114 of 400 s. Conductivity registration was stopped at  $t=400$  s. Similar experiments were carried

115 out with no compression as controls, to assess the release of salt from intact product into water.  
 116 Three replicates were carried out per product.

### 117 2.5. Partition coefficient of salt

118 The water / product partition coefficients  $K$  and initial salt concentrations  $C_p^0$  of the four  
 119 products were determined according to SL-PRV method developed by Lauverjat et al. (2009).  
 120 The values of  $K$  and  $C_p^0$  are global and correspond to the total amount of salt present. The  
 121 partition coefficients  $K$  were comprised between 0.7 and 1 and the initial salt concentrations of  
 122 the products  $C_p^0$  were between 13 g/L and 17 g/L.

### 123 2.6. Mass transfer model

124 Compression instantaneously generated a population of  $n$  particles denoted  $i$ , where  $i = \overline{1..n}$ .  
 125 For each particle, we note  $V_{pi}$  its volume ( $\text{m}^3$ ) and  $A_i$  its contact area ( $\text{m}^2$ ) with the surrounding  
 126 volume of water  $V_w$  ( $\text{m}^3$ ). For processes occurring over a much shorter time scale than diffusion,  
 127 the most mathematically tractable option is to consider salt release to be described by a mass  
 128 transfer coefficient  $k_p$  (m/s) and to consider the solute concentration of each piece  $C_{pi}$  to be  
 129 uniform. Changes in the salt concentration of the water  $C_w$  is therefore given by a mass balance  
 130 between the product and the water:

$$V_w \frac{dC_w}{dt} = k_p \sum_{i=1}^n A_i (K.C_{pi}(t) - C_w(t)) \quad (1)$$

131 where  $t$  is the time (s) and  $K$  is the water / product partition coefficient given by the ratio  
 132 of the salt concentration at the equilibrium between the water  $C_w^{eq}$  and the product  $C_p^{eq}$ :

$$K = \frac{C_w^{eq}}{C_p^{eq}} \quad (2)$$

133 The salt release from each particle of product is given by:

$$V_{pi} \frac{dC_{pi}}{dt} = -k_p A_i (K.C_{pi}(t) - C_w(t)) \text{ for } i = \overline{1..n} \quad (3)$$

134 This model is not tractable in practice. We therefore simplified these equations to generate  
 135 two usable models.

#### 136 Model 1: particles of uniform size

137 If the duration of the experiment is very short with respect to the time scale of the mass  
 138 transfer from the product to the water (i.e.  $t \ll V_{pi}/k_p A_i$  whatever  $i$ ), the concentrations in  
 139 each piece of product are similar and the population of pieces is equivalent to one product piece

140 of volume  $V_p = \sum_{i=1}^n V_{pi}$ , of contact area  $A = \sum_{i=1}^n A_i$  and of salt concentration  $C_p$  (Figure 2).  
 141 Equations 1 and 3 can be reduced to:

$$V_w \frac{dC_w}{dt} = k_p A (K.C_p(t) - C_w(t)) \quad (4)$$

$$V_p \frac{dC_p}{dt} = -k_p A (K.C_p(t) - C_w(t)) \quad (5)$$

142 The initial conditions are given by the salt concentration in water at  $t_0 = 150$  s and the initial  
 143 concentration in the product  $C_p^0$  :

$$C_w(t_0) = C_w^0 \text{ at } t_0 = 150 \text{ s} \quad (6)$$

$$C_p(t_0) = C_p^0 \text{ at } t_0 = 150 \text{ s} \quad (7)$$

144  $C_p^0$  and  $K$  were determined by the solid-liquid phase ratio variation method (SL-PRV) (Lau-  
 145 verjat et al., 2009). The contact area  $A$  and the mass transfer coefficient  $k_p$  were unknown *a*  
 146 *priori*. The value of  $k_p$  was obtained for each product by fitting this model to the kinetics of salt  
 147 release measured in water  $C_w(t)$  in the absence of compression (“control test”). The contact area  
 148  $A_0$  was calculated from the initial sample geometry ( $A_0 = 10.7 \text{ cm}^2$ ). Knowing  $k_p$ ,  $A$  was then  
 149 determined by fitting the model to  $C_w(t)$  measured during the compression tests. Regression  
 150 analysis was carried out with Matlab 7 (The Mathworks, Natick, MA).

#### 151 *Model 2: particles of non-uniform size*

152 If the size distribution of a population of particles is broad, then the the uniform-size model  
 153 does not correctly represent salt release because the time scale of the mass transfer from the  
 154 smallest particles to the water is equivalent to the duration of the experiment (i.e. there is  $i$  such  
 155 that  $t \sim V_{pi}/k_p A_i$ ). A second model was developed and applied to a single product generating  
 156 particles of heterogeneous size (250/40). Compression was considered to generate two populations  
 157 of particles with volumes  $V_{p1}$  and  $V_{p2}$ , contact areas  $A_1$  and  $A_2$  and salt concentration  $C_{p1}$  and  
 158  $C_{p2}$  (Figure 2). The mass balances of salt in water involve two terms representing the flux of  
 159 salt from each piece of product. Thus, we have:

$$V_w \frac{dC_w}{dt} = k_p A_1 (K.C_{p1}(t) - C_w(t)) + k_p A_2 (K.C_{p2}(t) - C_w(t)) \quad (8)$$

160 The mass balances in each volume are:

$$V_{p1} \frac{dC_{p1}}{dt} = -k_p A_1 (K \cdot C_{p1}(t) - C_w(t)) \quad (9)$$

$$V_{p2} \frac{dC_{p2}}{dt} = -k_p A_2 (K \cdot C_{p2}(t) - C_w(t)) \quad (10)$$

161 The total contact area  $A$  between the product and the water is given by:

$$A = A_1 + A_2 \quad (11)$$

162 Knowing the total volume of product  $V_p$ , the relationship between  $V_{p1}$  and  $V_{p2}$  is given by:

$$V_p = V_{p1} + V_{p2} \quad (12)$$

163 The initial conditions are:

$$C_w(t_0) = C_w^0 \text{ at } t_0 = 150 \text{ s} \quad (13)$$

$$C_{p1}(t_0) = C_p^0 \text{ at } t_0 = 150 \text{ s} \quad (14)$$

$$C_{p2}(t_0) = C_p^0 \text{ at } t_0 = 150 \text{ s} \quad (15)$$

164 Fitting the model to the experimentally measured salt kinetics  $C_w(t)$ , we were able to de-  
 165 termine  $A_1$ ,  $A_2$ ,  $V_{p1}$  and  $V_{p2}$ .  $k_p$  was determined with Model 1 based on the test without  
 166 compression (“control test”).

## 167 2.7. Data analysis

168 One-way analysis of variance (ANOVA) on mass transfer coefficients  $k_p$  and on total contact  
 169 area  $A$  with the products as factor were performed (Matlab7.0). When significant product  
 170 differences were observed ( $p < 0.05$ ), the results were compared using a multiple comparison test  
 171 (Matlab7.0).

## 172 3. Results

### 173 3.1. Sensory analysis

174 The TDS curves (Figure 3) show, for each product, the dominant attribute perceived at each  
 175 time point during the trial, for the panel as a whole. For products with high levels of protein,



176 the 250/40 product was perceived as crumbly from 2 s to 6 s and soft from 2 s to 17 s. It  
177 was then perceived salty from 13 s to 28 s with a maximum around 18 s. 250/0 was perceived  
178 moist, soft, crumbly and then salty from 14 s to 25 s (later and for a shorter period than for  
179 250/40). Products with low protein levels (150/0 and 150/40) were perceived as being soft  
180 and moist. The 150/0 product was perceived as salty from 11 s to 25 s, whereas 150/40 was  
181 perceived as being dominant salty from 6 s to 30 s. The presence of fat therefore led to the  
182 earlier perception of saltiness and a longer duration of this perception during the consumption  
183 of model dairy products. After 32 s, the TDS curves for all products were below the significance  
184 limit, indicating a lack of consensus concerning the dominant attribute.

### 185 *3.2. Influence of compression parameters on the release kinetics*

186 For the selection of appropriate parameters for use in the breakdown test, we assessed the  
187 influence of the compression parameters on the salt release kinetics for one product (250/40).  
188 The parameters considered were probe velocity (1 mm/s or 10 mm/s), level of strain (50 or 80%)  
189 and the number of compression cycles (1 or 5 cycles). Figure 4 shows the kinetics obtained.

#### 190 *Effect of probe velocity*

191 The velocity of the probe had no great impact on the release kinetics: curves were shifted  
192 to the right only for the lowest velocity (1 mm/s). Breakdown occurred 10 s later for a probe  
193 velocity of 1 mm/s than for a velocity of 10 mm/s (i.e. at 190 s rather than 150 s). The kinetics  
194 followed a similar pattern after this time point for both velocities. A velocity of 10 mm/s is  
195 closer to the conditions of natural mastication (Finney and Meullenet , 2005) and was therefore  
196 retained for subsequent experiments.

#### 197 *Effect of the level of strain*

198 Strain level affects salt release kinetics. Salt release was more rapid at 80% strain than at  
199 50% strain (Figure 4). This difference is further accounted for by the greater contact area at  
200 higher levels of strain, due to the greater product breakdown. The fracture strain of this product  
201 is about 80%(Panouillé et al., 2010). Thus, at 50% strain, the product is broken up into larger  
202 particles, which therefore have a smaller area of contact with the water. During mastication,  
203 the jaws and tongue impose high levels of strain. We therefore retained the 80% strain level for  
204 subsequent experiments.

#### 205 *Effect of the number of compression cycles*

206 The last parameter tested was the number of compression cycles (1 or 5 cycles). This pa-  
207 rameter had no effect on salt release kinetics (Figure 4). Indeed, the product was fully broken

208 up after the first compression cycle.

209 These preliminary tests made it possible to select the compression parameters: a probe  
210 velocity of 10 mm/s, a strain level of 80% and one compression cycle were retained for subsequent  
211 experiments.

### 212 *Effect of compression*

213 Figure 5 presents typical patterns of salt release for two products (250/0 and 250/40) without  
214 compression (“control test”) and with compression (probe velocity: 10 mm/s, strain level: 80%,  
215 one cycle of compression). In the absence of compression, salt was released slowly and continu-  
216 ously. By contrast, compression with a strain level of 80% significantly accelerated salt release,  
217 from 150 s onwards, due to the breakdown of the product and the generation of a greater contact  
218 area between product and water.

### 219 *3.3. Effect of the product contact area generation*

#### 220 *Mass transfer coefficient*

221 Model 1 was first fitted to the salt release kinetics in the absence of compression (“control  
222 test”), making it possible to calculate the mass transfer coefficients  $k_p$ . These coefficients ranged  
223 between 2 and  $3 \cdot 10^{-6}$  m/s. The product had no significant effect on the mass transfer coefficient  
224 ( $p > 0.05$ ).

#### 225 *Effect of compression on contact area*

226 By fitting model 1 (particles with uniform size) to the salt release kinetics after compression,  
227 we were able to determine the contact area generated by the compression. Figure 6-a presents  
228 the pattern of salt release from the time at which compression occurred (150 s) until the end  
229 of the experiments for three products (250/0, 150/0, 150/40) and the fitted release models. For  
230 these products, model 1 fit the data well: the measurement time was short enough to consider  
231 that the population of particles is equivalent to one piece of product. Figure 6-b shows the  
232 kinetics obtained for 250/40. Model 1 fitted the data poorly. We therefore used only model  
233 2 (non uniform size distribution) for this product. In this case, salt release slowed 50 seconds  
234 after the compression (at  $t=200$  s). Salt release was initially rapid, due to the contribution of  
235 all particles. We can therefore show, from the general model, that the slope of the curve at the  
236 origin is proportional to the total amount of product/water contact area  $A$ . Salt release was  
237 subsequently lower and due exclusively to release from the largest particles.

238 The contact areas generated by compression are shown on Figure 7. They were about 100  
239  $\text{cm}^2$  for 250/40 and 20 to 30  $\text{cm}^2$  for the others products (150/0, 150/40, 250/0). These areas

240 are about 10 times and 2 times larger, respectively, than the initial sample area. The 250/40  
241 product behaved markedly differently from the other products. Statistical analysis confirmed a  
242 strong product effect ( $p < 0.0001$ ) and distinguished two different classes of products: one class  
243 consisting of 250/40 and the other consisting of the other three products.

244 Visual inspection of the products after compression (Figure 8) confirmed these results: 250/40  
245 was fragmented into smaller pieces than the other products.

## 246 4. Discussion

### 247 4.1. Effect of product structure and composition on breakdown

248 The composition of the product affected the contact area generated by strong compression.  
249 Fat content had a strong effect for high dry matter, with 250/40 having a contact area 3.5 times  
250 that for 250/0.

251 In a previous study with a similar experimental device, Koliandris et al. (2008) obtained a  
252 good negative correlation between  $\text{Na}^+$  concentration at a given time (20 s after the breakdown)  
253 and the strain rupture of gels. However, it seems difficult to relate the salt release kinetics with a  
254 strain or stress rupture because salt release is dependent principally on the contact area generated  
255 by product breakdown, which is related to product microstructure and the propagation of cracks  
256 within the sample (Gunasekaran and Ak, 2003).

257 The observations reported here can be accounted for by product microstructure. Panouillé  
258 et al. (2010) characterised the rheological behaviour and the microstructure of the products used  
259 in this study. Measurements under small-amplitude oscillations showed that all these products  
260 displayed a gel-like behaviour ( $G' > G''$ , almost constant at all frequencies). All products had  
261 a fracture strain lower than 80% and were therefore fractured during the compression. The  
262 microstructure of the products was characterised by confocal laser scanning microscopy. Panouillé  
263 et al. (2010) showed that for all products, after gel formation, there was a visible protein network  
264 that was denser for the 250 products than for the 150 products. For 250/40 and 150/40, the fat  
265 was concentrated within the protein network and was almost absent from the serum phase. For  
266 250/40, a few flocculated and coalesced fat globules were observed. These results may account  
267 for the differences in contact area generated by compression. The concentration of the fat within  
268 the protein network may have weakened the protein network, facilitating the propagation of  
269 the fracture through the sample and resulting in the generation of smaller particles. However,  
270 this effect of fat depends on the processes used to manufacture the product, which should be  
271 investigated, along with other technological processes.

#### 272 4.2. Breakdown and sensory properties

273 For the products tested here, Panouillé et al. (2010) observed that the perception of saltiness  
274 increased with fat content. Indeed, a greater fat content leads to the generation of a larger  
275 contact area on compression, resulting in higher levels of salt release. We can assume that the  
276 breakdown pattern in the mouth is similar to that observed *in vitro* and that salt is released  
277 more rapidly from fat-containing samples than from fat-free samples.

278 The results obtained by TDS analysis support this hypothesis. For 250/40, crumbly was the  
279 dominant attribute perceived (Figure 3). This sensation was identified as dominant immediately  
280 after the introduction of the product into the mouth for 250/40, whereas it was identified as the  
281 dominant attribute 6 s later for 250/0. This suggests that 250/40 was more quickly fractionated  
282 by mastication than the other products, creating a greater contact area with saliva and resulting  
283 in the more rapid release of salt.

#### 284 4.3. Modeling breakdown and salt release during food consumption

285 In addition to an analysis of the effects of dairy product composition and structure on the  
286 breakdown of these products, this study constitutes the first step towards the modeling of salt  
287 release during food consumption.

288 During mastication, the product is fractured by action of the teeth and tongue actions, result-  
289 ing in the generation of particles. To model aroma compounds release during food consumption,  
290 Harrison et al. (1998) and Wright et al. (2003) calculated the particle size distribution. However,  
291 if the duration of the mastication is very short compared to the time scale of the mass transfer  
292 from the product to the water, as demonstrated in our study, the salt release can be modeled  
293 simply with a mass transfer coefficient, without the need for knowledge concerning the size dis-  
294 tribution of the particles. The main parameter to be determined is the area of contact between  
295 the particles and the saliva. During food consumption, the food is masticated for about 30 s  
296 (mean time observed for the products used in this study). The model considering the population  
297 of particles to be equivalent to one product piece of volume  $V_p$ , of contact area  $A$  and of salt  
298 concentration  $C_p$  (Model 1: uniform size particles) fitted the data well, for three products (Figure  
299 5). For the last product (250/40), as shown Figure 9, model 1 simulated well the experimental  
300 data for times of less than approximately 50 s when the area of contact is those estimated thanks  
301 to the model 2. For this product, after 50 s, the model 1 overestimated the salt release kinetics.  
302 Thus, the model 1 could be used to model salt release during food consumption for this kind of  
303 products because the mastication duration is shorter than 50 s. The main differences between

304 the conditions *in vitro* and *in vivo* are dilution by saliva (dependent on the saliva flow rate) and  
305 the changes in contact area occurring during mastication.

## 306 **5. Conclusion**

307 The experimental device and the mechanistic model developed here made it possible to mea-  
308 sure the contact area generated by compression for several model dairy products and to account  
309 for the impact of gel structure on salt release. The model developed constitutes a first step  
310 towards the modeling of salt release during food consumption and the contact area measured  
311 under control conditions provides information about the fracture properties of the material.

312 Product composition and microstructure affect the breakdown of the product and the sensory  
313 perceptions. The food consumption and the sensory perceptions involve a set of variables that  
314 can not be reproduced at laboratory scale. However, the models and the experimental device  
315 developed in this study are approximations which considers some important variables of the  
316 mastication process. Thanks to their relative simplicity in term of use, they could be used to  
317 guide the product formulation.

318 Finally, this study shows that tailoring the microstructure of the product to control product  
319 breakdown in the mouth is one possible way in which the release and perception of stimuli could  
320 be improved.

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375 **Tables and Figures**

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406 on the experimental data to determine the contact area generated during the  
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| Code   | Milk retentate powder<br>[g/kg] | Anhydrous milk fat<br>[g/100g DM] | Rennet<br>[g/kg] | Water<br>[g/kg] |
|--------|---------------------------------|-----------------------------------|------------------|-----------------|
| 250/40 | 250                             | 40                                | 1.27             | 573             |
| 250/0  | 250                             | 0                                 | 1.27             | 740             |
| 150/40 | 150                             | 40                                | 0.78             | 740             |
| 150/0  | 150                             | 0                                 | 0.78             | 850             |

Table 1: Code and composition of the model dairy products.

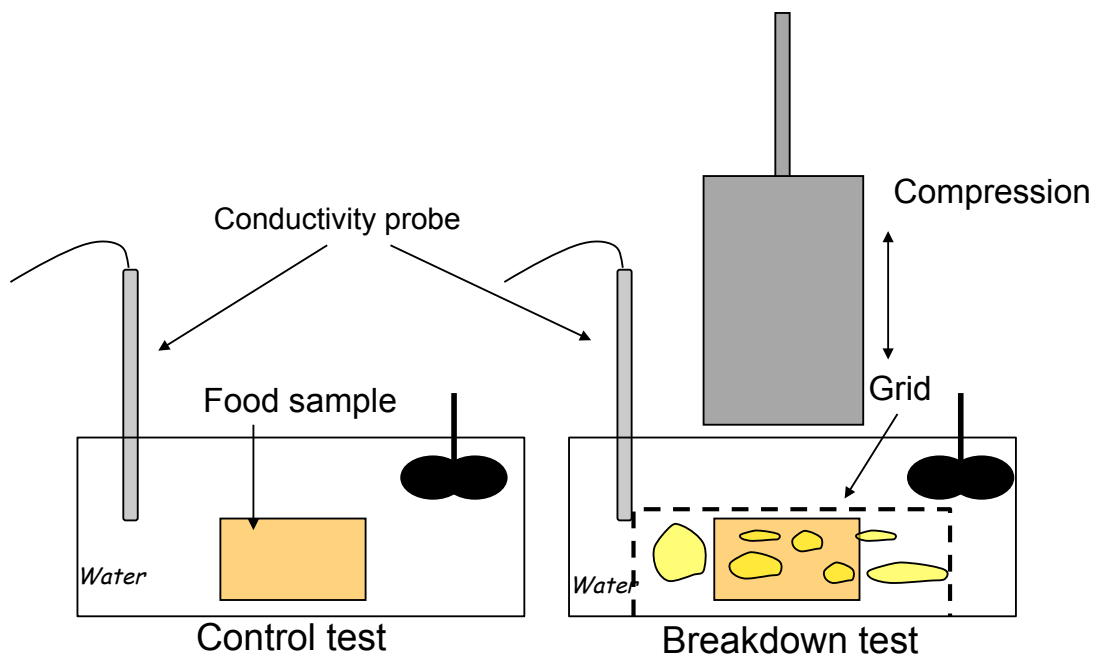


Figure 1: Schematic diagram of the experimental set-up for the breakdown test.

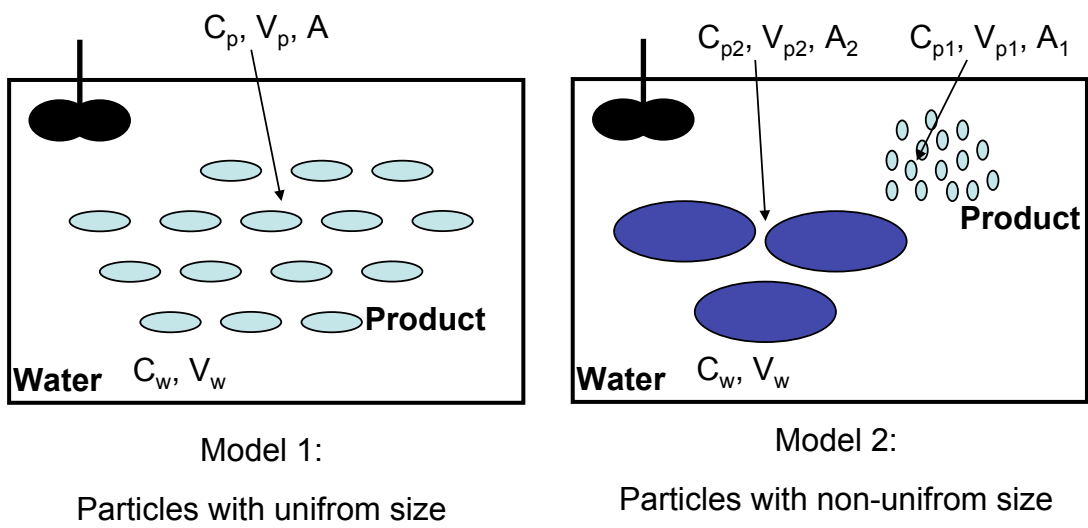


Figure 2: Principles and notations of the salt release models. Model 1 (left) considers the population of particles to be equivalent to one piece of product. Model 2 (right) considers the particle distribution to be approximated by two pieces of product of different sizes.

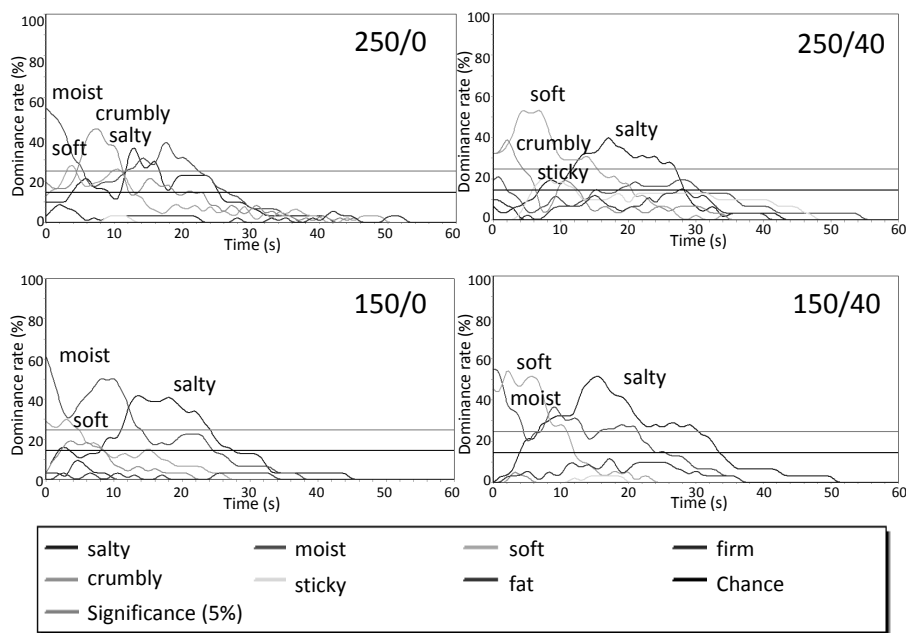


Figure 3: Temporal dominance of sensation (TDS) curves (dominance rate as a function of time) of the 4 products : 250/40, 250/0, 150/40, 150/0.

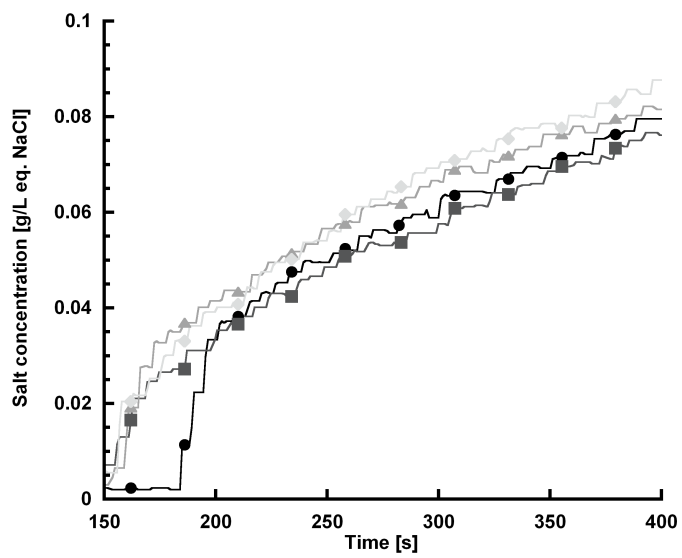


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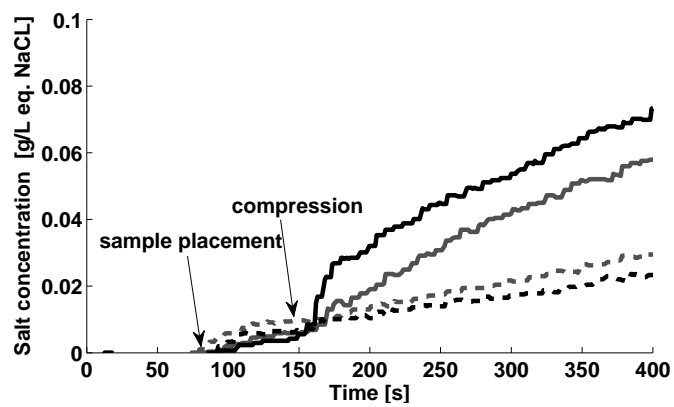


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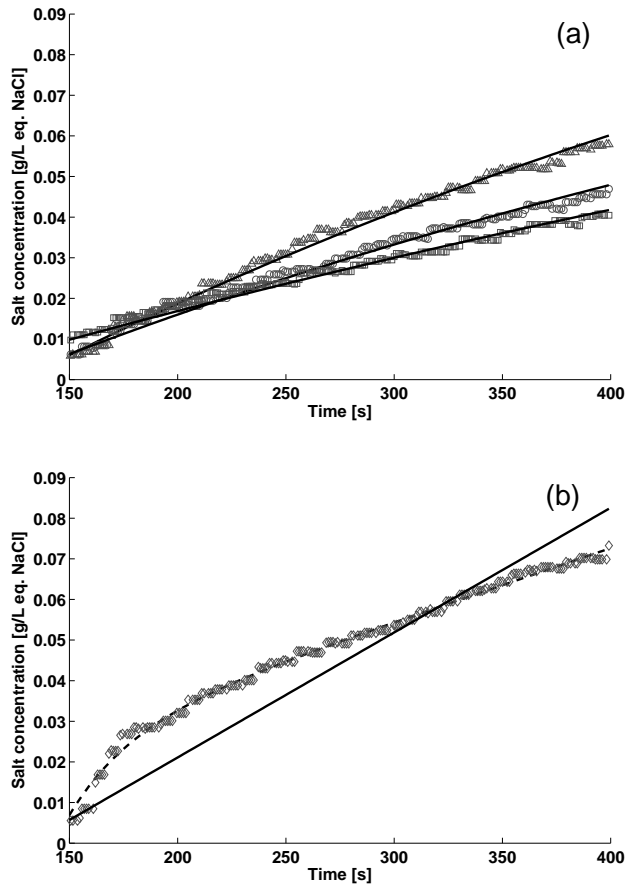


Figure 6: Experimental data and release model simulation. (a) Experimental data for 3 products ( $\Delta$  250/0,  $\circ$  150/40,  $\square$  150/0) and model 1 fittings (particles of uniform size, solid lines). (b) Experimental data for 1 product ( $\diamond$  250/40), model 1 fitting (particles of uniform size, solid line) and model 2 fitting (particles of non-uniform size, dotted lines). For 250/40 model 2 was used to determine the contact area generated during the breakdown test due to the poor agreement of the model 1 with the experimental data.



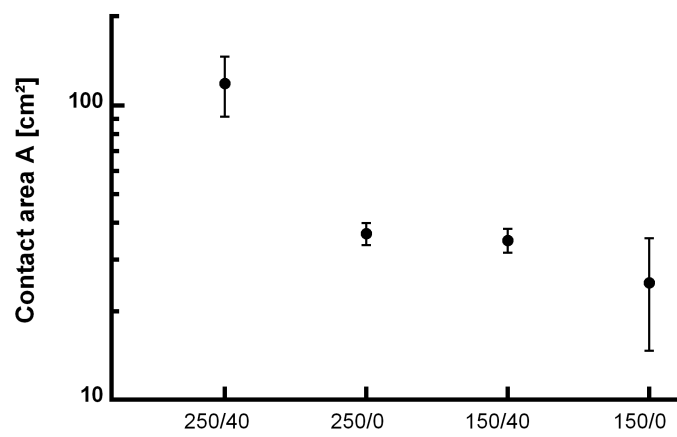


Figure 7: Contact area between the product and the water after compression for the various products studied.

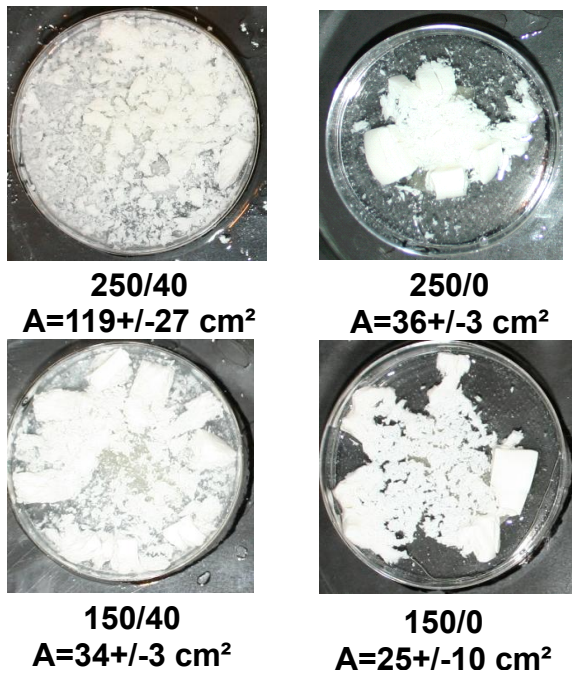


Figure 8: Model dairy products after the breakdown test.  $A$  is the area of contact between the product and the water calculated with the models.

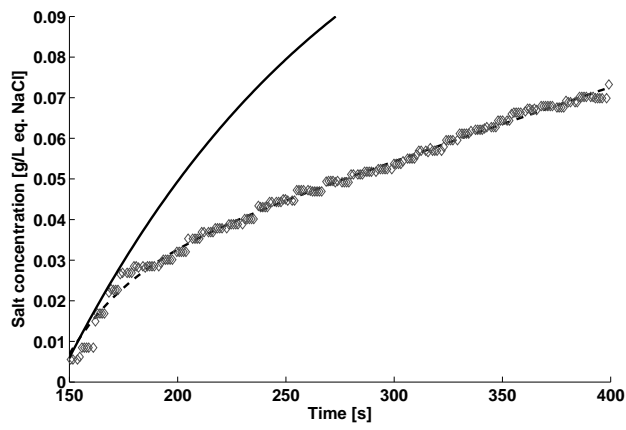


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