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1 **A biomechanical model of swallowing for understanding the influence of**
2 **saliva and food bolus viscosity on flavour release**

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15 **Abstract**

16 After swallowing a liquid or a semi-liquid food product, a thin film responsible for the dynamic profile
17 of aroma release coats the pharyngeal mucosa. The objective of the present article was to
18 understand and quantify physical mechanisms explaining pharyngeal mucosa coating. An
19 elastohydrodynamic model of swallowing was developed for Newtonian liquids that focused on the
20 most occluded region of the pharyngeal peristaltic wave. The model took lubrication by a saliva film
21 and mucosa deformability into account. Food bolus flow rate and generated load were predicted as
22 functions of three dimensionless variables: the dimensionless saliva flow rate, the viscosity ratio

23 between saliva and the food bolus, and the elasticity number. Considering physiological conditions,
24 the results were applied to predict aroma release kinetics.

25 Two sets of conditions were distinguished. The first one was obtained when the saliva film is thin, in
26 which case food bolus viscosity has a strong impact on mucosa coating and on flavour release. More
27 importantly, we demonstrated the existence of a second set of conditions. It was obtained when the
28 saliva film is thick and the food bolus coating the mucosa is very diluted by saliva during the
29 swallowing process and the impact of its viscosity on flavour release is weak. This last phenomenon
30 explains physically *in vivo* observations for Newtonian food products found in the literature.
31 Moreover, in this case, the predicted thickness of the mix of food bolus with saliva coating the
32 mucosa is approximately of 20 μm ; value in agreement with orders of magnitude found in the
33 literature.

34 Keywords: lubrication, pharynx, elastohydrodynamic, aroma, texture, model

35

36

37 **1. Introduction**

38 Food formulation has to take different recommendations to improve nutritional quality of foods (low
39 fat content, less salt and sugar) and to adapt food to specific people (as dysphagic patients) without
40 modifying their organoleptic qualities (flavour and texture perception). These organoleptic qualities
41 are closely related to the physiological process of food transformation during chewing and
42 swallowing (Weel et al., 2004; Boland et al., 2006). It is so necessary to study the processes of food
43 bolus formation (Woda et al., 2010 ; Yven et al., 2010) and of swallowing mechanisms in relation with
44 physical properties of food (Taniguchi et al., 2008; Tsukada et al., 2009) to formulate novel food
45 products.

46 Swallowing of a liquid or a semi-liquid food product generates a thin film of product coating the
47 pharyngeal mucosa (Levine, 1989) responsible for the dynamic profile of aroma release (Buettner et
48 al., 2001). The influence of rheology of liquid and semi-liquid food products on aroma release and
49 perception is an unclear and debatable issue in the literature (Hollowood et al., 2002; Cook et al.,
50 2003; Weel et al., 2004; Saint-Eve et al., 2006). We can assume that the conclusions did not match
51 because the experimental investigations covered very different rheological properties (from yield
52 stress fluids as yoghurt to shear-thinning fluids as hydrocolloids). Moreover, these analyses may have
53 been biased by the fact that rheological properties and physico-chemical properties governing aroma
54 release (such as mass transfer coefficient, Tréléa et al., 2008) are often coupled properties of the
55 product. To explain the role of product rheology on aroma release, we need to study the physical
56 phenomena governing pharyngeal mucosa coating.

57 To understand these phenomena, de Loubens et al. (2010) analysed the physiology and
58 biomechanics of swallowing. They showed that the thin film of product coating the mucosa is due to
59 a weak reflux during the pharyngeal peristalsis between the root of the tongue and the posterior

60 pharyngeal wall (Figure 1a). To physically represent this phenomenon and simplify the problem, they
 61 focused their attention on the most occluded region of the peristaltic wave. In this region, the
 62 pharyngeal peristalsis wave is equivalent to a forward roll coating process. Based on this
 63 physiological analysis, a fluid-mechanical model that considers lubrication by a saliva film was
 64 developed. However, mucosa deformability was not considered in their first model, whereas it is an
 65 important phenomena that may quantitatively improve the model predictions. In the present study,
 66 we consider that the pharyngeal peristalsis is equivalent to a forward roll coating process with
 67 deformable and lubricated surfaces (Figure 1b). In this process, the mucosa deform under the load L'
 68 applied by the pharyngeal constrictors muscles (Figure 1b). The purpose of this study was to develop
 69 an elastohydrodynamic model of the pharyngeal peristalsis in order to understand and quantify the
 70 role of saliva and the food bolus on the pharyngeal mucosa coating. The equation system was scaled
 71 by the elastic effects and solved numerically. A parametric study showed the influence of the
 72 different model parameters on food bolus flow rates and generated forces. The model was applied to
 73 flavour release and the predictions were compared with *in vivo* observations obtained for Newtonian
 74 liquid foods from the literature. Finally, main model assumptions were discussed.

75 **2. Elastohydrodynamic model of the pharyngeal peristalsis**

76 *2.1. Model hypothesis*

77 As de Loubens et al. (2010), we considered that the swallowing process is equivalent to a forward roll
 78 coating process (Figure 1). Moreover, we took the deformability of the mucosa into account. The
 79 general features of the forward roll coating process with deformable rolls for Newtonian fluids have
 80 been described by Coyle (1988). This author analysed the flow by means of two dimensionless
 81 numbers: the elasticity parameter E_s is the ratio of viscous to elastic forces:

$$82 \quad E_s = \frac{\mu_0 U'}{(2R')^2 E_e'} \quad (1)$$

83 and the load parameter F is the ratio of the external load to the elastic forces:

$$84 \quad F = \frac{L'}{(2R')^2 E_e'} \quad (2)$$

85 where E_e' is the effective elastic modulus of the substrate that covers the deformable rolls (Pa/m), μ'
86 the viscosity of the fluid (Pa.s), R' the rolls radius (m), U' the velocity (m/s) and L' the applied load per
87 unit of width (N/m).

88 Two limiting cases can be distinguished (Johnson, 1970). When F is low and E_s is high, the viscous
89 forces predominate. This case tends to the rigid roll limit that was the case developed for pharyngeal
90 peristalsis by de Loubens et al. (2010). When F is high and E_s is low, the elastic forces dominate and
91 the pressure profile is similar to that of a dry contact. This case is the large deflection limit. The
92 cylinders surfaces would intersect if there were no deformation. Coyle (1988) defined the effective
93 elastic modulus by $E_e' = E'/e_m'$, where E' is the Young modulus of the substrate (Pa) and e_m' its
94 thickness (m). Useful physiological data on the pharyngeal peristalsis are given in Table 1. From these
95 data and the results obtained by Coyle (1988), we can estimate that the pharyngeal peristalsis occurs
96 on the large deflection limit ($F \approx 3 \cdot 10^{-5}$ and $E_s \approx 8 \cdot 10^{-9}$), although the parameters have a wide range
97 of variation.

98 The present physical situation is therefore modeled with the lubrication approximation: the inertial
99 terms are neglected compared to the viscous terms in the Navier-Stokes equations. The use of the
100 lubrication approximation for the most occluded region of the pharyngeal peristalsis wave and the
101 fact that the flow can be considered as stationary was already justified by de Loubens et al. (2010). In
102 addition, we take the presence of a lubricating saliva film and mucosa deformability into
103 consideration.

104 Since the confusion concerning the role of food rheology on flavour release, we restrict our analysis
105 to homogeneous Newtonian food bolus. Moreover, in the paragraph concerning the model

106 applications (4.2), model predictions were compared with *in vivo* data obtained with Newtonian
 107 glucose solutions. As demonstrated by de Loubens et al. (2010), the main role of saliva during
 108 swallowing is to obstruct the contact. To represent this phenomenon, saliva is considered as being a
 109 Newtonian fluid too.

110 The geometry is symmetric along the x-axis (Figure 2). Relative quantities associated with saliva and
 111 the food bolus are referred to as 1 and 2, respectively. Between the two fluids, we ignored diffusion
 112 and surface tension effects. The dimensional values are identified by the symbol '. The flow rate of
 113 saliva q_1' (m^3/s) is assumed to be known and the flow rate of the food bolus q_2' is calculated. μ_i' (Pa.s)
 114 refers to the viscosities, e_m' the thickness (m) of the deformable layer of mucosa, $H'(x)$ the half gap
 115 between the two cylinders (m), H_0' the "negative-gap width" (m), $h_2'(x)$ the location of the interface
 116 between the food bolus and saliva (m), U' the cylinder velocity (m/s), L' the load per unit of width
 117 (N/m), and R' the radius (m).

118 2.2. Elastic model of the mucosa

119 Near the contact point, the undeformed roll surface profiles are locally approximated by parabolas:

$$120 \quad H'(x') = -H_0 + \frac{x'^2}{2R'} + \Delta H'(x') \quad (3)$$

121 where $\Delta H'(x')$ is the cylinder surface deflection and must be expressed in terms of model for the
 122 elastic deformation of the rolls. The deformation of the layer can be considered with different
 123 models. Skotheim and Mahadevan (2005) have carried out a detailed study of fluid-immersed
 124 compressible, incompressible and poro-elastic soft interfaces. The one-dimensional Constrained
 125 Column Model (CCM) is the most tractable and the least intensive at the computational level. It
 126 assumes that the local pressure p' is directly proportional to the local deflection $\Delta H'$:

$$127 \quad \Delta H'(x') = \frac{p'(x')}{E_e} \quad (4)$$

128 For large deflections and incompressible compliant layers such as mucosa, Carvalho and Scriven
 129 (1995) and Gostling et al. (2003) have proposed:

$$130 \quad E_e' = \frac{4E'}{e_m'} \quad (5)$$

131 They found good agreement between this model and most of the sophisticated models in terms of
 132 the flow rates and the generated forces. These two last assumptions were retained to model the
 133 surface deflection (Eq. 4 and 5).

134 2.3. Dimensionless variables

135 For high load, viscous forces are small compared to elastic forces, so the pressure should be scaled
 136 with the latter. Choosing H'_0 as the length scale is the most convenient choice because it allows the
 137 model to be written in two parameters only, namely the viscosity ratio:

$$138 \quad \alpha = \frac{\mu'_2}{\mu'_1} \quad (6)$$

139 and the elasticity number:

$$140 \quad N_e = E_s \left(\frac{2R'}{H'_0} \right)^{5/2} \quad (7)$$

141 where E_s is defined with the saliva viscosity: $E_s = \frac{\mu'_1 U'}{(2R')^2 E_e'}$.

142 The limit $N_e \rightarrow +\infty$ corresponds to the case where the undeformed rolls would touch. The limit $N_e \rightarrow 0$
 143 corresponds to the dry rolling contact. The dimensionless values defined for imposed velocity and
 144 gap are given by:

$$145 \quad x = \frac{x'}{\sqrt{2R'H'_0}}$$

$$146 \quad z = \frac{z'}{H'_0}$$

$$147 \quad u_i = \frac{u'_i}{U'}$$

$$148 \quad q_i = \frac{q'_i}{U' H'_0}$$

$$149 \quad p_i = \frac{p'_i}{E'_e H'_0}$$

$$150 \quad L = \frac{L'}{E'_e H'_0 \sqrt{2R' H'_0}}$$

151 2.4. Hydrodynamic model

152 The cylinder profile is given by:

$$153 \quad H(x) = -1 + x^2 + p(x) \quad (8)$$

154 The momentum conservation equations are solved in the lubrication approximation in their
155 dimensionless form:

$$156 \quad \frac{\partial p}{\partial x} = N_e \frac{\partial^2 u_1}{\partial z^2} \quad (9)$$

$$157 \quad \frac{\partial p}{\partial x} = \alpha N_e \frac{\partial^2 u_2}{\partial z^2} \quad (10)$$

$$158 \quad \frac{\partial p}{\partial z} = 0 \quad (11)$$

159 Defining $\eta = z/H(x)$ and $\beta = h_2(x)/H(x)$, and considering no wall slip, continuity of velocity and shear
160 stress at the interface between the food bolus and the saliva and symmetry, the boundary conditions
161 are:

$$162 \quad u_1(\eta = 1) = 1 \quad (12)$$

$$163 \quad u_1(\eta = \beta) = u_2(\eta = \beta) \quad (13)$$

$$164 \quad \left. \frac{\partial u_1}{\partial \eta} \right|_{\eta=\beta} = \alpha \left. \frac{\partial u_2}{\partial \eta} \right|_{\eta=\beta} \quad (14)$$

$$165 \quad \left. \frac{\partial u_2}{\partial \eta} \right|_{\eta=0} = 0 \quad (15)$$

166 After integration of (9) and (10), application of the boundary conditions (12), (13), (14) and (15) and
167 of the mass conservation, the flow rates are given by:

$$168 \quad q_1 = \frac{H^3(\theta)}{2N_e} \cos^2(\theta) \frac{dp}{d\theta} \left[-\frac{\beta^3}{3} + \beta - \frac{2}{3} \right] + H(\theta)(1-\beta) \quad (16)$$

$$169 \quad q_2 = \frac{H^3(\theta)}{2N_e} \cos^2(\theta) \frac{dp}{d\theta} \left[\beta^3 \left(1 - \frac{2}{3\alpha} \right) - \beta \right] + H(\theta)\beta \quad (17)$$

170 where $\theta = \arctan(x)$.

171 Upstream, we consider that the contact is fully submerged. Downstream, the film splits. In the large
172 deflection case, Coyle (1988) has demonstrated that this boundary condition has a slight effect on
173 the results, so we consider that:

$$174 \quad p\left(-\frac{\pi}{2}\right) = p\left(\frac{\pi}{2}\right) = 0 \quad (18)$$

175 After resolution, we calculate the resulting load:

$$176 \quad L = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{p(\theta)}{\cos^2(\theta)} d\theta \quad (19)$$

177 2.5. Resolution method

178 From (16) and (17), we obtain an algebraic equation:

179
$$\frac{2}{3}H(\theta)\left(1-\frac{1}{\alpha}\right)\beta^4 + \left[(q_1 - H(\theta))\times\left(1-\frac{2}{3\alpha}\right) + \frac{q_2}{3}\right]\beta^3 + \left[\frac{H}{3} - q_1 - q_2\right]\beta + \frac{2}{3}q_2 = 0 \quad (20)$$

180 and a differential equation on the pressure:

181
$$\frac{dp}{d\theta} = \frac{3Ne(q_1 + q_2 - H(\theta))}{H(\theta)^3 \cos(\theta)^2 \left[\beta^3\left(1-\frac{1}{\alpha}\right) - 1\right]} \quad (21)$$

182 Where

183
$$H(\theta) = -1 + \tan(\theta)^2 + p(\theta) \quad (22)$$

184 Equations (20), (21) and (22) were solved using Matlab7 software. Even so, the integration had to be
 185 performed backwards in space (from $\pi/2$ to $-\pi/2$) to obtain numerical stability. q_2 is the unknown
 186 variable. For a set of parameters (q_1 , α , Ne), we iterated on q_2 until the boundary conditions (18)
 187 were verified.

188 **3. Parametric study**189 *3.1. Mono-layer case*

190 Numerical solutions were validated by comparing the results in the monolayer case with those of
 191 Coyle (1988). Figure 3 shows the flow rate q_1 and the load L as a function of the elasticity number N_e .
 192 As shown by Coyle (1988), from the results presented Figure 3, the flow rate and load dependence
 193 with N_e can be approximated by the relationships:

194
$$q_1 \approx 0.5N_e^{0.5} \text{ when } q_2 = 0 \quad (23)$$

195
$$L \approx 1.3 + 1.7N_e^{0.55} \text{ when } q_2 = 0 \quad (24)$$

196 When N_e tends to zero, the flow rate decreases and the load tends to 1.3. This value corresponds to a
 197 dry rolling contact and was verified analytically (Coyle, 1988).

198 3.2. Food bolus flow rates

199 Figure 4-a shows the influence of N_e and Figure 4-b the influence of the saliva flow rates q_1 at $N_e=1$
 200 on the food bolus flow rates q_2 for different cases. The food bolus flow rate q_2 decreases when N_e
 201 tends to zero corresponding to the dry rolling contact. When there is no saliva at the interface ($q_1=0$),
 202 q_2 dependence with N_e and α can be expressed with a relationship similar to (23):

$$203 \quad q_2 \approx 0.5(\alpha N_e)^{0.5} \text{ when } q_1 = 0 \quad (25)$$

204 Increasing the viscosity ratio α increases q_2 whereas saliva lubrication decreases q_2 . The influence of
 205 the saliva flow rate q_1 decreases when N_e increases. When the relationship:

$$206 \quad N_e \approx 4q_1^2 \quad (26)$$

207 is verified, the contact is over-flooded by saliva and q_2 tends to zero.

208 The viscosity ratio α has a strong influence on the food bolus flow rate q_2 when the saliva flow rate q_1
 209 is low. Its impact drop sharply when q_1 increases.

210 3.3. Load

211 Figure 5-a shows the influence of N_e and Figure 5-b the influence of q_1 at $N_e=1$ on the generated load
 212 L for different cases. When the contact is not lubricated by saliva, we obtain a relationship equivalent
 213 to (24):

$$214 \quad L \approx 1.3 + 1.7(\alpha N_e)^{0.55} \text{ when } q_1 = 0 \quad (27)$$

215 When α increases, L increases. When α is smaller than 1, L decreases with q_1 , whereas L increases
216 with q_1 when α is higher than 1. The dependence of L on q_1 is highly reduced when N_e is weak due to
217 the fact that the contribution of hydrodynamic pressure to the load is negligible.

218 3.4. Pressure and gap profiles

219 Figure 6 shows pressure (a and b) and gap profiles (c and d) for $N_e=1$ and $N_e=10^{-3}$ for different cases.
220 The pressure sharply increases as the fluid is dragged into the narrowing channel, after which the
221 channel widens and the pressure drops. When α is higher than 1 the pressure profile developed with
222 α and the saliva flow rate q_1 reduces its development and, inversely, when α is lower than 1. When
223 N_e is weak, the pressure profile is less dependent on α and q_1 as shown in Figure 6-b for $N_e = 10^{-3}$. It
224 tends to a parabola corresponding to a dry rolling and the surfaces are more and more parallel and
225 closer (Coyle, 1988): the pressure profile is dominated by the elastic deformation of the mucosa.

226 4. Applications

227 The aim of this section is to provide quantitative results for typical physiological parameters, to apply
228 these results to *in vivo* aroma release and to compare the predictions with *in vivo* experiments found
229 in the literature.

230 4.1. Application to swallowing

231 Coating flows often present instabilities and the film varies in a wavy, sinusoidal-like manner across
232 the substrate. This type of film thickness non-uniformity is usually referred to as ribbing. It is a
233 consequence of an imbalance between surface tension forces and the pressure gradient present
234 within the downstream nip region that generate vortex in the film-split region. In the case of a bi-
235 layer coating, the two fluids are mixed together under the vortex action at the contact output. Chong
236 et al. (2007) observed that ribbing is present over a wide range of operating parameters for negative
237 gaps. We can thus consider that ribbing and vortex occur during swallowing and that the food bolus
238 is therefore mixed with the saliva film. The interesting model outputs in terms of flavour release are

239 the total thickness e' of the mixture of the food bolus with saliva ($e'=e'_1+e'_2$) and the rate of dilution r
 240 of the food bolus in saliva defined by:

$$241 \quad r = 100 \frac{e'_2}{e'_1+e'_2} \quad (28)$$

242 In order to apply the model to pharyngeal peristalsis, the mathematical model was used to calculate
 243 the thickness of bolus e'_2 deposited on the pharyngeal mucosa at imposed velocity U' and load L' . A
 244 value of L' to be reached was fixed and (20), (21) and (22) were solved as explained in 2.5. We
 245 iterated on q'_2 and H'_0 until (18) and (19) were verified. In fact, the action of the pharyngeal
 246 constrictors muscles is equivalent to setting a normal force on the rolls, referred to as load L' (de
 247 Loubens et al., 2010).

248 Figure 7 shows the total thickness (in μm) as a function of the rate of dilution (in %) for different
 249 parameters representative of different physiological conditions (Table 1).

250 Regardless of the parameters, the values of the elasticity number N_e are lower than the 1 and, as
 251 previously explained, the situation is therefore similar to the dry rolling contact. The load is due to
 252 the elastic forces and not to the hydrodynamic pressure.

253 When the viscosity ratio α is 1 (cases a1, b1, c1), the deposited thickness is constant regardless of the
 254 dilution rate is. When the viscosity ratio increases (comparison between the cases a1 and a10, for
 255 example), there are two sets of conditions. The first one is obtained when the food bolus is not very
 256 diluted with saliva ($r \rightarrow 0\%$) and the viscosity ratio has a considerable influence on the total thickness
 257 e' . The second one is obtained when the food bolus dilution increases ($r \rightarrow 100\%$) and the total
 258 thickness tends to a constant.

259 In the cases a1, the rate of dilution between the two sets of conditions is about 45%, resulting in an
 260 initial saliva thickness e'_1 of approximately 5 μm .

261 When the dilution ratio is maximal, the saliva entirely obstructs the contact and the bolus cannot
262 coat the mucosa. The limit value of saliva thickness is approximately $10\ \mu\text{m}$ in the case a.

263 The comparison between cases a and b illustrates the strong role of the peristalsis wave velocity U'
264 When U' is multiplied by 5, the total thickness is multiplied by 2.5. Moreover, the limit rate of
265 dilution r and the limit of saliva thickness between the two sets of conditions previously described
266 increase when the wave velocity increases: in case a they are about 45% and $5\ \mu\text{m}$ and 55% and $15\ \mu\text{m}$
267 in case b. The saliva thickness value necessary to over-flood the contact increases from about 10
268 to $25\ \mu\text{m}$ ($r = 100\%$) as well.

269 The comparison of cases a10 and c10 shows that increasing the Young modulus of the mucosa E'
270 reduces the total thickness. The values of E' reported in Table 1 have one decade of difference. This
271 parameter is difficult to obtain *in vivo* and we have therefore used the Young modulus obtained from
272 human skin *in vivo* (Diridollou et al., 2000) and of human pharyngeal tissue in *post mortem* tension
273 (Kim et al., 1998). The mechanical behavior of the mucosa would require more considerations. In
274 fact, mucosa presents a viscoelastic behavior (Kim et al., 1998) and, as a result, the Young modulus
275 obtained at the time scale of the process should be introduced into the model (Cohu and Magnin,
276 1997).

277 4.2. Application to flavour release

278 Predictions of aroma release kinetics

279 The results of the pharyngeal mucosa coating model were used in a mechanistic model that predicts
280 aroma release (Doyennette et al., 2011). Figure 8 shows the kinetics of aroma release in the nasal
281 cavity predicted by the mechanistic model for different viscosity ratio α and rates of dilution r
282 calculated with the present model. In this section, we considered that the physico-chemical
283 properties of the food bolus are independent of its viscosity.

284 Two sets of conditions can be distinguished according to the physiological parameters and the
285 viscosity ratio. When the initial thickness of saliva and the dilution are weak ($r \rightarrow 0\%$, cases 3 and 4),
286 viscosity has a considerable effect on the decreasing part of the aroma release kinetics, whereas
287 when the dilution with saliva is strong ($r \rightarrow 100\%$, cases 1 and 2), viscosity has no effect on aroma
288 release. Figure 7, we show that for typical physiological parameters and a food bolus viscosity of
289 50 mPa.s, the order of magnitude of the limit value of saliva thickness that distinguishes the two
290 cases is between 5 and 15 μm .

291 Comparison with *in vivo* aroma release kinetics

292 In this section, the model predictions are compared with the results obtained in the literature.

293 Doyennette et al. (2011) carried out an *in vivo* investigation of the influence of viscosity on aroma
294 release. They used glucose solutions as test fluids that varied widely in viscosity (from 0.7 to
295 405 mPa.s at 35°C). They concluded that the solution coating the pharyngeal mucosa was highly
296 diluted with saliva. To show this, they compared the maximal relative concentration of kinetics C_{max}
297 obtained *in vivo* with their model predictions for two different cases.

298 Figure 9 shows the maximal concentration of kinetics C_{max} obtained *in vivo* and predicted by the
299 model in two different cases as a function of the viscosity of the glucose solution. They observed a
300 maximal difference of 40% *in vivo* on C_{max} , depending on the glucose viscosity of the solution.
301 However, when they simulated aroma release kinetics by considering that the residual thickness of
302 the product was not diluted by saliva ($r=0\%$), they observed differences of 97% between the products
303 whereas, when they considered a rate of dilution r of approximately 85%, their predictions were in
304 agreement with the *in vivo* observations. Thus, it was necessary to suppose that the food bolus was
305 highly diluted by saliva to explain the *in vivo* observations.

306 The biomechanical model developed in the present study makes it possible to understand the
307 physical origins of these observations: the initial thickness of saliva coating the mucosa is sufficiently

308 thick to dilute the food bolus coating the mucosa at the level of the most occluded region of the
309 pharyngeal peristaltic wave and to break the viscosity influence on coating and flavour release.
310 Moreover, the thickness of the residual film that coats the mucosa after swallowing was estimated at
311 approximately 15 μm in their study and this value is close to those calculated with the present model
312 (Figure 7).

313 5. Discussion about non-Newtonian behavior

314 In despite of different assumptions performed in the model, this last is able to explain the physical
315 origins of *in vivo* observations for Newtonian fluids. The main assumptions concern the physical fluids
316 properties (saliva and food bolus) and especially their rheological behavior that we discuss in this
317 section.

318 5.1. Rheology of saliva

319 In the present model of pharyngeal peristalsis, saliva was considered as a Newtonian fluid although it
320 presents complex rheological properties as shear thinning behavior (Stokes et al., 2007),
321 viscoelasticity (Stokes et al., 2007), extensional viscosity (Harward et al., 2010) and normal stress
322 (Stokes et al., 2007). Moreover, the intensity of its properties depends greatly upon the method of
323 stimulation (Stokes et al., 2007).

324 To discuss about the interest to consider shear thinning behavior in the model, Figure 10 shows the
325 shear rate distribution (calculated by the present model) in the contact between the root of the
326 tongue and the posterior pharyngeal wall for different levels of lubrication by saliva and for mean
327 physiological conditions. When saliva thickness increases, mucosa are more and more close and
328 parallel. At the interface between the food bolus and the saliva, there is a gap of shear stress due to
329 the continuity of shear stress and the difference of viscosity between the two fluids. For the different
330 cases, shear rates vary between 1 and 10^4 s^{-1} , approximately. Stokes et al. (2007) shows that the
331 shear viscosity of saliva vary at maximum between 20 and 1 mPa.s for shear rates comprise between

332 2 and 5.10^3 s^{-1} . These variations are relatively important; knowing that, the thickness of product
 333 varies with the square of the viscosity in the monolayer case. At the light of the present results, the
 334 shear thinning behavior of saliva should change quantitatively the model predictions.

335 Saliva has a highly elastic nature (Stokes et al., 2007) that has to be compared to the time scale of the
 336 coating process during swallowing. This time scale is given by the ratio l'/U' , where l' is the length of
 337 the contact ($\approx 10 \text{ mm}$, Figure 10), is about 20 ms. For saliva, Stokes et al. (2007) reported that the
 338 relaxation times of saliva are from 30 ms to 1 s. Being superior to the time scale of the pharyngeal
 339 mucosa coating process, viscoelasticity can have an influence on the coating phenomena.

340 Saliva presents also an extensional viscosity μ'_E (Harward et al., 2010). According to the results of
 341 Harward et al. (2010), the extensional viscosity depends on the strain rate and can reach 120 times
 342 the shear viscosity. In the momentum conservation equation, we can demonstrate that the ratio of

343 the stresses due to the extensional viscosity to the shear viscosity is given by $\frac{\mu'_E}{\mu'_1} \left(\frac{h'}{l'} \right)^2$, where h' is

344 the gap between the surfaces ($\approx 100 \mu\text{m}$, Figure 10). The value of this ratio is about 0.01 ($\ll 1$). We
 345 can conclude that extensional effects of saliva should have a slight effect on the coating of mucosa.

346 The shear of saliva induces normal stress effects (Stokes et al., 2007) that could participate to
 347 support the load L' applied by the constrictor muscles. Normal stress N'_1 is about 10-100 Pa for shear
 348 stresses comprise between 10 and 2000 s^{-1} (Stokes et al., 2007). In the contact between the roots of
 349 the tongue and the posterior pharyngeal wall, these effects could generate a load $L_{N'_1}$ given by $N'_1 \cdot l'$,
 350 approximately. An order of magnitude of $L_{N'_1}$ is 1 N/m. This value represents only 10% of the load L'
 351 applied by the constrictor muscles. We can so conclude that the normal stress effects of saliva must
 352 have a moderate effect on the coating phenomena during swallowing.

353 Thus, at the light of the simulations obtained with the present model, we can conclude that the shear
 354 thinning behavior and the viscoelasticity of saliva should affect mucosa coating phenomena and
 355 would be interesting to study in detail. However, these phenomena could affect the results only

356 quantitatively. In fact, qualitatively, the existence of the two sets of conditions demonstrated in this
357 study is due to obstructions effects by saliva. Moreover, the behavior law of saliva has to be
358 determined on a large scale of shear rates that is difficult to obtain experimentally and the effect of
359 viscoelasticity on lubrication-flows characteristics is a “largely-unresolved problem” (Zhang and Li,
360 2005).

361 5.2. Rheology of food bolus

362 A second interesting question is the role of food bolus rheology on coating phenomena. Food bolus
363 can present all kind of rheological properties from liquid to semi-solid food products or chewing solid
364 food. In the present model, we choose to only explore the viscous effects in order to not over-
365 sophisticate the model and to be representative of the experimental conditions of Doyennette et al.
366 (2011) and compare thus the results of these two different approaches.

367 However, as saliva, it is clear that more complex rheological properties can impact on coating
368 phenomena. For example, biopolymers and hydrocolloids used as thickeners present shear thinning
369 behaviors. Food bolus can also present a yield stress. The yield stress effects and the shear thinning
370 behavior can have a great impact on the coating phenomena because the shear rates generated in
371 the contact vary from 0 to 10^4 s^{-1} . It could be interesting to develop a specific experimental device as
372 in our previous study (de Loubens et al., 2010) with deformable rolls to study the influence of
373 complex rheological properties on coating (as inhomogeneous food bolus for example). To study
374 pharyngeal mucosa coating, modeling stays an interesting approach because it allows us to evaluate
375 physical quantities that are very difficult to measure *in vivo*.

376 6. Conclusion

377 To conclude, the elastohydrodynamic model of swallowing provides physical explanations as to the
378 role of saliva on the food bolus coating and flavour release. After being successfully compared with *in*
379 *vivo* experiments, this type of approach is promising for designing food products with specific aroma

380 release kinetics or for adapting food product properties to people who suffer from swallowing
381 disorders. However, the food bolus presents complex behaviours and the development of *in vitro*
382 systems to model swallowing may be of great interest for studying the role of the rheological
383 properties of the food bolus on the pharyngeal mucosa coating and flavour release.

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387 **Disclosures**

388 No conflicts of interest, financial or otherwise, are declared by the authors.

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464 Table 1: Physiological variables and approximate corresponding values.

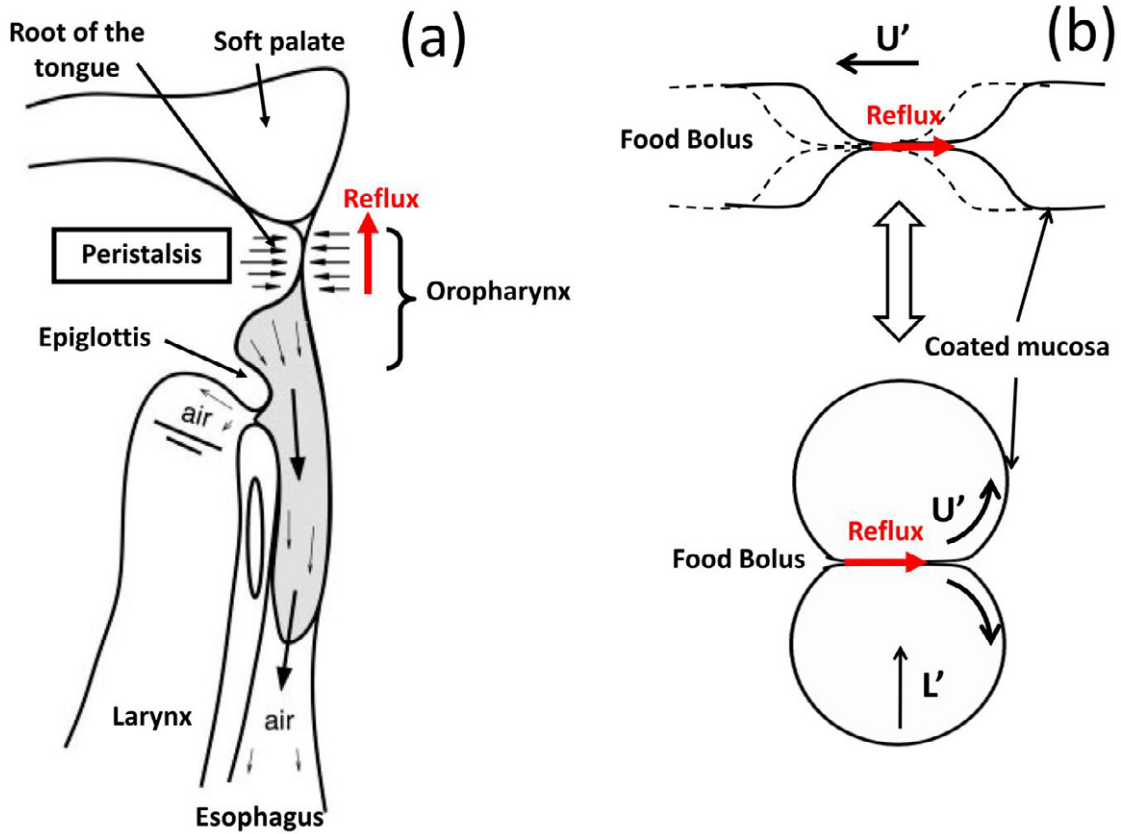
Description	Symbol	Typical values	References
Saliva thickness	e_1'	no data	
Saliva viscosity	μ_1'	1-10 mPa.s	Schipper et al., 2007; Stokes et al., 2007
Bolus viscosity	μ_2'	> 1 mPa.s	
Wave velocity	U'	0.1-0.5 m/s	Dantas et al., 1990; Meng et al., 2005; Chang et al., 1998
Radius	R'	40 mm	estimated from Chang et al., 1998
Elasticity modulus of the mucosa	E'	20-200 kPa	Diridollou et al., 2000; Kim et al., 1998
Mucosa thickness	e_m'	1-4 mm	Diridollou et al., 2000
Load	L'	10-60 N/m	de Loubens et al., 2010
Elasticity parameter	E_s	$\sim 8 \cdot 10^{-9}$	calculated with (1)
Load parameter	F	$\sim 3 \cdot 10^{-5}$	calculated with (2)

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470 Figure 1: (a) Pharyngeal peristalsis (adapted from Pal et al., 2003). (b) Diagram of the peristaltic wave

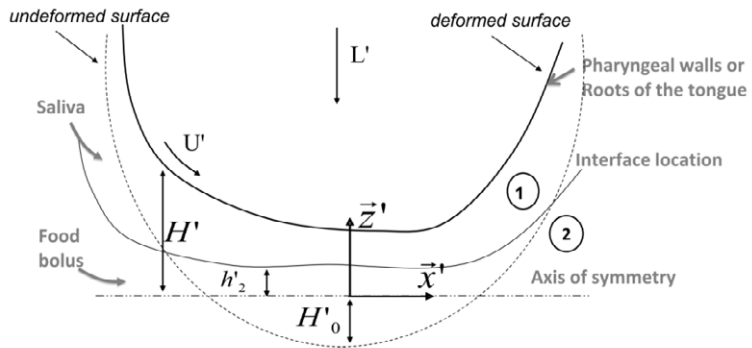
471 and associated study system. Near the most occluded point, the pharyngeal walls are in rotation

472 compared to each other. U' is the wave velocity (m/s) and L' the load applied by the pharyngeal

473 constrictor muscles (N/m), adapted from de Loubens et al. (2010).

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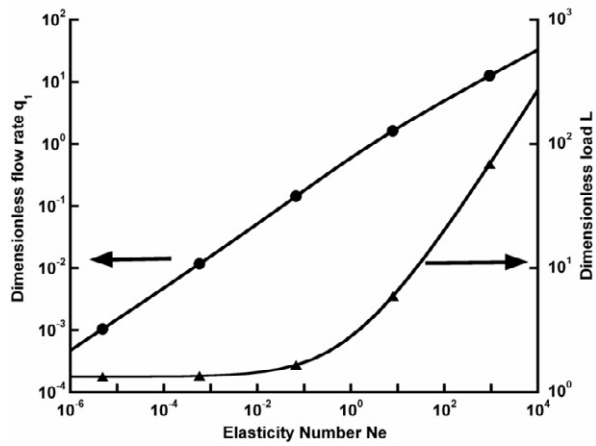


476

477 Figure 2: Diagram of definition and notations. U' is the wave velocity (m/s), L' the load applied by the
 478 pharyngeal constrictors muscles (N/m), $H'(x')$ the mucosa location (m), $h'_2(x')$ the interface location
 479 between the food bolus and the saliva and H'_0 the negative-gap width.

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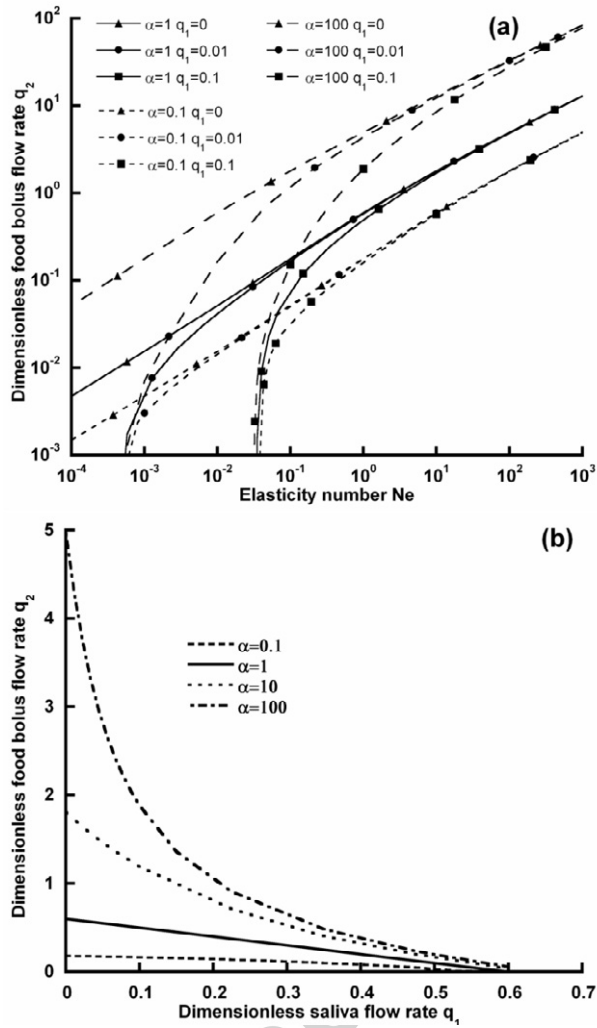


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483 Figure 3: Dimensionless flow rate q_1 (-●-) and load L (-▲-) as a function of the elasticity number N_e in484 the mono-layer case ($q_2=0$).

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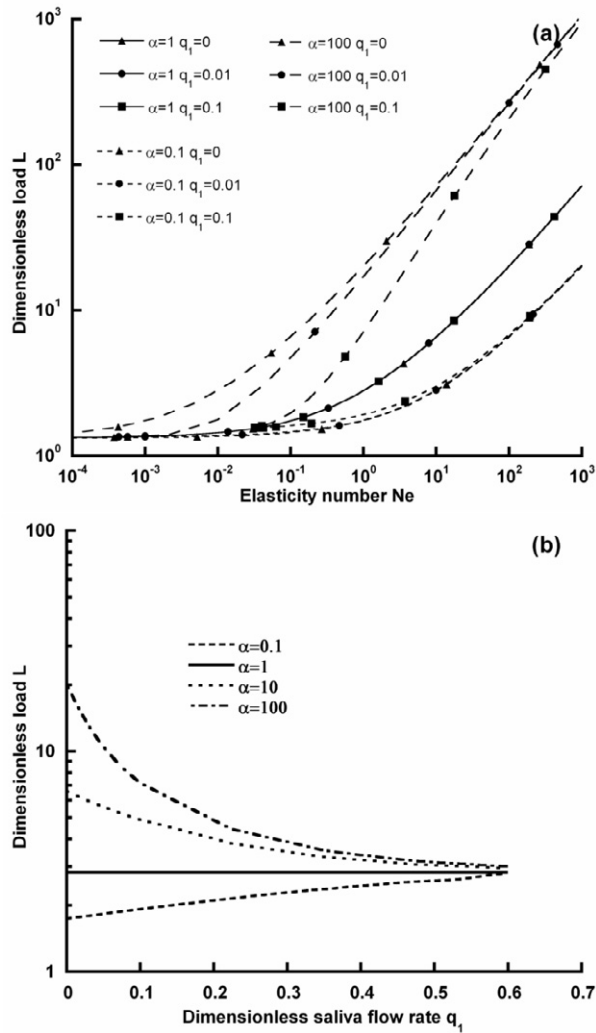


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488 Figure 4: Dimensionless food bolus flow rate q_2 as a function of the elasticity number N_e for different
 489 viscosity ratios α and dimensionless saliva flow rates q_1 (a) and as a function of dimensionless saliva
 490 flow rate q_1 for different viscosity ratios α for $N_e=1$ (b).

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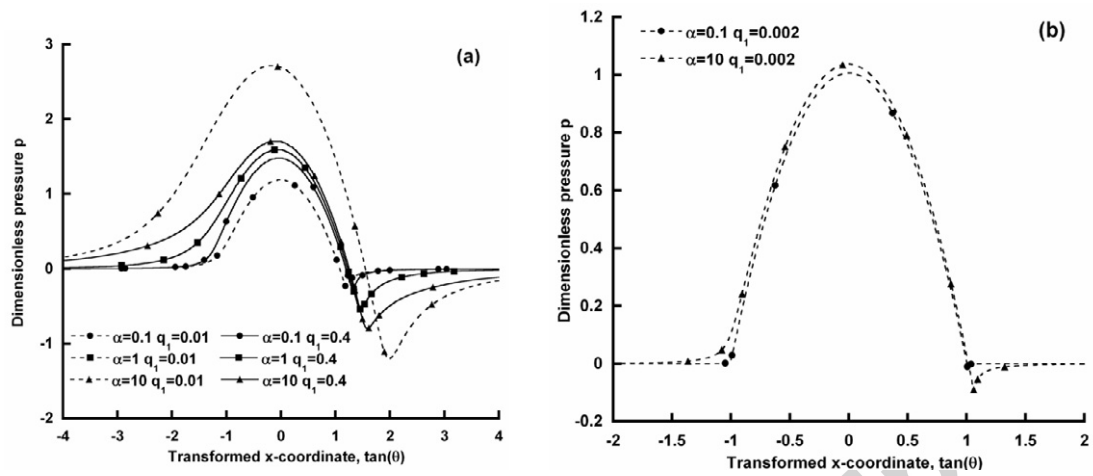


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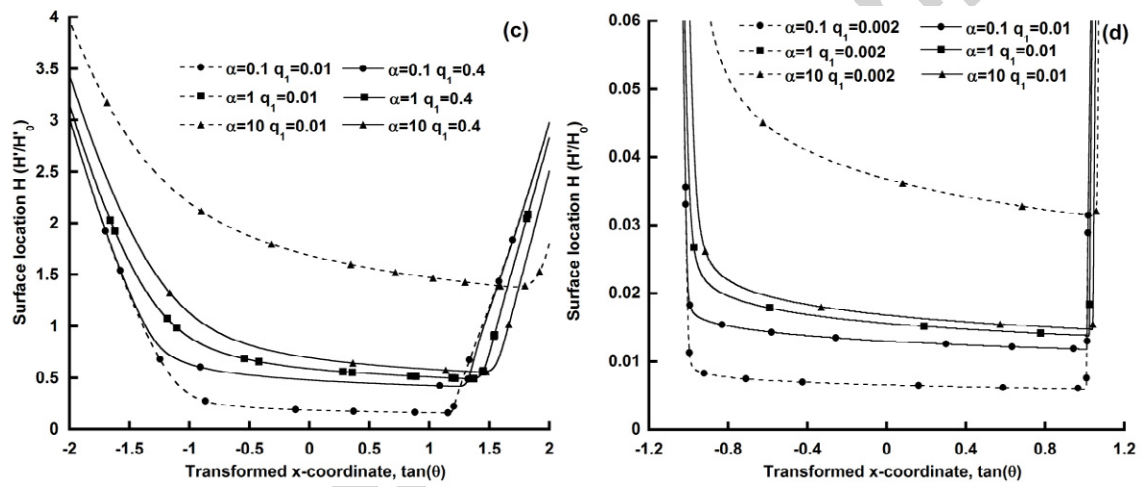
494 Figure 5: Dimensionless load L as a function of the elasticity number N_e for different viscosity ratio α
 495 and dimensionless saliva flow rates q_1 (a) and as a function of the dimensionless saliva flow rate for
 496 different viscosity ratios α at imposed gap and velocity for $N_e=1$ (b).

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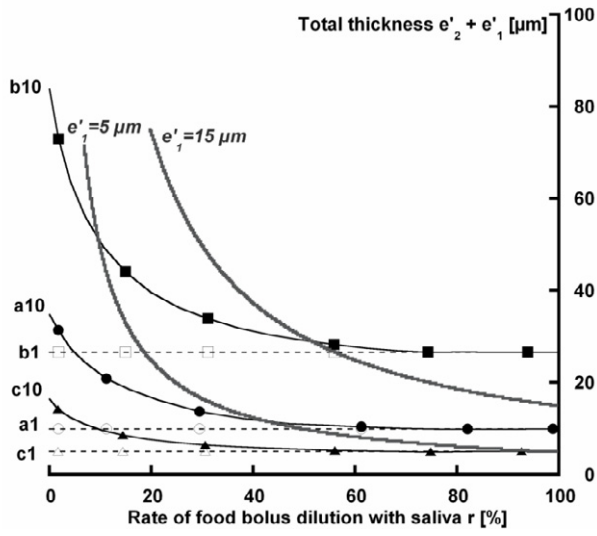


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501 Figure 6: Dimensionless pressure profiles p (a and b) and gap profiles H (c and d) for different
 502 viscosity ratio α and different dimensionless saliva flow rates q_1 at $N_e=1$ (a and c) and $N_e=10^{-3}$ (b and
 503 d).

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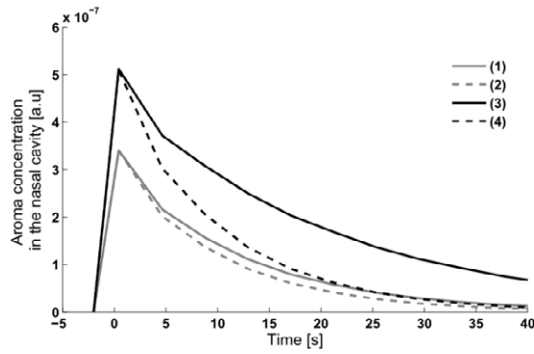
Cas n°	U' [m/s]	E' [kPa]	μ_2' [mPa.s]	α	E_s	F
a1 (○)	0.1	20	5	1	$4 \cdot 10^{-9}$	$8 \cdot 10^{-5}$
a10 (●)	0.1	20	50	10	$4 \cdot 10^{-9}$	$8 \cdot 10^{-5}$
b1 (□)	0.5	20	5	1	$2 \cdot 10^{-8}$	$8 \cdot 10^{-5}$
b10 (■)	0.5	20	50	10	$2 \cdot 10^{-8}$	$8 \cdot 10^{-5}$
c1 (△)	0.1	200	5	1	$4 \cdot 10^{-10}$	$8 \cdot 10^{-6}$
c10 (▲)	0.1	200	50	10	$4 \cdot 10^{-10}$	$8 \cdot 10^{-6}$

507

508 Figure 7: Total thickness of food bolus and saliva $e' = e_1' + e_2'$ coating the pharyngeal mucosa as a509 function of the dilution rate of the food bolus with saliva $r = 100 \frac{e_2'}{e_1' + e_1'}$ and iso-values of saliva510 thickness e_1' (grey lines) ($e_m' = 4$ mm, $R' = 4$ mm, $\mu_1' = 5$ mPa.s, $L' = 10$ N/m).

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Cas n°	α	r (%)	$e'_2 + e'_1$
1	10	40	12
2	1	40	10
3	10	10	20
4	1	10	10

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515 Figure 8: Aroma release kinetics predicted by the mechanistic model developed by Doyennette et al.

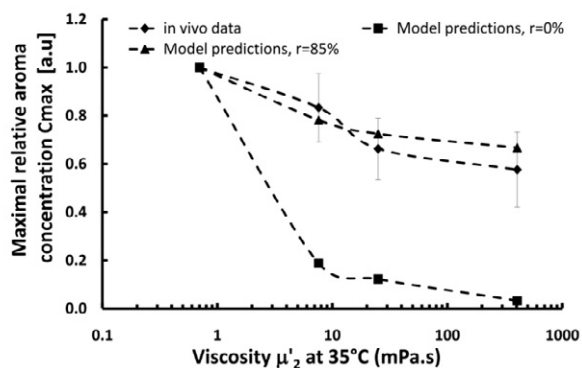
516 (2011) for different rates of dilution of the food bolus with saliva ($r = 100 \frac{e'_2}{e'_1 + e'_1}$) and total

517 thicknesses ($e'_1 + e'_2$) predicted with the present elasto-hydrodynamic model. The time 0 s corresponds

518 to the swallowing events. ($U' = 0.5$ m/s, $E' = 20$ kPa, $e'_m = 4$ mm, $R' = 4$ mm, $\mu'_1 = 5$ mPa.s, $L' = 10$ N/m)

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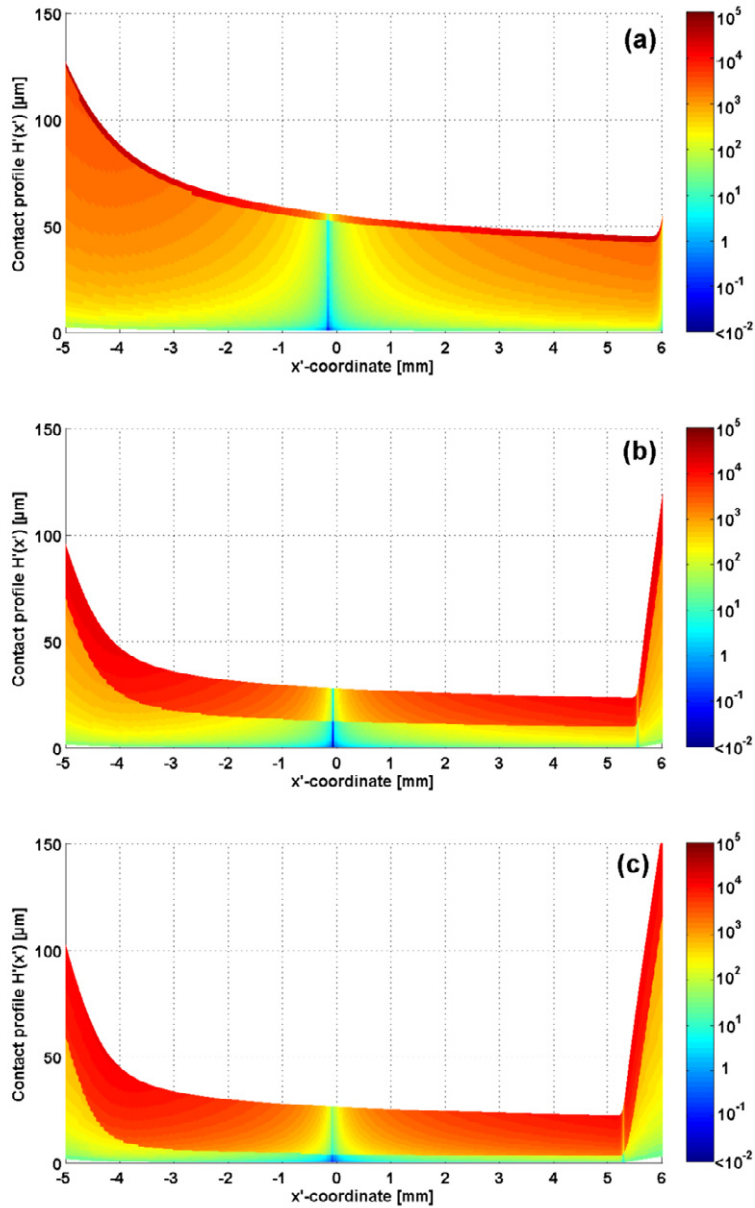


521

522 Figure 9: Maximal relative concentration of aroma release kinetics C_{\max} as a function of the viscosity
 523 of glucose solutions μ'_2 : *in vivo* data (\blacklozenge), model predictions without dilution with saliva ($r=0\%$, \blacksquare),
 524 model predictions with a rate of dilution of product with saliva r of 85% (\blacktriangle). Error bars represent the
 525 standard deviation on the *in vivo* data. Data from Doyennette et al. (2011).

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528

529 Figure 10: Example of shear rate distribution (isovalues of shear rate in 1/s) in the contact for
 530 different level of saliva lubrication: $e_1=2.6 \mu\text{m}$ and $e_2=61 \mu\text{m}$ (a), $e_1=13 \mu\text{m}$ and $e_2=17 \mu\text{m}$ (b),
 531 $e_1=22 \mu\text{m}$ and $e_2=4.2 \mu\text{m}$ (c). The z' -coordinate 0 correspond to the axis of symmetry ($U'=0.5 \text{ m/s}$,
 532 $E'=20 \text{ kPa}$, $e_m'=4 \text{ mm}$, $R'=4 \text{ mm}$, $\mu_1'=5 \text{ mPa}\cdot\text{s}$, $\mu_2'=10 \text{ mPa}\cdot\text{s}$, $L'=10 \text{ N/m}$).

Highlights

We modeled pharyngeal peristalsis.

We analysed the great role of saliva and mucosa deformability on mucosa coating by Newtonian food bolus.

We concluded that the food bolus coating the mucosa is very diluted by saliva during the swallowing process.

Thus the impact of product viscosity on flavor release is weak.

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