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1 Real time ultrasound assessment of contact
2 progress between food gels and tongue
3 mimicking surfaces during a compression

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Abstract

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An *in vitro* study was conducted to further explore the potential of an emerging ultrasound

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method for monitoring in real time the progress of the contact between gels with different physical

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properties and tongue mimicking surfaces (TMSs) during uniaxial compressions. A 1-MHz ultrasound

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transducer was used to measure the apparent reflection coefficient (R^*) of the interface between

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TMSs (of varied roughness) and gels (agar and/or gelatin). The patterns of R^* clearly depended on the

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gels capacity to deform and mould the asperities of the TMSs during compression. Rough TMSs

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induced a significant decline of R^* values, demonstrating an increase of the fraction of the TMSs in

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direct contact with the gels. Rigidity, fracture properties or adhesion energy of gels influenced the

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kinetics of contact progress and associated patterns of R^* variations. Moreover, the presence of a thick

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lubrication film between the gels and the TMSs promoted the transmission of ultrasound waves (acting

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as a coupling agent) and led to decreasing values of R^* . Such phenomena were observed both when

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depositing a water lubrication film of controlled thickness on the TMSs (to mimic salivary film) and

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when considering gels with high water release capacities. The study confirms the potential of

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ultrasound methods for exploring physical phenomena related to interactions between food and

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tongue surface. Such developments could better contribute to unravel the determinants of texture

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perceptions during food oral processing.

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Key words

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Oral processing; Tongue; Roughness; Agar; Gelatin; Ultrasound

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1. Introduction

1.1. Role of the tongue in food oral processing and texture perceptions

Food oral processing plays a major role in consumers' appreciation of food as it encompasses dynamic, multi scale and multi-sensory perceptions. Food is subjected to multiple biomechanical and chemical processes in oral cavity (Hutchings & Lillford, 1988; Stokes et al., 2013). It is chewed by the teeth, moistened by the saliva, mixed and sheared by the action of the tongue, the palate and the cheeks, adjusted to suitable oral temperature, so that it can be transformed into a bolus ready to be swallowed in safe and comfortable conditions (Hiemae, 2004). Each one of these actions leads to the stimulation of sensory receptors that make it possible to monitor the changes in ingested food during oral processing.

Even if the consumer needs to adapt his or her strategy of oral processing to the wide diversity of food structures, the manipulation of food between the tongue and the palate is a step required for every food products and at every moment of oral processing. The dynamic physical interactions at tongue-food interface give rise to the activation of various mechanoreceptors located in tongue, and which highly contribute to the perception of food texture (Bukowska et al., 2010). Since the tongue plays such a crucial part in the sensory experience of the consumer, a better understanding of texture perceptions resulting from tongue-food-palate interactions may provide important benefits for the design of new foods with improved sensory properties.

Moreover, the tongue also makes it possible to evaluate in real time the changes of the mechanical status of the bolus in order to decide the most appropriate moment for triggering a safe swallowing sequence (J. Chen, 2009; Hutchings & Lillford, 1988). Precisely, understanding the mechanisms of texture perceptions between the tongue and the palate could be helpful for the design of an alternative food supply for specific populations facing swallowing disorders (dysphagia). The response to this challenge requires the unraveling of the dynamic structural and mechanical

71 transformations undergone at tongue-food interface during oral processing (Foegeding et al., 2017;
72 Hutchings & Lillford, 1988; Panouillé et al., 2016; Szczesniak, 2002).

73 **1.2. Need for in-situ and dynamic instrumental characterizations**

74 The development of technical approaches is essential for exploring the physical phenomena
75 involved in texture perceptions. Numerous studies have attempted to mimic some specific sequences
76 of food oral processing with mechanical testing or rheological approaches (J. S. Chen & Stokes, 2012).
77 Even though these technics are suitable for the characterization of the transformations in the bulk of
78 food, they do not make it possible to comprehend the physical information related to the surface
79 properties, which are critical for tactile mechano-sensations. Tribology has also been proposed as an
80 effective tool to describe, at the end of oral processing or right after swallowing, the friction
81 mechanisms due to the interaction between the surface of the tongue and food bolus (Stokes et al.,
82 2013). However, from the introduction in the oral cavity to swallowing, food undergoes major
83 transformations, in such a way that oral processing goes from rheology to tribology dominant phases.
84 As a consequence, the development of *in-situ* and non-destructive methods suitable for the
85 continuous evaluation of the different phases of oral processing represents a critical research gap
86 (Foegeding et al., 2017).

87 **1.3. The potential of ultrasound techniques**

88 Ultrasound (US) methods could help to address this challenge. US imaging has already been
89 used in the oral cavity for various applications, including the study of food bolus transportation during
90 swallowing (de Wijk et al., 2011; Galén & Jost-Brinkmann, 2010; Peng et al., 2000), of tongue shape
91 and motions during speech (Stone, 2005), of functional disorders such as dysphagia (Hsiao et al., 2012;
92 Kim & Kim, 2012; Rommel & Hamdy, 2016) or also of obstructive sleep apnea events (J.-W. Chen et al.,
93 2014; Chien et al., 2017; Weng et al., 2017). The wide diversity of these fields of application confirms
94 the capability of US methods for the real-time exploration of dynamic mechanisms in oral cavity.

95 Furthermore, ultrasound waves are sensitive to the physical properties of the media and
96 interfaces they propagate through. For instance, ultrasound technics have thus been proposed to
97 characterize food composition, structure, or transformation processes in various products such as
98 meat, fruits, vegetables, emulsions or gels (Awad et al., 2012).

99 A first exploratory study has investigated the variations of the apparent reflection coefficient
100 (referred to as R^* hereafter) of ultrasound waves at the interface between non-deformable tongue
101 mimicking surfaces (TMS hereafter) and agar/gelatin mixed gels with various physical properties
102 (Mantelet et al., 2020). The results have shown that the US method has a high potential for the
103 characterization of the capability of food gels to mold themselves into the surface asperities. The
104 properties of both TMSs (roughness, lubrication) and food (Young's modulus, syneresis) were shown
105 to have an impact on R^* values. In static conditions, the apparent reflection coefficient was significantly
106 larger in the following situations: (i) tongue asperities were high and dense; (ii) lubrication levels were
107 low; and (iii) gels were less rigid. The apparent reflection coefficient conveyed the ability of food gels
108 to mold themselves to surface asperities or to form a coupling film of liquid at the interface. These
109 preliminary experiments were conducted in static conditions, with the aim to mimic the initial contact
110 between food and the surface of the tongue. However, no mechanical load was applied to the food
111 samples and it is now required to go further and investigate the behavior of the US response of the
112 system during the break down of food.

113 For that purpose, the present study aims at investigating the evolution of R^* during a uni-axial
114 compression mimicking the initial step of food oral processing. The same TMSs and model gels as those
115 considered in the first study have been used to explore the impact of their respective properties on
116 the variations of R^* (Mantelet et al., 2020).

117 2. Material and Methods

118 2.1. Model foods

119 Eight food gels identical to those previously considered for static conditions were prepared
120 following the same protocol (Mantelet et al., 2020). These gels are composed of agar (HP700IFG, Kalys,
121 Bernin, France) and gelatin (Bloom 250 PS 8/3, Rousselot, Gent, Belgium), sucrose (Daddy, Cristalco,
122 Paris, France) and water. For one of the eight samples Tween 20 (CAS: 9005-64-5 FG, Sigma-Aldrich, St
123 Louis, MO, USA) emulsifier was used to alter sample's surface wettability. All the gels underwent
124 identical thermal treatments, so that to dissolve sucrose, agar and gelatin at different heating steps.
125 Firstly, solutions of water with sucrose were prepared and stirred for 30 min at room temperature
126 (20°C). Secondly, agar powder was incorporated (if required) and all solutions were heated to 100°C,
127 ensuring the complete dissolution of agar. Thirdly, solutions were cooled and stabilized for 5 min to
128 60°C. Lastly, gelatin powder was added (for gels with gelatin) and all solutions were stirred for 20 min
129 at 60°C. Solutions at 60 °C were then poured in polyethylene cylindrical molds and left at 19 °C during
130 15 h-18 h. The gels cylinders of 30 mm in diameter and 10 mm in height were individually unmolded
131 at the last moment before the experiments. The gels can be classified in two main categories: $Ag_{0.3}$,
132 $Ag_{1.8}$ and $Ag_1Ge_{0.75}$ are agar dominant samples, whereas $Ge_{3.5}$, $Ag_{0.3}Ge_{3.5}$, $Ag_{0.7}Ge_{5.85}$, Ge_7 and Ge_7T are
133 gelatin dominant samples. It is important to note that Ge_7T differs from Ge_7 only by the presence of
134 Tween 20. Introducing this emulsifier led a to a decrease of the contact angle (from 40 to 0°) (Mantelet
135 et al., 2019). The underlying objective was to investigate whether the wettability of the gels is likely to
136 influence the patterns of due to differences in water film spreading at the interface between the TMS
137 and the food. Table 1 summarizes, for each of the eight gels considered here, the type of dominant
138 polymer, the composition and the Young's modulus obtained from previous characterizations
139 (Mantelet et al., 2020).

140 **2.2. Tongue mimicking surfaces**

141 As in our previous study, three cylinders of PVC (polyvinyl chloride) were used as TMSs
142 (Mantelet et al., 2020). The diameter of the PVC cylinders (50 mm) was kept larger than that of model
143 foods in order to ensure that they fully rest on the TMSs. The height of the cylinders (20 mm) was

144 chosen to be in accordance with the acoustic properties of PVC (Mantelet et al., 2020). Three types of
145 TMSs were used in this study, with different surface roughness characteristics imprinted by sand
146 papers during the course of cylinder moulding. Referred to as $R_0\beta_0$, $R_1\beta_1$ and $R_1\beta_2$, the TMSs differ
147 specifically by their arithmetical mean height Ra (mean \pm standard deviation of the height of the
148 asperities, respectively equal to 2.5 ± 0.1 , 58.2 ± 5.3 and 52 ± 11.2 μm) and by their correlation length β
149 (related to the density of the asperities and respectively, with mean \pm standard deviation equal to
150 35 ± 0.4 , 206 ± 4 and 243 ± 12 μm). Both the above mentioned parameters were obtained through
151 profilometry measurements and were found to be reproducible for each TMS production (Mantelet et
152 al., 2020). The mean height of the asperities on the surface of real tongues has been estimated to
153 range from 40 and 100 μm , showing that $R_1\beta_1$ and $R_1\beta_2$ displayed physiological relevant values (Uemori
154 et al., 2012). Conversely, $R_0\beta_0$ can be considered as smooth when compared to $R_1\beta_1$, $R_1\beta_2$, or to real
155 tongues. This TMS can thus be used as a control, making it possible to discuss the impact of surface
156 roughness with negligible effects of contact progress between the gels and the TMSs.

157 For the sake of simplicity, water was used as a lubricant to mimic the lubrication of the tongue
158 surface by saliva. Four lubrication levels were considered, referred to as dry, low, medium and high
159 (Mantelet et al., 2020). Dry (absence of lubricant) and high (water film of 1 mm thick) levels were
160 voluntarily chosen to compare highly contrasting conditions. The high lubrication level is much higher
161 than orders of magnitude of salivary film thickness. This condition made it possible to ensure that
162 water was the only medium present at the interface between the food and the TMS. The underlying
163 objective was to investigate whether the wettability of the gels is likely to influence the ultrasound
164 response at the interface between the TMS and food, due to potential differences in water film
165 spreading at the interface. Low and medium levels correspond to 15 and 40 μm thick water films
166 respectively, deposited on the TMS with a spray in a controlled and reproducible way.

167 **2.3. Compression protocol**

168 A tension-compression machine (TA.XT plus, stable Micro System, Surrey, United Kingdom)
169 was used to simulate the tongue/palate compression (see Figure 1). The TMS was mounted on the
170 base of the apparatus, while a circular aluminum probe (diameter 40 mm) was used to play the role of
171 the hard palate. The food samples underwent 80 % uni-axial compressions at 10 mm.s^{-1} , which was
172 the highest value of velocity attainable with the set-up. The compression protocol was composed of
173 different steps.

174 Firstly, before each test, the TMS was cleaned with a dish soap (Liquide Vaisselle Main
175 Ecologique, Prop, Paris, France) and dried. The TMS was then lubricated following one of the four
176 conditions described above. The food sample to be tested was unmoulded and deposited on the TMS
177 right before the experiment, to prevent any syneresis, drying and sagging over time. Then, the
178 mimicking palate was put in contact with the food sample and the following compression sequence
179 was applied: a static holding step of 3 s at 0 % strain, followed by a compression step of 80 % at 10
180 mm.s^{-1} , and finally a second holding step of 3 s.

181 The experiments were conducted at room temperature (mean \pm standard deviation equal to
182 $19 \pm 1 \text{ }^\circ\text{C}$), and at least in triplicate (and up to four times) for each set of conditions (*i.e.*, for a given food
183 gel on a TMS of a given roughness and with a given lubrication level).

184 **2.4. Ultrasound measurements**

185 The ultrasonic measurements aim at monitoring the evolution of R^* during the compression
186 of the different food gels on the bio-mimicking set up described above. The device and the procedure
187 used for ultrasound measurements is the same as in our previous paper (Mantelet et al., 2020).

188 **2.4.1. Ultrasonic device**

189 The device was composed of a mono-element piezoelectric transducer (V103RM, Olympus,
190 Shinjuku, Tokyo, Japan) with a central frequency of 900 kHz (longitudinal waves). The US transducer
191 was positioned underneath the TMS (silicon grease was used as coupling agent). The transducer was

192 connected to a US pulser-receiver (Sonatronic, Evry, France), which produced a negative squared pulse
193 signal (500 ns width, 80 Volt amplitude) for the emission of the US pulse, and which digitalized the
194 radio frequency (*rf*) signals corresponding to the pulse echo response of the system (12-bit
195 quantification, 100 MHz sampling rate, 38 dB gain). The acquisition of the *rf* signals was done in real
196 time during the compressing tests using a dedicated user-interface developed with LabVIEW®
197 (LabVIEW, National Instrument, Austin, Texas, USA). The pulse recurrence frequency was of around 90
198 Hz. The typical number of signals acquired during a compression was of around 70.

199 **2.4.2. Signal processing**

200 The sets of *rf* signals obtained for each compression test were processed with MATLAB® (The
201 MathWorks, Natick, Massachusetts, USA). R^* was calculated for each individual *rf* signal, following
202 the protocol extensively described in our previous study (Mantelet et al., 2020). To summarize it
203 briefly, the first step consisted of high-frequency noise reduction with a low-pass filter (15 MHz cutoff
204 frequency) applied to the Fast Fourier Transform (FFT) of the *rf* signals. The *rf* signals were composed
205 of two main echoes (see Figure 1.b): E_0 corresponds to the acoustic energy reflected at the interface
206 between the TMS and the food gel, whereas E_1 is the response of the interface between the food gel
207 and the palate. During the uniaxial compression (see Figure 1.c), the time of flight of E_1 decreases and
208 tends to get closer to E_0 . The present study focuses on E_0 but some undesired artefacts may occur by
209 the end of the compression due to overlapping between E_0 and E_1 . Time intervals of interest (4 μ s
210 width) centered on the maximum of the modulus of the Hilbert transform of echo E_0 (see Figure 1.b)
211 were determined to track the echo of the TMS. The amplitude A_0 , defined as the modulus of the FFT
212 of these temporal windows at 900 kHz, was then calculated for each *rf* signal. Finally, R^* was obtained
213 following:

$$R^*(\varepsilon) = \frac{A_0(\varepsilon)}{A_{0,\text{ref}}} \quad \text{Eq 1}$$

214 Where ε is the ratio of compression displacement to initial gel height (ranging from 0 to 80 %)
215 corresponding to each rf signal and $A_{0,ref}$ is a reference value of the amplitude A_0 recorded before
216 lubricating the TMS and depositing the food sample.

217 For better interpretation, the variations of R^* during the compression were also compared to
218 their initial value and ΔR^* is defined as follows:

$$\Delta R^*(\varepsilon) = R^*(\varepsilon) - R^*(\varepsilon = 0) \quad \text{Eq 1}$$

219 In this way, it becomes easier to compare and analyze the amplitude of the variations of R^*
220 across the different experimental conditions.

221 3. Results and discussion

222 The results and discussion are structured in three distinct subsections, so that to discuss
223 successively the impact of (i) tongue roughness, (ii) food properties and (iii) tongue lubrication on the
224 variations of R^* during the compression of the food gels on TMSs. For all figures, the curves with
225 identical colors correspond to replicates of identical conditions.

226 3.1. Impact of surface roughness on R^*

227 Figure 2.a represents the values of R^* before the compression ($\varepsilon = 0$) of the gels $Ag_{0.3}$, $Ge_{3.5}$,
228 Ge_7 on the three TMSs $R_0\beta_0$, $R_1\beta_1$, and $R_1\beta_2$ (in absence of lubrication). The three food gels selected here
229 provide an overview of the various behaviors observed throughout the whole set of food samples. In
230 the case of the smoothest TMS ($R_0\beta_0$), similar values of R^* were reported across the three food samples
231 (around 33%). Contrarily, the presence of rough asperities on $R_1\beta_1$, and $R_1\beta_2$ led to higher and dispersed
232 values of R^* across the three gels. The apparent reflection coefficient of US waves crossing the TMSs
233 depends on the gap of acoustic impedance Z between the TMSs ($Z \simeq 3.1 \text{ MPa.s.m}^{-1}$ in PVC) and
234 surrounding media (Mantelet et al., 2019). In the present case, the surrounding media can be
235 composed of air ($Z \simeq 420 \text{ Pa.s.m}^{-1}$), food gels (Z laying from 1.6 to 1.75 MPa.s.m^{-1}) or of water ($Z \simeq$
236 1.5 MPa.s.m^{-1}) (Mantelet et al., 2019). Air has a negligible acoustic impedance when compared to PVC,

237 food gels and water (the two latter being similar). The higher the gap of acoustic impedance at the
238 interface, the higher amplitude of US echo E_0 and subsequent value of R^* . If air fully covers a TMS, we
239 are in the case of a full reflection of the US wave and R^* is close to 100%. If contrarily the TMS is fully
240 imprinted with gels, R^* has been show to range from 30 to 34%, depending on the acoustic impedance
241 of the different gels (related to both mass density and compressibility) (Mantelet et al., 2019). When
242 a food sample is deposited on the TMS, a mix of air and gel in direct contact with the TMS is observed,
243 with intermediate values of R^* . Consequently, R^* has been shown to be an indirect indicator of the
244 effective contact ratio between the food gel and the TMS (Mantelet et al., 2020). As a consequence,
245 Figure 2.a highlights that prior to the uni-axial compression, the surface $R_0\beta_0$ displayed a better
246 mechanical coupling with the food gels than the two other surfaces ($R_1\beta_1$ and $R_2\beta_2$).

247 Concerning ΔR^* , an increase of ΔR^* during the compression of the gels means a spreading of
248 the surface of air in direct contact with the TMS. Conversely, a decrease of ΔR^* means that the surface
249 of gel or water in direct contact with the TMS tends to increase. Figure 2.b shows the variations of ΔR^*
250 during a compression test for the same gels and TMSs (no lubrication). In the case of the smoothest
251 TMS ($R_0\beta_0$), no apparent variations of ΔR^* were reported during the compression of the different gels
252 (blue curves in Figure 2.b), except in some cases at higher strains (higher than 70%). As pointed out
253 previously (Figure 1.c), the possibility of E_1 to overlap with E_0 at the end of the compression sequence
254 might be responsible for this observed abnormal variation of amplitude at higher strains. Setting aside
255 these undesired artefacts, the results suggest that the contact surface between the TMS $R_0\beta_0$ and food
256 was not altered during the compression tests. For these three gels, R^* was shown to range between
257 33 and 34 % before the beginning of the compression (see Figure 2.a), suggesting a full contact
258 between the TMS and the food.

259 Contrarily to $R_0\beta_0$, variations of ΔR^* were observed for the rough TMSs $R_1\beta_1$ and $R_2\beta_2$ during
260 the compression (see Figure 2.b). These results suggest that the nature of the media in direct contact
261 with the asperities of the TMSs varies when the food gel is under load. Interestingly, different trends

262 were observed throughout the three gels in Figure 2.b. For gels $Ge_{3.5}$ and $Ag_{0.3}$, a slight increase of US
263 reflectivity was first observed, followed by a decreasing trend during the second portion of the
264 compression. However, for these two gels, no major differences were observed between $R_1\beta_1$ and $R_1\beta_2$.
265 The largest variations of ΔR^* were reported for Ge_7 , which subsequently decreased by 15% after 80%
266 strain (see Figure 2.b₁). Interestingly, a faster decrease was observed on $R_1\beta_1$ at the beginning of the
267 compression but later attaining the similar position as $R_1\beta_2$ by the end of compression.

268 This result suggests that tongue roughness parameters may influence the evolution of the
269 contact between the food gel and the asperities of the TMSs. $R_1\beta_1$ and $R_1\beta_2$ have similar values of R_a
270 (average value of the height of asperities) and mainly differ by their correlation length β which suggests
271 a higher density of surface asperities for $R_1\beta_1$ than for $R_1\beta_2$. As a consequence, the geometry of surface
272 asperities may have an impact on the pattern of ΔR^* evolution during the compression. However, the
273 gap of R^* at the end of the compression was similar to what it was at the beginning (around 12% higher
274 for $R_1\beta_1$ than for $R_1\beta_2$).

275 3.2. Impact of food properties on R^*

276 The food gels considered in the present study mainly differ by the composition of their
277 agar/gelatin ratio. Due to phase separation mechanisms between agar and gelatin (Clark et al., 1983;
278 McEvoy et al., 1985), the gels can be arranged in two groups: gelatin dominant gels consisting in a
279 continuous phase of gelatin with, if appropriate, agar inclusions ($Ge_{3.5}$, $Ag_{0.3}Ge_{3.5}$, $Ag_{0.7}Ge_{5.85}$, Ge_7), and
280 conversely agar dominant gels composed of a continuous phase of agar with, if present, inclusions of
281 gelatin ($Ag_{0.3}$, $Ag_1Ge_{0.75}$, $Ag_{1.8}$). Our previous study made it possible to show that for each type of
282 samples, the higher the Young's modulus, the lower the capacity of the gels to mold the asperities of
283 the TMS under the action of their own weight (without any imposed compression in that study), and
284 the higher the apparent reflection coefficient R^* (Mantelet et al., 2020). This is clearly related to the
285 link between the materials rigidity and the transition from a partial to a full contact (Degrandi-
286 Contraires et al., 2013). However, the rigidity of the food samples is not sufficient to explain the

287 variations of R^* . As an example, $Ag_{0.3}$ and $Ge_{3.5}$ had similar values of rigidity but different values of R^*
288 prior to their compression. The adhesive energy of the food gels on the surface of PVC may be a
289 contributing factor to the capacity of the gels to mold themselves into the asperities of the TMSs. Such
290 properties are likely to vary according to the nature of the dominating polymer and to its level of
291 concentration (Shull, 2002). The potential role of water release mechanisms (acting as a coupling
292 media at the interface between the gel and the TMS and promoting the transmission of the US waves)
293 was also considered to explain the different behaviours reported for the two groups of samples. For
294 equal Young's moduli, the structure of agar dominant samples (double helix) could be more favorable
295 to the release of free water (syneresis) than the one of gelatin dominant samples (triple helix). Such
296 expelled water could act as a coupling media with the TMS and lead to lower values of R^* for agar than
297 for gelatin dominant samples (Santagiuliana et al., 2018). Once the water is released into the interface,
298 the adhesion forces get disrupted, making syneresis the prominent factor.

299 Figure 3.a shows the variations of the applied force F during the compression of the four gelatin
300 dominant gels. For these same gels, Figure 3.b displays the variations of ΔR^* on the same deformation
301 scale, while Figure 3.c represents the initial values of $R^*(\epsilon=0)$ as a function of the Young's moduli of
302 the samples. Similarly, Figure 4 displays the same parameters as in Figure 3, but for agar dominant
303 gels: F versus ϵ in Figure 4.a, ΔR^* versus ϵ in Figure 4.b, and $R^*(\epsilon=0)$ versus E in Figure 4.c. The results
304 given in Figure 3 and Figure 4 were obtained with the TMS $R_1\beta_1$, and for the dry lubrication level.

305 $Ge_{3.5}$ was the gelatin dominant gel with the lowest level of concentration in biopolymer (and
306 consequently with the lowest Young's modulus – 2.2 kPa). It also displayed the lowest level of variation
307 of ΔR^* , suggesting that during the compression, the amount of direct contact between the asperities
308 of the TMS and the food did not deviate from the initial level. By adding only 0.3 % of agar (in
309 comparison with $Ge_{3.5}$), $Ag_{0.3}Ge_{3.5}$ displayed larger evolutions of ΔR^* , with a slight increase during the
310 first step of the compression, generally followed by a decrease, until recovering their initial values (ΔR^*
311 comprised between -2 and +5% at the end of the compression). However, disparate behaviors were

312 displayed across the four trials repeated for $Ag_{0.3}Ge_{3.5}$, suggesting that for this sample, the presence of
313 agar inclusions led to heterogeneous variations of the conditions of the contact with the TMS. The two
314 last gelatin dominant gels had a significantly higher Young's moduli (32.1 and 24.0 kPa for $Ag_{0.7}Ge_{5.85}$
315 and Ge_7 respectively). Both model food displayed declining trends of ΔR^* variations at the end of the
316 compression (by 7 to 10 and 12 to 14 % for $Ag_{0.7}Ge_{5.85}$ and Ge_7 respectively). For $Ag_{0.7}Ge_{5.85}$, which was
317 the most rigid, this decline of ΔR^* was faster at the beginning of the compression (between 0 and 15
318 % strain), followed by an increase at the very end of the compression (beyond 75 % strain). The
319 increase at the end coincides with the decrease reported on the force curve, which allows us to identify
320 the fracture of the food sample.

321 Now when we consider agar dominant samples (see Figure 4), it is noticeable that $Ag_{0.3}$ did not
322 go through significant variations of F and ΔR^* during the compression. Due to the low rigidity of $Ag_{0.3}$
323 ($E = 4.2$ kPa), the amplitude of the load transmitted to the interface during the compression may not
324 have been high enough so that to alter the nature of the media in direct contact with the TMS.
325 Moreover, the low values of R^* reported before the beginning of the compression ($R^*(\epsilon=0) = 45.9$ %)
326 indicate that even before the beginning of the compression, the coupling between the food and the
327 TMS was already close to the threshold, providing a very little scope for further improvement.
328 Although, distinct force-deformation curves were reported for more rigid gels like $Ag_1Ge_{0.75}$ and $Ag_{1.8}$,
329 with fracture occurring between 45 and 55%. A rapid decrease of ΔR^* was observed in the first part of
330 the compression (before 40 % deformation), all the more so when the Young's modulus of the sample
331 was high (between 10 and 18 % for $Ag_1Ge_{0.75}$ while between 24 and 28 % for $Ag_{1.8}$). During this first
332 half of the compression, analogous patterns of ΔR^* were displayed inside the different food
333 references. These tendencies suggest that a significant increase of the amount of gels in contact with
334 the TMS occurred during the first part of the compression. After 40 % strain, the ΔR^* curves exhibit
335 more individual behaviors, each showing an increase of R^* that reflects relaxation mechanisms leading
336 to the withdrawal of the food sample from the asperities of the TMS.

337 3.3. Impact of surface lubrication on R^*

338 The experiments depicted in the first two parts of this discussion focused on investigating the
339 behavior of R^* in absence of lubrication at the interface between the TMS and the food. However,
340 accounting for lubrication is also a critical issue for seeking to understand the role of the salivary film
341 at this interface. In this feasibility study, a particular importance was granted to working with a stable
342 and reproducible fluid, reason why water was preferred over real saliva. A recent work by our group
343 displayed that in absence of mechanical loading (other than gravity), the lubrication of the TMS with
344 water drastically affects the US response of the interface (Mantelet et al., 2020).

345 Ge_7 and Ge_7T were chosen to illustrate the effect of the lubrication of the TMS during a
346 compression. These two samples differ by the presence of Tween 20 in Ge_7T , an emulsifying agent
347 used to modify surface tension properties (all by keeping the elastic properties unchanged in
348 comparison with Ge_7). For the four lubrication conditions, Figure 5 shows the variations of ΔR^* as a
349 function of strain for Ge_7 (Figure 5.a₁ and 5.b₁) and Ge_7T (Figure 5.a₂ and 5.b₂). Two distinct surface
350 profiles were considered: $R_0\beta_0$ for Figures 5.a₁ and 5.a₂, $R_1\beta_2$ for Figures 5.b₁ and 5.b₂.

351 Lower decrement rates of ΔR^* were reported during the compression of Ge_7 on the TMS $R_0\beta_0$
352 (mostly comprised between -0.2 and -1%), with no specific patterns underscored across the four
353 lubrication conditions. On the same TMS $R_0\beta_0$, slightly higher decreases were displayed with Ge_7T :
354 between 0 and -1.2% for most of the tests, and as low as between -2 and -4% in some isolated cases
355 which were not related to a specific lubrication condition. For both samples, the initial value of R^* was
356 inferior to 40%, suggesting that even before the beginning of the compression, the food gels were
357 almost fully bonding the interface of the TMS. As a consequence, the margin available for improving
358 the contact during the compression was low, explaining why low variations of ΔR^* were displayed.

359 Different trends of variations were reported throughout the four lubrication conditions for the
360 profile $R_1\beta_2$.

361 The dry lubrication level led to the highest variations of ΔR^* , with a decrease by -8 to -10% for
362 Ge_7 and by -13 to -16% for Ge_7T . These observations suggest a significant improvement of the acoustic
363 coupling at the interface between the TMS and the food. Interestingly, the initial value of R^* was lower
364 for Ge_7T (mean \pm standard deviation equal to $63.6 \pm 0.4\%$) than for Ge_7 (mean \pm standard deviation
365 equal to $68.1 \pm 2.3\%$). As a consequence, Ge_7T displayed a higher capacity to fill the asperities of the
366 TMS during the compression. A reason for these tendencies could be that Tween 20 may promote the
367 adhesive properties of Ge_7T , then altering the balance between adhesive and elastic forces that are
368 jointly ruling the interaction between the food and the TMS.

369 Conversely, the high lubrication level led to the lowest variations of ΔR^* , with a slightly linear
370 decrease (between -1 and -2% both for Ge_7 and Ge_7T). Lower initial values of R^* (before the beginning
371 of the compression) suggest a homogeneous coupling between the gels and the TMS, and hence
372 provided limited scope of further improvement during the compression. In this case, the film of water
373 (with an acoustic impedance similar to that of gels) acts as a coupling agent and fills the asperities of
374 the TMS. The results in Figure 5.b₁ and 5.b₂ suggest that when a load is applied to the food sample
375 during the compression, the film of water at the interface does not affect the coupling at the interface.

376 With relevance to the physiological orders of magnitude of the salivary film thickness
377 (Pramanik et al., 2010), the low and medium levels of lubrication made it possible to observe how the
378 patterns of ΔR^* evolve between dry and high levels. For both levels, ΔR^* first displayed a slight
379 increase, before a more pronounced decrease during the second portion of the compression. The
380 curves related to low and medium levels followed similar trends for most of the compression
381 sequences. It was only at the end of the compression that lower values of ΔR^* were observed for the
382 low level (in a more prominent way for Ge_7T). Even though the difference of water film thickness
383 between low and medium levels is small, one can notice that it is large enough to detect changes in
384 the US response that are induced by the spreading of the lubricating film at the interface between the
385 food and the TMS. In particular, for the low level, the higher wettability of Ge_7T compared to Ge_7

386 (contact angles previously assessed: around 0° and 40° respectively (Mantelet et al., 2019)) was likely
387 to promote the spreading of the lubricating film, which may contribute to the explanation of the higher
388 decrease rate of ΔR^* reported for this sample.

389 4. Conclusions

390 In this study, non-deformable surfaces were considered as TMSs to study the impact of surface
391 roughness and lubrication on the variations of R^* during the compression of different food gels with
392 different physical properties.

393 The findings show that both the height and the width of the asperities on the TMSs induces
394 high variations of the apparent reflection coefficient during the compression of the gels, corresponding
395 to the progressive molding of food into the surface asperities of the TMSs. Highly diverse patterns were
396 displayed across the different food gels. Rigidity of gels was also found to impact the kinetics of
397 increase of direct contact area between TMSs and gels. Moreover, two specific trends of behavior have
398 been reported depending on whether the dominant polymer in gels was agar or gelatin. The results
399 suggested that agar dominant products had higher capability for water release or syneresis during the
400 compression. This syneresis phenomenon was observed with the ultrasound method as it led to the
401 formation of a coupling film at the interface between the TMS and the food, resulting in a decrease of
402 the US reflectivity. For the same reasons, lubrication with water at the interface between the gels and
403 the TMSs tended to mitigate the evolution profiles of R^* during a compression.

404 In the context of food oral processing, the apparent reflection coefficient could help to
405 understand how food gels mold themselves into the surface asperities of the tongue, or how a coupling
406 film of liquid at the interface between the food and the tongue may spread. The method has thus a
407 potential for providing an indirect estimation of the contact area between the tongue surface and
408 food, which would be worthwhile for clarifying the mechanisms underlying sensory perceptions during
409 oral processing (Ares et al., 2007; Szczesniak, 2002). Such an approach could indeed help
410 understanding how the mechanical loads can be transmitted to the mechanoreceptors in the vicinity

411 of tongue asperities (e.g. in relation with firmness sensations), how the interactions of food and the
412 salivary film with tongue asperities may rule the perceptions of moistness, or also how the fraction of
413 tongue surface in contact with food influence the diffusion of chemical compounds responsible for
414 taste perceptions on tongue surface.

415 However, much more work will need to be done before being able to judge the applicability of
416 our method for such issues. In this view, many physiological issues will need to be accounted for,
417 starting with considering deformable tongue mimicking samples and progressively moving to more
418 realistic motions (involving both compressional and shear motions). All along these improvements, the
419 method should bring new insights for unravelling the determinants of texture perceptions during the
420 manipulation of food between the tongue and the palate.

421 The shearing of food between the tongue and the palate gives rises to important texture
422 perceptions, particularly for understanding swallowing trigger points. Characterizing the thickness of
423 food samples in tongue-palate tribo-pair is a critical missing information for the identification of the
424 lubrication regime of the system (Rudge et al., 2019). In future work, we could also try to investigate
425 whether an ultrasound method could be used in order to reach this objective.

426 A longer term perspective could be to extend the development of the method to *in vivo*
427 applications, with measurements conducted directly on the consumer. Finally, a broader diversity of
428 more realistic food types should be considered (e.g., with irregular shapes and micro or macroscopic
429 structural heterogeneities), and the evolving properties of the food bolus during oral processing should
430 also be examined (e.g., particle size reduction, saliva incorporation).

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530 [Figure captions list](#)

531 Figure 1: (a) Experimental set-up. (b) Schematic representation of the set-up with a typical US
532 *rf* signal composed of two echoes E_0 and E_1 respectively corresponding to the reflections of the US
533 waves at the interface between the TMS and the food gel, and between the food gel and the artificial
534 palate. (c) M-mode image describing the evolutions of the US response of the system during a
535 compression. The color map corresponds to the amplitude of the *rf* signals (arbitrary units, from blue
536 to yellow).

537 Figure 2: (a) Means and standard deviations of R^* before the beginning of the compression
538 ($\epsilon=0$) of three types of gels ((a_1) Ge_7 , (a_2) $Ge_{3.5}$ and (a_3) $Ag_{0.3}$) on the different TMSs. (b) Variations of
539 ΔR^* during the compression of three types of gels ((b_1) Ge_7 , (b_2) $Ge_{3.5}$ and (b_3) $Ag_{0.3}$) on the different
540 TMSs. The results were obtained under dry lubrication conditions.

541 Figure 3: For the four gelatin dominant gels ($Ge_{3.5}$, $Ag_{0.3}Ge_{3.5}$, $Ag_{0.7}Ge_{5.85}$ and Ge_7): (a) variations
542 of the force F applied during the compression, (b) variations of ΔR^* during the compression, (c)
543 variations of R^* before the beginning of the compression as a function of the Young's modulus (error
544 bars corresponding to standard deviations and a broken line draws the linear regression for indicative
545 purpose). The results were obtained with $R_1\beta_1$ under dry lubrication conditions.

546 Figure 4: For the three agar dominant gels ($Ag_{0.3}$, $Ag_1Ge_{0.75}$ and $Ag_{1.8}$): (a) variations of the force
547 F applied during the compression, (b) variations of ΔR^* during the compression, (c) variations of R^*
548 before the beginning of the compression as a function of the Young's modulus (error bars
549 corresponding to standard deviations and a broken line draws the linear regression for indicative
550 purpose). The results were obtained with $R_1\beta_1$ under dry lubrication conditions.

551 Figure 5: For the four lubrication levels, variations of ΔR^* during the compression of two types
552 of food gels on two types of TMSs: (a_1) Ge_7 and $R_0\beta_0$, (a_2) Ge_7T and $R_0\beta_0$, (b_1) Ge_7 and $R_1\beta_2$ and (b_2) Ge_7T
553 and $R_1\beta_2$.

554

Tables

555

556 Table 1 – Description of the gels in terms of dominant polymer (either agar or gelatin),
 557 composition (all of them containing 15 wt% of sucrose), and Young’s modulus (average \pm standard
 558 deviation).

Gel	Dominant Polymer	Composition (wt%)				Young’s modulus (kPa)
		Water	Agar	Gelatin	TWEEN	
					20	
<i>Ag_{0.3}</i>	Agar	84.7	0.3	-	-	4.2 \pm 3.2
<i>Ag₁Ge_{0.75}</i>	Agar	84.25	1	0.75	-	58.4 \pm 14.7
<i>Ag_{1.8}</i>	Agar	83.3	1.8	-	-	132.0 \pm 9.7
<i>Ge_{3.5}</i>	Gelatin	81.5	-	3.5	-	2.2 \pm 0.4
<i>Ag_{0.3}Ge_{3.5}</i>	Gelatin	81.2	0.3	3.5	-	12.7 \pm 2.9
<i>Ag_{0.7}Ge_{5.85}</i>	Gelatin	78.45	0.7	5.85	-	32.1 \pm 7.2
<i>Ge₇</i>	Gelatin	78	-	7	-	24.0 \pm 2.2
<i>Ge₇T</i>	Gelatin	77.25	-	7	1.5	17.2 \pm 1.8

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Figure 1

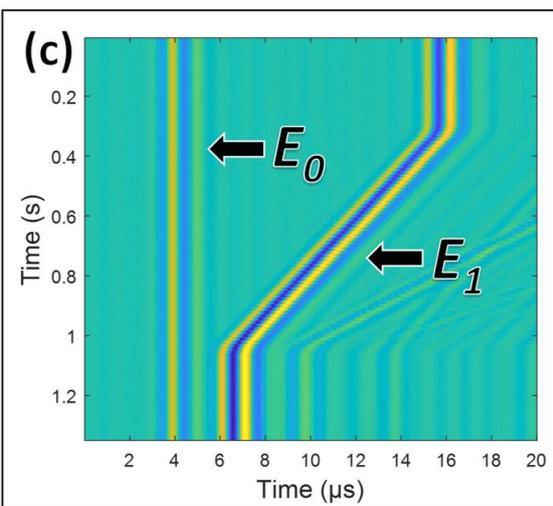
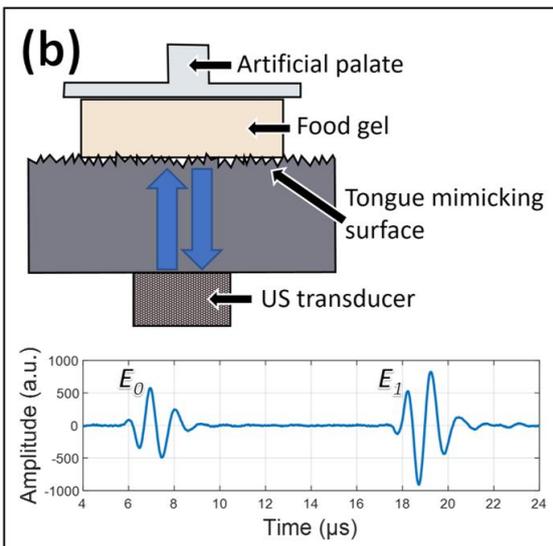
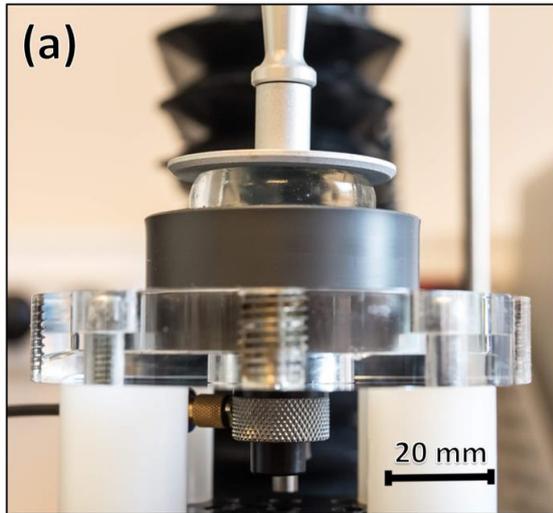


Figure 2

