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Ultrasound monitoring of a deformable tongue-food gel system during uniaxial compression—an in vitro study

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Abstract

This study presents a novel ultrasound method for exploring the mechanical deformability of artificial tongue models (ATMs) topped with agar and/or gelatin food gels during uniaxial compression. The ATMs were made from polyvinyl alcohol and displayed different levels of rigidity and surface roughness. We quantified deformation of the ATM-food system as it underwent compression induced by a texture analyzer. We collected real-time measurements via an ultrasound transducer (1 MHz) placed beneath the ATM, enabling to monitor non-invasively the ultrasound time of flight (ToF) and the apparent reflection coefficient (R^*) of the ATM-food interface. The results on ToF reflected the tie between the level of force and ATM deformation; they were also precise enough to identify gel fracture. R^* was a crucial parameter influenced by both ATM properties (rigidity, surface roughness) and food gel properties (syneresis, ability to mold to surface asperities).

Keywords

Food texture, Oral processing, Ultrasound, Artificial tongue models, Biomimetic set-up

1. Introduction

52
53 Food texture perception is the result of complex and dynamic phenomena, which occur
54 simultaneously during food oral processing. Understanding the dynamics of texture perception is
55 hence of paramount interest for food scientists who seek to understand and model consumers'
56 sensorial experience of food (Renard, Van De Velde, & Visschers, 2006; Wilkinson, Dijksterhuis, &
57 Minekus, 2000). As technological advances are made, new and more precise techniques for
58 characterizing food properties (e.g., structure, rheology, and tribology) have been developed (Stokes,
59 Boehm, & Baier, 2013). However, it remains difficult to precisely associate mechanical measurements
60 with sensory attribute ratings and to follow texture dynamics during oral processing. The human oral
61 cavity is very complex and equipped with different types of mechanoreceptors, which can detect
62 both static and dynamic stimuli. The tongue is a crucial organ within the oral cavity: it moves food
63 back and forth, facilitating proper mastication and the safe swallowing of boli. It also plays a very
64 important role in texture perception, especially when food is compressed between the tongue and
65 the palate (Ishihara et al., 2013; Kohyama, Ishihara, Nakauma, & Funami, 2021). During oral
66 processing, the deformation of food over the tongue surface creates clusters of different stimuli,
67 which are perceived by the mechanoreceptors and then sent to the brain for further processing,
68 including texture determination. There is a growing body of literature that underscores how
69 understanding the tongue's physiological properties can shed light on changes in food structure
70 during oral processing and the resulting diversity of texture perceptions (Engelen & Van Der Bilt,
71 2008; Ketel, de Wijk, de Graaf, & Stieger, 2020; Van Vliet & Primo-Martín, 2011). Therefore, it is
72 essential to further explore the dynamic interactions taking place between food and oral surfaces.

73 To effectively monitor such interactions, it is necessary to use a non-destructive technique that can
74 be applied in real time. Ultrasound-based approaches have shown great promise and have been
75 successfully employed to visualize tongue movement and bolus swallowing (Gao et al., 2013; Peng,
76 Miethke, Pong, & Lin, 2007). Nevertheless, ultrasound images only provide qualitative information.
77 Therefore, there has been a need to develop ultrasound-based methods with quantitative metrics

78 that can more precisely reveal the occurrence of events at the tongue-food interface. However,
79 quantifying the propagation of ultrasound waves in the human oral cavity can be quite difficult.
80 There is thus a need to develop an oral biomimetic set-up where the behavior of ultrasound waves
81 can be studied in a controlled manner. Mantelet, Restagno, Souchon, & Mathieu (2020) and
82 Mantelet, Srivastava, Restagno, Souchon, & Mathieu (2020) developed a novel ultrasound method
83 for analyzing the tongue-food interface *in vitro*; their research performed a detailed examination of
84 ultrasound reflectivity at the tongue-food interface, characterizing the effects of food properties,
85 lubrication, and tongue surface roughness. This proof-of-concept work utilized rough but non-
86 deformable tongue-mimicking surfaces made of polyvinyl chloride (PVC). It was found that the
87 reflectivity of ultrasound waves (as estimated via the apparent reflection coefficient, R^*) at the
88 tongue mimic-food interface could be exploited to monitor changes in contact over time. This
89 research also clarified the influence of food properties and lubrication on R^* and, thus, on interface
90 interactions.

91 However, the PVC tongue-mimicking surfaces did not very realistically recreate an actual human
92 tongue, and there was thus further room for improvement. Therefore, in this present article we have
93 introduced a novel artificial tongue-mimicking model (referred to as an ATM hereafter) made of
94 polyvinyl alcohol (PVA). In recent years, PVA has been used in biomedical engineering to model
95 arteries and oral mucosa (Chatelin et al., 2014; Fromageau et al., 2007; Gennisson et al., 2007; Jiang,
96 Liu, & Feng, 2011; Mamada, Fridrici, Kosukegawa, Kapsa, & Ohta, 2011). Tongue mimics made with
97 PVA were also used in our previous study dealing with oral tribology (Srivastava et al., 2021). PVA is a
98 water-soluble synthetic polymer and can be used to form hydrogels. The rigidity of PVA hydrogels
99 can be controlled by varying the number and kinetics of the freezing and thawing cycles (Fromageau
100 et al., 2007). This ability to control hydrogel rigidity made PVA a good fit for our study system.

101 The deformability of the PVA based ATM meant that it could be used in compression experiments in
102 which changes in tongue thickness over time were quantified using an ultrasound parameter called

103 time of flight (ToF). The data gathered helped reveal the relationships among tongue dynamics, food
104 properties, and system deformation. Using the PVA based ATM, we also studied variability in R^* in
105 response to ATM properties (i.e., surface roughness, Young's modulus values, and water-release
106 capacity) and food gel properties (i.e., Young's modulus values and water-release capacity), as such
107 factors influence the tongue-food interface and, in turn, affect interactions between food and the
108 tongue.

109 **2. Materials and methods**

110 **2.1. Preparation and characterization of food gels**

111 Preparation of the food gels

112 Eight different model gels (Table 1) made of agar and/or gelatin were prepared as described in
113 Mantelet et al. (2020a and b). First, a sucrose solution (white sugar [Cristalco, Paris, France] dissolved
114 in water) was prepared via stirring at 20 °C for 30 min. If needed, agar powder (HP700IFG, Kalys,
115 Bernin, France) was incorporated, and the mixture was heated to 100 °C (until agar was completely
116 dissolved) in a flask sealed with aluminum foil to limit any loss of water. After the agar powder was
117 completely dissolved, the mixture was cooled to 60 °C. This temperature was maintained, and gelatin
118 (Bloom 250 PS 8/3, Rousselot, Gent, Belgium) was added (if required); the mixture was continuously
119 stirred for 20 min. Once the gelatin was completely dissolved, the solution was poured into
120 cylindrical molds (30 mm in diameter, 10 mm in height) made of polyethylene and exposed to
121 conditions promoting gelation (20 °C for 15–18 h). The gel was unmolded just before the experiment
122 to prevent any loss of water or shape over time. Table 1 summarizes the mechanical properties of
123 the gels, which were characterized during the aforementioned research.

124 Water-release capacity of the food gels

125 The water-release properties of these food gels were also quantified using a protocol adapted from
126 Sala, Stieger, & van de Velde (2010). Three Whatman™ filter paper disks (110 mm diameter; GE

127 Healthcare Life Sciences, Chicago, USA) were placed on the base plate of a texture analyzer (TA.XT
128 plus, Stable Micro Systems, Surrey, United Kingdom). A given gel was deposited on the disks and
129 subjected to uniaxial compression (20% strain rate, 10 mm/s); there was a 5 s holding period. The
130 maximum strain rate was chosen to avoid gel breakdown. The amount of water released was
131 determined by comparing filter disk mass before and after the compression test. This methodology
132 was somewhat modified in the case of the Ag_{0.3} gel because the latter was very fragile and released
133 water even without being compressed. Therefore, this gel was left on the filter disks for 5 sec and
134 was then removed, without the application of any external stress. The paper was then weighed as in
135 the case of the other gels. The results are presented in Table 1. However, in all future comparisons,
136 we assumed that Ag_{0.3} had highest water-release capacity.

137 **2.2. Preparation and characterization of the artificial tongue models**

138 Preparation of the artificial tongue models

139 First, PVA powder (Sigma Aldrich, Saint-Louis, USA) was dissolved in ultra-pure water (at 10% w/w)
140 under stirring for 2 h at 80 °C. The solution was then cooled until it reached room temperature. The
141 solution was subsequently poured into cylindrical molds (50 mm in diameter, 20 mm in height) that
142 contained abrasive paper at the bottom. The choice of ATM thickness is based on values reported in
143 literature which ranged from 10 mm to 40 mm (Nakamori et al., 2020; Beghini et al., 2017; Ishihara
144 et al., 2013). To simulate two levels of surface roughness, two types of abrasive paper were used: (i)
145 P80 sandpaper (grain size = 200 μm; Struers, Champigny-sur-Marne, France) and (ii) P40 sandpaper
146 (grain size = 425 μm; Norton, Saint-Gobain, France). Hereafter, they are referred to as R₁ and R₂,
147 respectively. The molds were sealed and frozen at -20 °C for 10 h. They were then thawed for 14 h at
148 20 °C. The freezing and thawing cycles were adjusted to attain the desired rigidity (Fromageau et al.,
149 2007). Two types of ATMs were prepared: a soft ATM (C₂), which underwent two cycles, and a hard
150 ATM (C₆), which underwent six cycles. After the completion of the requisite number of cycles, the

151 ATMs were unmolded and stored in reverse osmosis treated water at room temperature (20 °C) for
152 several months.

153 Mechanical properties of the artificial tongue models

154 ATM rigidity was measured using uniaxial compression tests carried out with a texture analyzer
155 (speed: 10 mm/s; strain rate: up to 20%; at least 3 replicates performed). This protocol was adapted
156 from the work of Gao, Nakao, Ishihara, Funami, & Kohyama (2016). The resulting Young's modulus
157 values are presented in Table 2.

158 Water-release capacity of the artificial tongue models

159 The ability of the ATMs to release water under mechanical compression was also quantified. For each
160 ATM, any surface water was gently absorbed with Kimtech™ absorbent wipes (Kimberly-Clark, Irving,
161 TX, USA) until the tissue came away dry. Subsequently, three layers of absorbing Whatman™ filter
162 paper (110 mm diameter; GE Healthcare Life Sciences, Chicago, USA) were placed between the
163 texture analyzer probe and the tongue's rough surface to fully collect the water released. We chose
164 to use a strain rate of 5% and a holding time of 5 sec to avoid any damage to the tongue's surface
165 from the aluminum probe. The difference in paper mass was then determined as previously
166 described to estimate water-release capacity (Table 2).

167 Surface roughness profiles of the artificial tongue models

168 ATM surface roughness was analyzed via profilometry. Measurements were obtained using a contact
169 profilometer (Dektak XT, Bruker, Billerica, MA, USA) with a 50-nm-radius stylus and 1 mg of applied
170 force. For each ATM, three 30 mm surface scans were performed (one-dimensional, 45° of rotation
171 between each scan). Vision 64 software (Bruker, Billerica, MA, USA) was used to control, analyze, and
172 perform slope corrections before employing an algorithm in MATLAB (The MathWorks, Natick,
173 Massachusetts, USA) to calculate roughness. Two parameters were chosen: the mean height of
174 surface asperities (Ra) and correlation length, which is inversely related to asperity density (β).

175 Although only two types of sandpaper were used, the freezing and thawing cycles had an impact on
176 surface roughness as well. The values are presented in Table 2.

177 **2.3. Ultrasound measurements**

178 As in Mantelet et al. (2020a and b), the ultrasound set-up (Figure 1) comprised a texture analyzer, a
179 tongue-mimicking surface (a PVA based ATM in this study), and a mono-element piezoelectric
180 ultrasound transducer (central frequency of 1 MHz; V103RM, Olympus, Shinjuku, Tokyo, Japan); the
181 latter was placed beneath the ATM. Before starting each experimental test, the water on the surface
182 of the ATM was gently removed using absorbent wipes (Kimtech™, Kimberly-Clark, Irving, TX, USA)
183 until the tissue came away dry. The food gels were gently unmolded and placed on top of the ATM.
184 The texture analyzer was used to apply a controlled uniaxial deformation (of up to 8 mm at 10 mm/s)
185 to the ATM-food gel system using a circular aluminum probe (diameter: 40 mm). Ultrasound
186 measurements were made prior to the food being placed on the ATM (i.e., reference measurements)
187 and in real time during the compression period. To this end, the transducer, acting as both an emitter
188 and a receiver (pulse-echo mode), was used in tandem with a pulser-receiver (Sonatronic, Evry,
189 France). The pulser-receiver system was used to generate negative square wave pulses (width: 500
190 ns, amplitude: 80 V) and to digitize the radio frequency (*rf*) signals corresponding to the system's
191 pulse echo response (12-bit quantification, 100 MHz sampling rate, 38 dB gain). The frequency of
192 pulse recurrence was around 90 Hz. A LabVIEW (National Instrument, Austin, Texas, USA) interface
193 was used for real-time acquisition of the *rf* signals during the compression period.

194 **2.4. Signal processing**

195 Similarly to the work done in our previous research Mantelet et al. (2020a and b), the apparent
196 reflection coefficient of ATM-food interface (R^*) was calculated on all the ultrasound signals of each
197 test. ATM deformability had an impact on both the amplitude and the time of occurrence of the
198 ultrasound waves reflecting off the ATM-food gel interface. The deformations induced during
199 compression shortened the path to be covered by the waves. As a consequence, the time needed for

200 the waves to travel between the emission source and back was shorter as well. Thus, in addition to
201 R^* , here we have used another ultrasound parameter: time of flight (ToF).

202 Each experimental test is composed of a set of signals which have been analyzed using Matlab.
203 Figure 2a shows the typical shape of an *rf* signal, composed of two main echoes: E_0 for the tongue-
204 food interface, E_1 for the food-palate interface. Figure 2b shows the M-Mode representation of the
205 whole set of signals acquired during a test, where signal amplitude is coded in color and thus allows
206 to trace the evolution of the echoes identified in Figure 2a. For each signal, noise reduction was
207 implemented via a low-pass filter (cut-off frequency: 10 MHz). To precisely characterize ATM
208 deformation, it was crucial to accurately determine the ToF for the echo, E_0 , associated with the
209 ATM-food gel interface over the entire course of a given test. E_1 echo was not processed for this
210 study. Using the reference signal, a time window was automatically defined; it had a width of 5 μ s
211 and was centered with respect to the Hilbert-transformed peak amplitude of the signal. This window
212 of reference was then cross-correlated with all the *rf* signals acquired during a given test, allowing
213 the automatic detection of the ToF associated with E_0 .

214 The ToF associated with the echo E_0 corresponds to the time required for the ultrasonic wave to
215 return to the sensor after being reflected at the interface between the ATM and the food. The
216 thickness (e) of the ATM is proportional to this time of flight ToF:

$$217 \quad e = \frac{1}{2} \cdot ToF \cdot c$$

218 Where c is the propagation speed of ultrasound waves in the 10% PVA hydrogels (1540 m/s at 20 °C;
219 Gennisson et al., 2007). Finally, the deformation of the ATM (Δe) was deduced by subtracting the real
220 time thickness (e) of the ATM from its initial value e_0 . As an example for validation of the accuracy of
221 the method, we compared it with deformation measurements assessed with the texture analyzer. To
222 do so, we considered the compression of an ATM without any food. The deformation applied was
223 20%, with a velocity equal to 10 mm/s (similarly to as done for the tests in presence of food). Three

224 repetitions were performed. The obtained average curves with standard deviation envelopes can be
225 compared in Figure 3. The obtained graphs hence show that the deformation measurements by both
226 ultrasound and texture analyzer are in agreement, confirming the relevance of the ultrasound
227 velocity value (1540 m/s) used for the calculation, and validating the method for tongue deformation
228 assessment.

229 To reliably calculate R^* at the ATM-food gel interface, it was necessary to accurately estimate the
230 amplitude of E_0 . For all the *rf* signals, time windows encompassing E_0 had a width of 5 μ s and were
231 defined so as to be centered around the ToF for E_0 . A Hanning window was applied, and the
232 amplitude of E_0 was defined as the maximum amplitude of the power spectrum (the Fourier
233 transform of the autocorrelation function) for the window obtained. R^* was defined as E_0 's
234 amplitude during a given test, expressed as a percentage of E_0 's amplitude during the reference
235 measurements (i.e., when there was no food gel on the ATM). Consequently, the evolution of ToF
236 and R^* were computed for the entire duration of an experimental test, as illustrated in Figure 2c
237 which focuses on the compression step.

238 3. Results and discussion

239 To begin with, the biomimetic set-up with different ATMs was developed. The roughness and rigidity
240 values (Table 2) of the ATMs fabricated for this study were found to be in accordance with the values
241 reported for real human tongues. Ishihara et al., (2013) has reported the rigidity of the human
242 tongue at rest as 12.2 ± 4.2 kPa and at contracted state as 122.5 ± 58.5 kPa. Moreover, the surface
243 asperities height (filiform papillae) of human tongue was reported between 50 - 150 μ m (Andablo-
244 Reyes et al., 2020; Wang, Wang, Upadhyay, & Chen, 2019). Also, Andablo-Reyes et al. (2020)
245 reported average diameter of filiform papillae around 350 μ m. Hence the characteristics of the
246 developed ATMs were in good accordance with the values published in literature on human tongues.
247 The results and discussion on these ATMs are discussed below and have been structured into two
248 main parts that each focus on one of ultrasound parameters: (i) ToF and (ii) R^* .

249 **3.1. Characterizing the deformation of the artificial tongue models—ToF**

250 It is important to investigate the deformation of the tongue during oral processing because this
251 phenomenon can directly change food bolus characteristics and stimulate the mechanoreceptors
252 responsible for texture perception. In this study, our *in vitro* approach allowed us to measure the ToF
253 of the ultrasound waves reflected off of the ATM-food gel interface, providing an accurate estimate
254 of ATM deformation during the uniaxial compression of the system. The maximum possible degree of
255 ATM deformation (in the absence of food) was 40% because initial ATM thickness was 20 mm, and
256 the level of deformation applied to the system was fixed at 8 mm. It is also important to have in mind
257 that the diameter of the ultrasound beam (less than 10 mm) is lower than the diameter of the gels.
258 Thus, the deformations measured by ultrasound only reflect what is happening in the central part of
259 the ATM, which can be assumed as planar.

260 Effect of food properties

261 When the soft (C_2R_2) ATM was used, varied profiles of force (as measured by the texture analyzer)
262 were observed over the range of food gels (plate displacement: 8 mm at 10 mm/s; Figure 4a). The
263 ToF values obtained during these experimental tests showed that ATM deformation changed over
264 time (Figure 4b). Force and ATM deformation showed similar trends. When tests were performed
265 using the hard (C_6R_2) ATM, we saw the same patterns and similarity in metric values (Figures 4c and
266 4d). These results are encouraging because they underscore the relationship between ATM
267 deformation and the force applied to the system during compression. The *in situ* and non-invasive
268 characterization made possible here with ultrasound gives promising long term *in vivo* perspectives.
269 Forces and deformations indeed constitute very relevant information to monitor during oral
270 processing, but they remain impossible to characterize so far. The ToF values also showed that it was
271 possible to identify the fracture point of food gels during compression. Like the level of force, tongue
272 deformation was found to be sensitive to the sudden breakage of food gels. Out of the eight food

273 gels, $Ag_{0.3}$ was the only one that fractured during compression, and this event was easily observed in
274 both the ATM deformation results and the force results.

275 It is also clear from the results that ATM deformation was affected by the mechanical properties of
276 the food gels. For example, because $Ag_{0.3}$ and $Ge_{3.5}$ were softer, they did not cause as much ATM
277 deformation as did the more rigid food gels like $Ag_{1.8}$. To understand this phenomenon, it is useful to
278 make the comparison with the situation of two springs connected in series. Total deformation is the
279 sum of the strains experienced by the individual springs. Hence, the softer gels more equally shared
280 the deformation resulting from system compression, whereas the more rigid gels did not, leading the
281 ATM to deform more in compensation.

282 Effect of artificial tongue model properties

283 The human tongue is a complex muscular organ that is also a hydrostat. In other words, its volume
284 remains constant when its rigidity is modulated or when it is in motion (Napadow, Chen, Wedeen, &
285 Gilbert, 1999). Tongue rigidity changes considerably over the course of oral processing to better
286 manage the bolus and texture perception. We used the PVA based ATM to investigate the role of
287 rigidity in food deformation. We measured force and ATM deformation during experimental tests in
288 which the different food gels were placed on the soft and hard ATMs (C_2R_2 and C_6R_2 , respectively;
289 values following compression: Figure 5). ATM rigidity affected the relationship between the level of
290 force and ATM deformation. For both ATM types, the different food gels formed clusters that were
291 based on the gels' mechanical properties). It represents that the diversity in mechanical property of
292 gels were suitable for this study. Some food gels, like $Ag_{0.3}$, resulted in little tongue deformation,
293 while others, like $Ag_{1.8}$, led to nearly 8 mm in deformation in the soft ATM, suggesting that the food
294 gels themselves were not deformed at all. Taken together, the clusters of points for each ATM type
295 followed a specific pattern, which was comparable to the curves obtained for the Young's modulus
296 values during ATM compression. It is thus evident that the hard ATM led to greater force than did the
297 soft ATM. Moreover, ATM rigidity also influenced food deformation kinetics. Using $Ag_{0.3}$ as an

298 example, both the force and ATM deformation results show that gel fracture occurred earlier on the
299 hard ATM than on the soft ATM (Figure 4). These results highlight that ATM rigidity plays an
300 important part in shaping the extent and kinetics of food deformation.

301 The human tongue has a particular surface topology due to the presence of different papillae.
302 However, the latter's role in the bulk deformation of food has yet to be thoroughly explored. In this
303 study, force and ATM deformation displayed different patterns over time when certain food gels
304 (notably gelatin-dominant gels) were placed on ATMs with the same rigidity but different surface
305 roughness. For example, in case of the gelatin-dominant gels $Ge_{3.5}$ and Ge_7 , the effect of surface
306 roughness on tongue deformation was much more pronounced for the hard ATM (Figures 6a, b),
307 since the deformation curve for C_6R_1 was more distant from C_6R_2 when comparing C_2R_1 with C_2R_2 . The
308 explanation could be that, when the cylindrical gels were compressed on top of the ATM, a barreling
309 effect arose from friction and adhesion coming into play (Brennan & Bourne, 1994; Pons & Fiszman,
310 1996). Barreling effects occur when there is friction between a plate and a specimen, which results in
311 a state of triaxial stress instead of the ideal state of uniaxial stress. Since gelatin polymers have
312 adhesive properties and release less water, the degree of friction might have been greater. The agar-
313 dominant gels did not display such a pattern, perhaps because of their higher degree of water
314 release.

315 This explanation could also apply to the results for the hard ATM, which released less water during
316 compression. Furthermore, the number of freezing and thawing cycles positively affected mean peak
317 asperity height (Table 2). The presence of taller asperities with negligible water in the interphase
318 region should have enhanced adhesion between the food gels and the ATM. Greater adhesion can
319 enhance barreling effects, lowering the uniaxial force exerted on the system.

320 **3.2. Analysis of the tongue model-food gel interface— R^***

321 R^* is the parameter used to quantify the apparent reflection of ultrasound waves at the interface
322 between the ATM and the food gels, and its value is greatly dependent on the media's difference in

323 acoustic impedance (Mantelet et al., 2019). R^* has been shown to be a key parameter for
324 understanding the characteristics of the tongue-food interface (Mantelet et al., 2020a and b). More
325 specifically, it was found that there was a pronounced difference in acoustic impedance between a
326 PVC tongue-mimicking surface and various food gels, resulting in the strong reflection of ultrasound
327 waves at the interface. Here, in contrast, the PVA based ATM and the food gels appeared to have
328 similar acoustical impedance, PVA being thus more representative of the acoustic properties of
329 human soft tissue. However, it may also mean that the quantity of acoustic energy reflected by the
330 ATM-food gel interface was limited. That said, there were clear differences in R^* among food gels
331 (Figure 7a). Results for the C_2R_2 ATM underscore the sensitivity of our ultrasound method when it
332 comes to analyzing the interface between the PVA ATM (with its more biologically realistic
333 properties) and the food gels. Previous research has examined variation in R^* for a PVC tongue-
334 mimicking surface (Mantelet et al., 2020a and b). The presence of trapped air at the interface was
335 found to be a key factor affecting R^* variations. The value of this parameter was at a minimum when
336 no air was present, representing a state of perfect coupling between the ATM and food gel; in
337 contrast, when R^* was maximum, coupling was imperfect due to significant amounts of trapped air.
338 Factors that can alter air presence are water release or mechanical deformation. The results obtained
339 here were similar to those seen in the previous study. R^* values varied depending on food gel type
340 and the amount of water present at the interface.

341 Effect of food gel properties

342 Polymers like agar or gelatin form very different structures upon gelation, resulting in products that
343 differ in rigidity and water-release capacity (Santagiuliana, Piqueras-Fiszman, van der Linden, Stieger,
344 & Scholten, 2018). Consequently, we observed a variety of changes in R^* over time: it decreased,
345 plateaued, or increased over the course of compression, indicating the presence of a nonlinear
346 response. It was therefore necessary to study the data quantitatively. When the values of R^* were
347 examined and compared for two time points (Figure 7b), t_0 (test begins—food gel is deposited on the

348 ATM) and t_1 (test ends following the compression period), it was evident that two main factors were
349 at play. Syneresis and the gel's ability to mold itself to ATM surface asperities appeared to govern
350 changes in R^* over time.

351 At t_0 (Figure 7b), the R^* value for $Ag_{0.3}$ was quite low since the latter was an extremely soft food gel
352 that released a large amount of water, improving contact with the ATM's surface. $Ge_{3.5}$ had a
353 comparatively higher R^* value despite its nearly equivalent Young's modulus value because it
354 released less water. The values at t_0 can shed some light on why some food gels might be perceived
355 as dry or wet when deposited on the tongue.

356 When the food gels were compressed on the ATM, the main trend observed was a decrease of R^*
357 since the application of stress tended to improve contact at the interface. The R^* values following
358 compression (t_1) provided much needed insight into the role of food gel and ATM properties in
359 predicting the degree of improvement in contact. The higher the gel's gelatin concentration, the
360 higher the initial R^* value, suggesting poorer levels of contact. There was thus greater room for
361 improvement when the uniaxial stress was applied. This difference was starker for the more rigid
362 gelatin-dominant gels since the force exerted to achieve 8 mm in deformation was much higher,
363 resulting in better contact between the food gel and the ATM.

364 Effect of artificial tongue model properties

365 ATM properties also influenced the R^* values. When examining how ATM rigidity type (C_2R_2 = soft
366 and C_6R_2 = hard) affected the results obtained with the food gels $Ag_{0.3}$, $Ge_{3.5}$, Ge_7 , and Ge_{7T} , it was
367 found that R^* was higher at the start of the tests (t_0) for C_6R_2 compared to C_2R_2 (Figures 8a and 8b).
368 The greater the number of freezing-thawing cycles, the denser and more rigid the PVA becomes,
369 affecting the polymer's ability to release water. The resulting absence of water at the interface could
370 explain why R^* was higher for the C_6R_2 ATM. As discussed previously, low levels of lubrication at the
371 interface can augment adhesion, resulting in a barreling effect and an uneven decline in compression
372 force. This barreling effect might lead to uneven surface deformation as well as air pockets, thus

373 increasing R^* . Another explanation could be that the hard ATM underwent six cycles of freezing and
374 thawing, more greatly affecting its surface roughness (peak height) even though sandpaper grain size
375 was the same. Increased asperity height could have led to more air being trapped at the interface,
376 boosting R^* values.

377 When rigidity was controlled, ATM surface roughness (C_2R_1 vs. C_2R_2) was found to affect R^* values
378 (Figures 9a and 9b): it resulted in different temporal patterns in R^* for the three gelatin-dominant
379 gels ($Ge_{3.5}$, Ge_7 , Ge_{7T}). R^* values were higher for C_2R_1 than for C_2R_2 , which was an unexpected result
380 because one would assume that higher asperities would lead to more trapped air, enhancing wave
381 reflection. However, it should also be noted that, compared to C_2R_1 , C_2R_2 had a larger peak
382 correlation length (β) (i.e., wider peaks) and hence a lower peak density. Peak density could affect
383 surface topography overall, potentially explaining this unexpected observation.

384 The comparison of the R^* values for Ge_7 versus Ge_{7T} sheds light on the ability of TWEEN to modify
385 interface characteristics (Figure 9c). As a surfactant, TWEEN lowers the surface tension of water,
386 promoting its spread under conditions of compression and expelling the air trapped among
387 asperities. It seems likely that the properties of the surfactant in Ge_{7T} reduced the difference in the
388 R^* values when this food gel was used on ATMs of different surface roughness.

389 4. Conclusions

390 In this study, we used PVA based ATMs with different bulk rigidities and surface roughness profiles to
391 investigate the role of tongue deformability in the mechanical compression of food gels by a hard
392 palate. The ToF of the ultrasound wave traveling to and from the ATM-food gel interface was used as
393 a key metric for characterizing the overall deformation of the system. The ToF values helped
394 estimate ATM deformation during the uniaxial compression of the food gels and were found to fit
395 with the force exerted on the system. R^* , or the apparent reflection coefficient, has been employed
396 in previous studies to analyze tongue-food dynamics. It was found to be effective here as well for

397 characterizing real-time changes at the ATM-food gel interface over the course of compression,
398 including changes in the relationship between contact dynamics and both gel properties (i.e., Young's
399 modulus values, water-release capacity) and ATM properties (i.e., deformability and surface
400 roughness). More importantly, this study demonstrated that, despite the similarities in the acoustical
401 impedance of the ATMs and the food gels, it was possible to accurately quantify reflection at a rather
402 small scale. Consequently, this approach may hold promise for *in vivo* applications involving
403 biological tissues and food, which have similar acoustical properties.

404 The study also underscored the utility of PVA in ATM design, given that it is a material that can better
405 replicate tongue rigidity and roughness, a need that still exists in food oral processing research.
406 Additionally, our findings showed that ultrasound techniques could be useful for tracking
407 quantitative information related to mechanical interactions between the tongue and the palate.

408 Future work using this set-up will focus on investigating how ultrasound indicators respond when
409 investigating systems with more complex, heterogeneous model foods. The broader goal is to
410 progressively bridge the gap between model food and real food. Future research will also better
411 account for the complexity of food oral processing, a greater diversity of motion (mixing shearing and
412 compression) will be simulated and tongue shape, oral cavity anatomy and oral temperature will be
413 more realistically recreated to further put ultrasound techniques to the test, prior to their more
414 widespread use *in vivo*.

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419

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Figure Captions

516 Figure 1: (a) Schematic representation of the experimental set-up; Pictures of (b) the polyvinyl
517 alcohol artificial tongue model (ATM) and (c) the ATM topped with a food gel.

518 Figure 2: (a) A typical *rf* signal, composed of two main echoes: E_0 for the tongue-food interface, E_1 for
519 the food-palate interface; (b) Ultrasound M-mode imaging of the entire set of signals obtained during
520 an experiment and (c) Variation of ToF and R^* (calculated on the basis of E_0) during a compression.

521 Figure 3: Estimation of the tongue deformation (without food) by ultrasound time of flight and
522 texture analyzer.

523 Figure 4: (a) Force and (b) estimated ATM deformation over time as food gels were compressed on
524 the soft ATM (C_2R_2); (c) Force and (d) estimated ATM deformation over time as food gels were
525 compressed on the hard ATM (C_6R_2). The cloud around each line represents the standard deviation;
526 at least six replicates were performed for each experimental test. The markers of different shapes
527 were used to enhance the readability of the graphs. The dotted line on ATM deformation plot
528 represents the maximum deformation imposed by the texture analyzer.

529 Figure 5: Force and estimated ATM deformation following compression (time t_1) for the experimental
530 tests conducted with all the food gel types on ATMs differing in rigidity (C_2R_2 = soft and C_6R_2 = hard).
531 Each color corresponds to a certain food gel type, whereas the two symbols distinguish between the
532 ATM types.

533 Figure 6: Effect of surface roughness on estimated ATM deformation during the compression of the
534 food gels (a) $Ge_{3.5}$ and (b) Ge_7 . The cloud around each line represents the standard deviation.

535 Figure 7: (a) R^* values during the compression of the food gels on the soft ATM (C_2R_2); the cloud
536 around each line represents the standard deviation; the markers of different shapes were used to
537 enhance the readability of the graphs. (b) R^* values before compression began (t_0), and after
538 compression ended (t_1), and the difference between the two (t_0-t_1). The error bars represent the
539 standard deviations.

540 Figure 8: Effect of ATM rigidity on R^* during the compression of the food gels on (a) the soft ATM
541 (C_2R_2) and (b) the hard ATM (C_6R_2). The error bars represent the standard deviations.

542 Figure 9: Effect of surface roughness on R^* during the compression of the food gels (a) $Ge_{3.5}$, (b) Ge_7 ,
543 and (c) Ge_{7T} . The cloud around each line represents the standard deviation.

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559 Tables

560 Table 1: Description of the food gels (Diameter: 30 mm; Height: 10 mm): composition (they all
561 contained 15% wt of sucrose), Young's modulus values, and water-release capacity. Standard
562 deviations are provided when applicable.

563 Table 2: Description of the ATMs (Diameter: 50 mm; Height: 20 mm): Young's modulus values,
564 surface roughness profiles, and water-release capacity. Standard deviations are provided when
565 applicable.

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581 **Figure 1**

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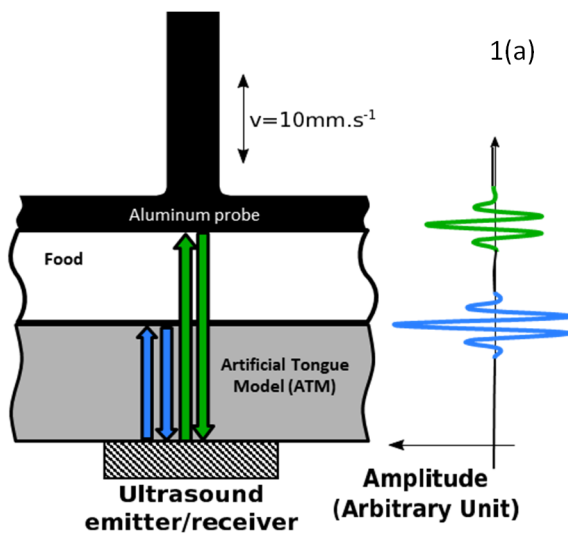
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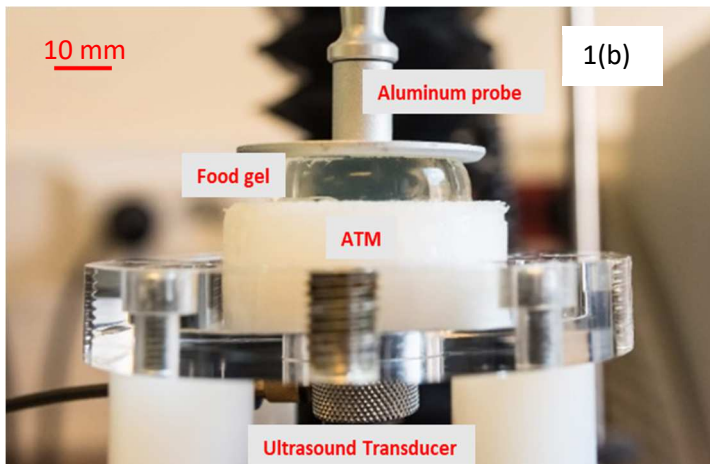
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601 **Figure 2**

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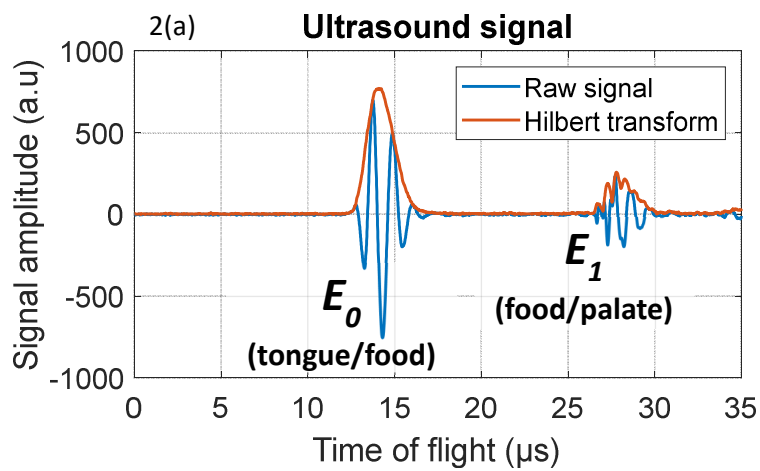
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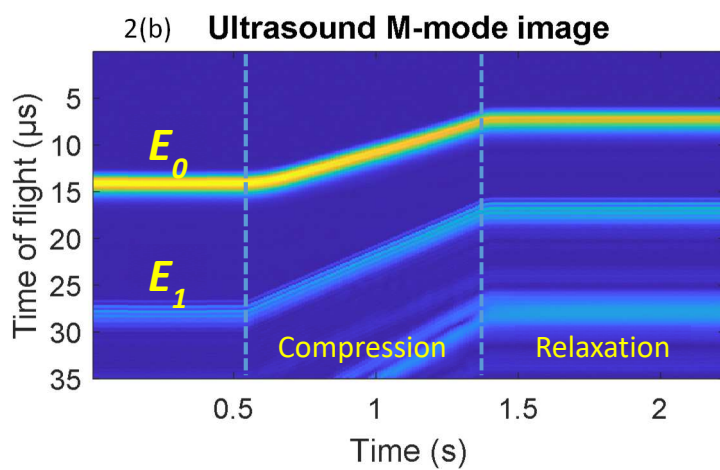
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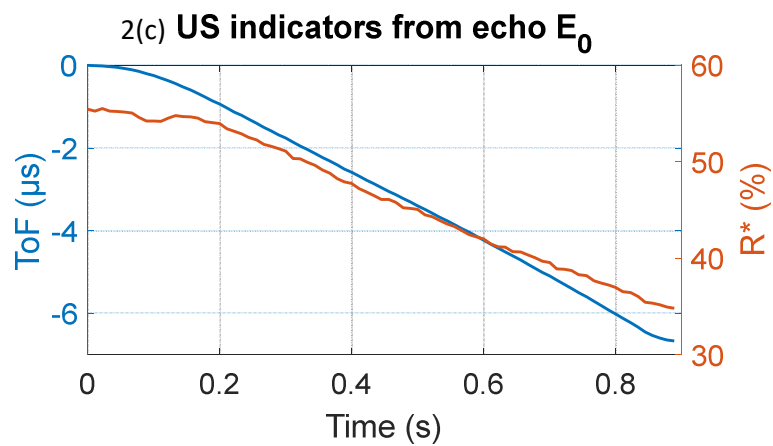
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621 **Figure 3**

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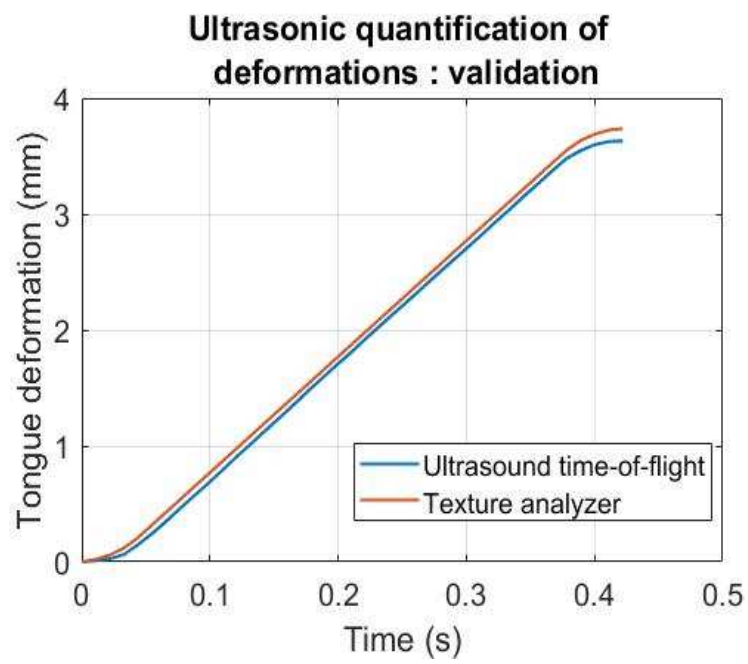
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641 **Figure 4**

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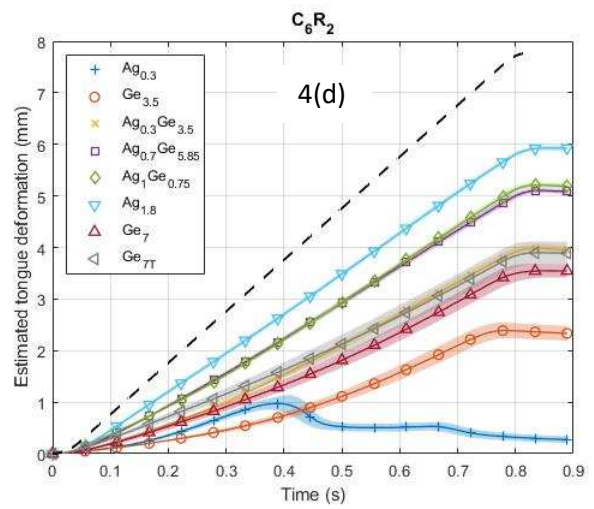
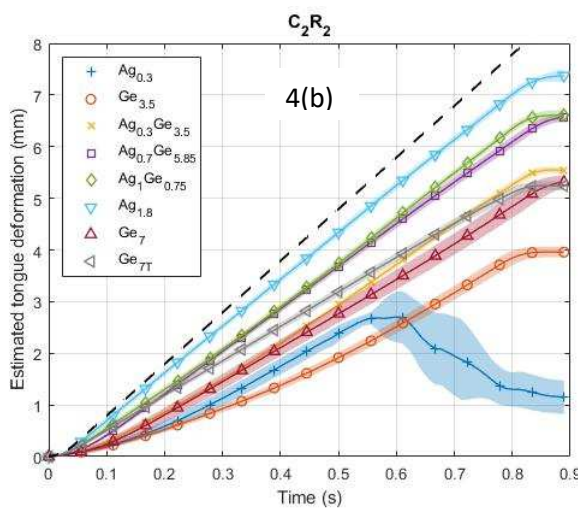
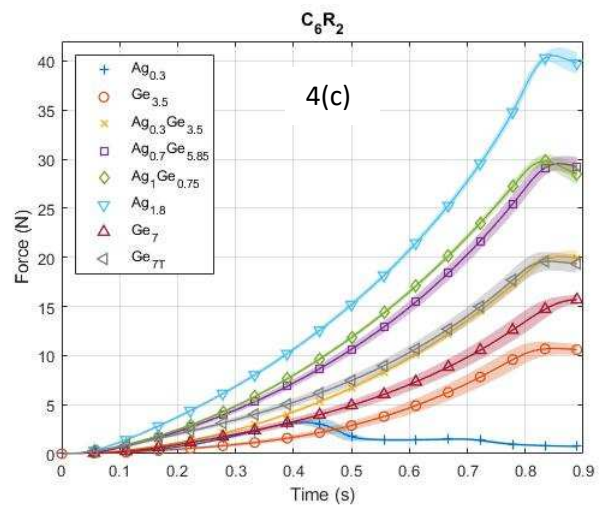
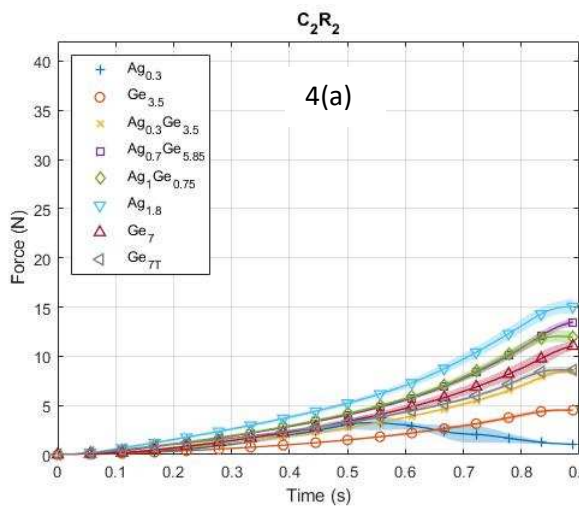
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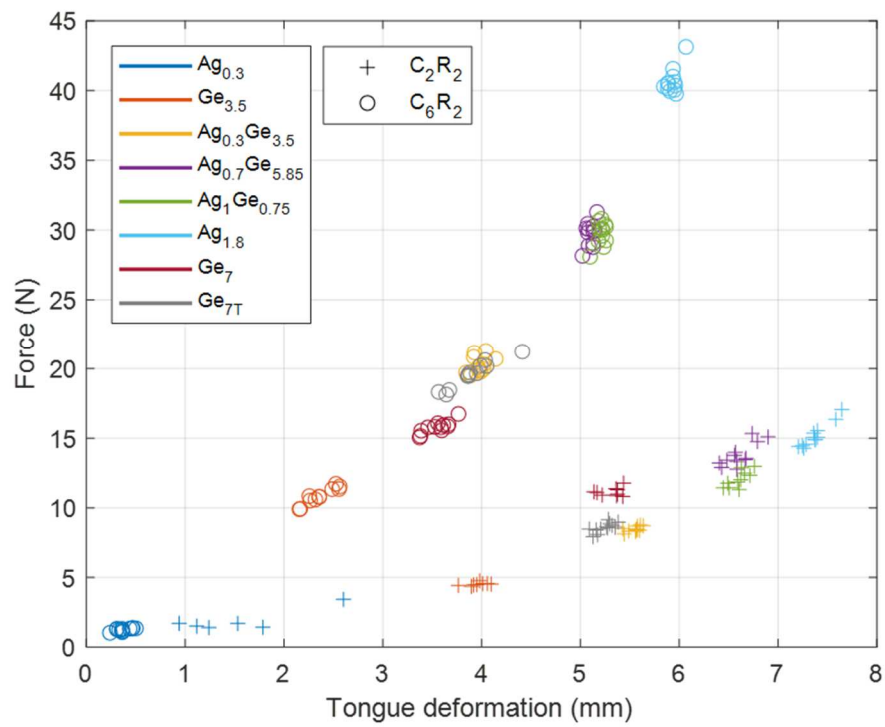
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660 Figure 5

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Figure 6

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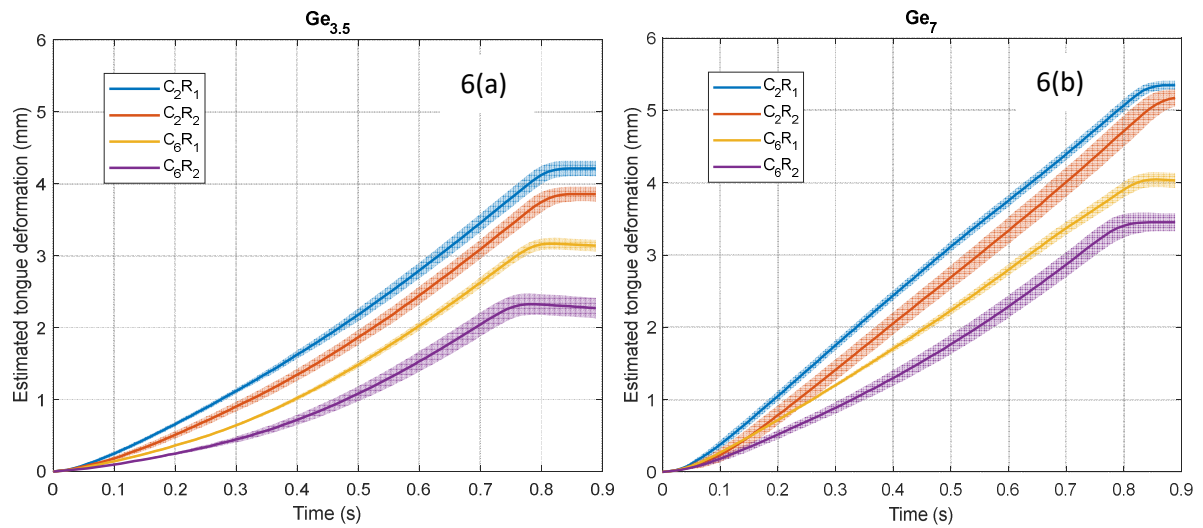
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Figure 7

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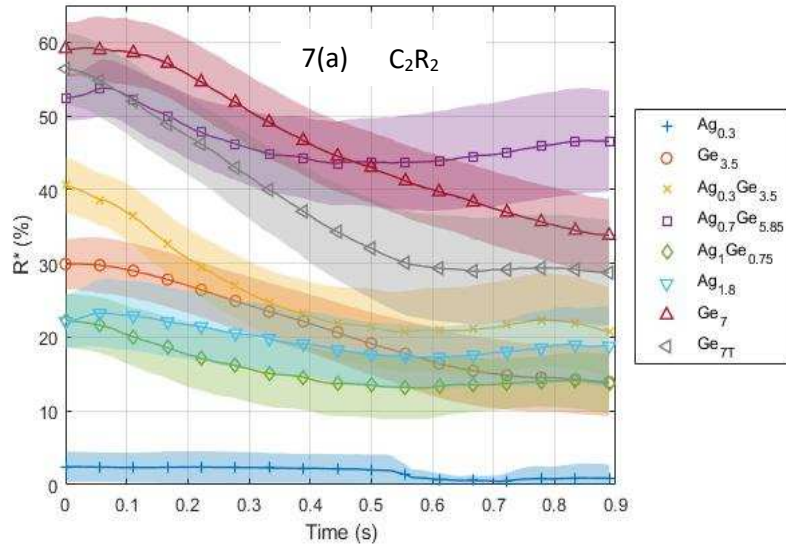
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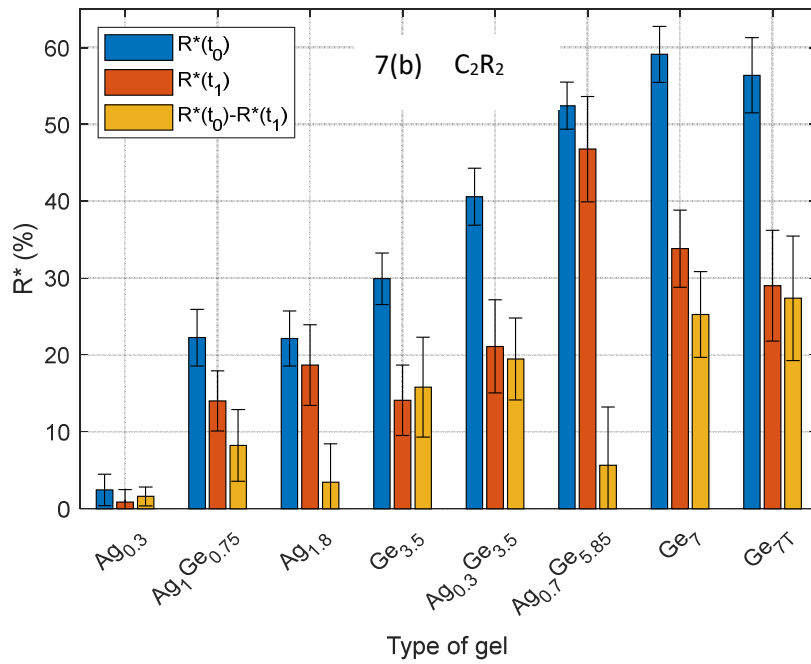
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Figure 8

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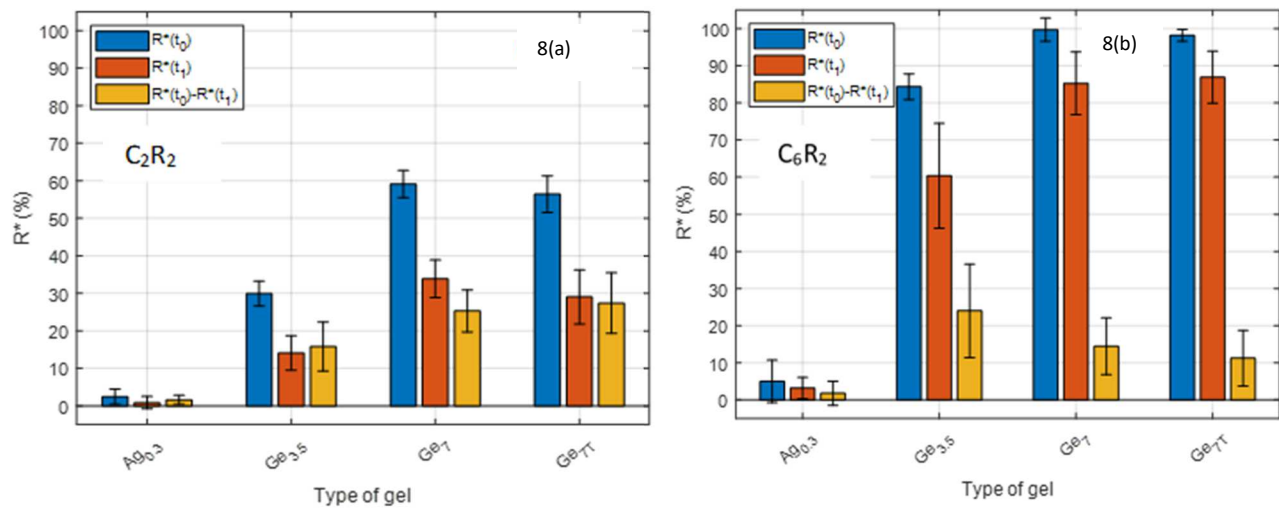
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Figure 9

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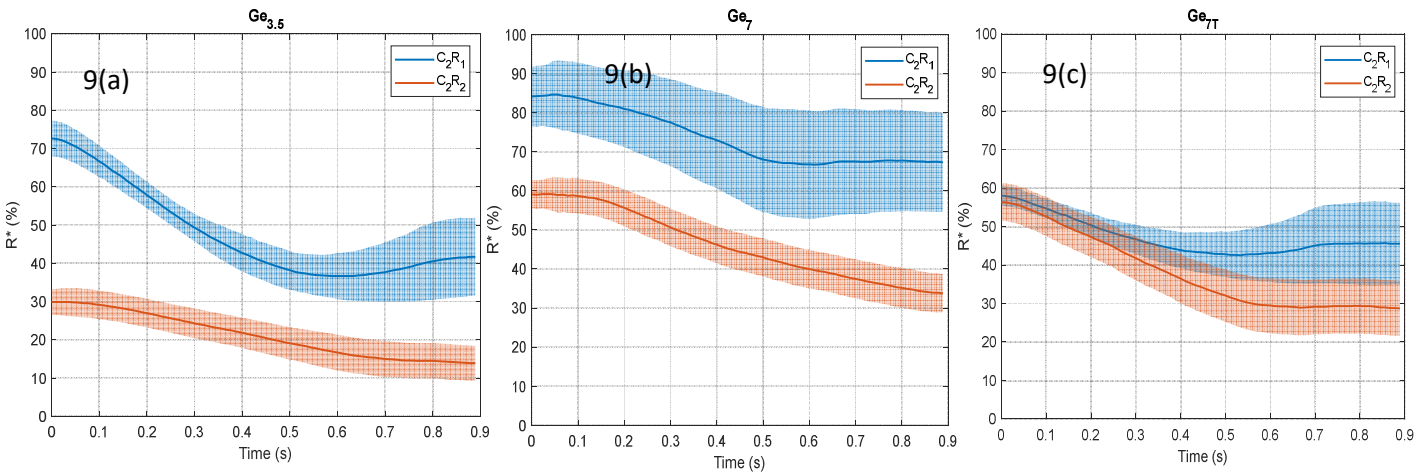
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Table 1

| Gel type | Composition (% wt) | | | | Young's modulus (kPa) | Water released (g) |
|--|--------------------|------|---------|-------|--------------------------|-----------------------|
| | Water | Agar | Gelatin | TWEEN | | |
| | | | | 20 | | |
| <i>Ag_{0.3}</i> | 84.7 | 0.3 | - | - | 4 ± 3 | 0.150 ± 0.020* |
| | | | | | | (without compression) |
| <i>Ag₁Ge_{0.75}</i> | 83.25 | 1 | 0.75 | - | 58 ± 15 | 0.257 ± 0.020 |
| <i>Ag_{1.8}</i> | 83.2 | 1.8 | - | - | 132 ± 10 | 0.151 ± 0.012 |
| <i>Ge_{3.5}</i> | 81.5 | - | 3.5 | - | 2 ± 0.1 | 0.028 ± 0.002 |
| <i>Ag_{0.3}Ge_{3.5}</i> | 81.2 | 0.3 | 3.5 | - | 13 ± 3 | 0.029 ± 0.004 |
| <i>Ag_{0.7}Ge_{5.85}</i> | 78.45 | 0.7 | 5.85 | - | 32 ± 7 | 0.015 ± 0.003 |
| <i>Ge₇</i> | 78 | - | 7 | - | 24 ± 2 | 0.015 ± 0.002 |
| <i>Ge₇T</i> | 76.5 | - | 7 | 1.5 | 17 ± 2 | 0.012 ± 0.001 |

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Table 2

| ATM type | No. of freezing/ thawing cycles | Young's modulus (kPa) | Surface profile (μm) | | Water released (g) |
|-------------|---------------------------------------|-----------------------------|-----------------------------------|--------------------|-----------------------|
| | | | Peak height | Correlation | |
| | | | (R_a) | length (β) | |
| C_2R_1 | 2 | 23 ± 1 | 42 ± 1 | 289 ± 36 | 0.022 ± 0.002 |
| C_2R_2 | 2 | 18 ± 1 | 72 ± 14 | 435 ± 62 | 0.031 ± 0.003 |
| C_6R_1 | 6 | 71.2 ± 1 | 55 ± 3 | 341 ± 62 | 0.015 ± 0.002 |
| C_6R_2 | 6 | 71 ± 2 | 103 ± 3 | 429 ± 63 | 0.018 ± 0.003 |

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