Elina Nurkkala, Markus Hannula, Craig S. Carlson*, Anu Hopia, Jari Hyttinen, and Michiel Postema

Micro-computed tomography shows silent bubbles in squeaky mozzarella

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Abstract: The sound of food is of influence on how its flavour is perceived. Although rarely studied in psychoacoustics, cheese may have a resonating internal structure in the audible spectrum. It has been speculated that this structure or small bubbles that are formed as a result of fermentation are responsible for creating audible acoustic responses. The purpose of this study was to design a mechanical methodology to create audible acoustics from cheese samples and to quantify bubble presence in a sample. One hundred and two samples of mozzarella cheese with 1.5±0.4-cm^3 volumes were subjected to shear from a wetted steel blade, whilst orthogonal force, blade acceleration, and acoustic response were continuously monitored. In addition, micro-computed tomography was performed. It was found that under our measurement conditions, mozzarella was forced to squeak in 10% of the experiments, at fundamental squeak frequencies up to 2 kHz, which indicates that the acoustics come from a resonating porous structure, rather than from resonating bubbles. The micro-computed tomography showed a bubble density of 51 cm^{-3}. This low bubble density may account for the absence of a high-frequency component in the spectra analysed. Our results confirm the presence of small bubbles in squeaky mozzarella, but these generate frequencies much higher than those recorded.

Keywords: Squeaky cheese, acoustic food, bubbles in cheese, poroacoustics, soft porous structure, μCT.

1 Introduction

The sound of food is of influence on how its flavour is perceived [1]. Not only does sound influence human perception, it has also been observed to influence the process of food ripening itself [2–4]. The creation of sound may be attributed to internal components that amplify audible frequencies. The most commonly studied structures are gas bubbles. A bubble may pulsate and thus create audible sound, if its host medium is subjected to internal or external pressure. The former type of sound is referred to as passive acoustics, the latter as active acoustics [5].

Relating acoustic responses to internal structures is rather challenging overall in dynamic fluid systems, as opposed to quasistatic solid and gelating systems. Cheese is thus an interesting study object, as it is composed of solid, gel, liquid, and gas components, whose dynamics are on a scale of hours rather than seconds. The interest in cheese as a scientific study object representing biomaterials is highlighted by the numerous publications on tomographic imaging modalities for comparing the internal structure of various kinds of cheese [6–8]. Although typically published in dairy science journals, dairy fermenting processes and imaging thereof have attracted attention from biomedical engineering communities, too [9–11]. Acoustic cheese research has concentrated on crack monitoring [12], eye-formation monitoring [13], and sterilisation [14].

Only sporadic research has been dedicated to the acoustics of squeaky cheeses, which include Cypriot halloumi, Italian mozzarella, Finnish *leipäjuusto*, Mexican Oaxaca, and American cheese curd [15–18]. Of these, mozzarella is known to exude water after manufacture [19]. The existence of microscopic cavities inside mozzarella had been observed with scanning electron microscopy [20, 21], but using this process, it was not determined whether the cavities contained gas or liquid.

The acoustic response of porous materials might originate from individual cavities or from an entire connecting resonating structure [22, 23]. Alternatively, individual cavities might become interconnected through shear [24].

In this study, we recreated audible mozzarella acoustics and quantified the presence of gas bubbles using micro-computed tomography, also referred to as μCT, and related bubble presence to mozzarella acoustics.

***Corresponding author: Craig S. Carlson,** BioMediTech, Faculty of Medicine and Health Technology, Tampere University, Korkeakoulunkatu 3, 33720 Tampere, Finland and School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, 1 Jan Smutslaan, Braamfontein 2050, South Africa, e-mail: craig.carlson@tuni.fi
Elina Nurkkala, Markus Hannula, Jari Hyttinen, BioMediTech, Faculty of Medicine and Health Technology, Tampere University, Tampere, Finland
Anu Hopia, Functional Foods Forum, Faculty of Medicine, University of Turku, Turku, Finland
Michiel Postema, BioMediTech, Faculty of Medicine and Health Technology, Tampere University, Tampere, Finland and School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, Braamfontein, South Africa

2 Materials and methods

Throughout the experiments, a Cartesian coordinate system was adopted, where the positive x-axis was defined as the direction of shear in the horizontal xy-plane from the point of view of the operator.

2.1 Preparation

For the acoustic procedure, mozzarella cheese (Granarolo S.p.A., Bologna, Italy), prepackaged in 125-g pieces, was kept under 7°C cooling until commencing an experiment. For each acoustic experiment, a slice was manually cut off to the dimensions $x \times y \times z = 13 \pm 2 \times 20 \pm 1 \times 5 \pm 1\,\mathrm{mm}^3$, whilst the remainder of the piece was kept under cooling. These dimensions corresponded to a sample volume of $1.5 \pm 0.4\,\mathrm{cm}^3$ [25].

For the μCT procedure, a cylindrical sample of mozzarella cheese (Granarolo) with a 5.5-mm diameter and a 5.0-mm height was cut out of a 125-g piece using a 1-ml plastic cylinder. This cylinder containing the sample was sealed before scanning.

The acoustic experiments were performed at 20°C ambient temperature. The temperature inside the μCT chamber was constant at 28°C.

2.2 Acoustic procedure

A Leikkuulauta bambu board (Tokmanni Oy, Mäntsälä, Finland) of dimensions $x \times y \times z = 33 \times 18 \times 1.2\,\mathrm{cm}^3$ was positioned on top of SOEHNLE Page Compact 300 scales (Leifheit AG, Nassau, Germany). A distance of 13 mm had been marked on the board, for consistent placement of cheese samples.

Directly after a cheese sample had been placed between two markers, a wetted 6.8003.22 steel blade (Victorinox AG, Ibach-Schwyz, Switzerland) was applied manually by an operator to the top of the sample and moved subsequently in positive and negative x direction twice, whilst gently being pushed with a 4 ± 1-N force in z-direction.

Throughout the procedure, audio footage was recorded using an iPhone SE (first generation) cellular (Apple Inc., Cupertino, CA, USA) at a 40.1-kHz sample rate. Audio was stored in `.m4a` format for offline processing.

Throughout the procedure, video footage was captured using an A52s 5G cellular (Samsung Electronics Co., Ltd., Suwon, Korea) at 30 frames per second in landscape orientation. Each frame comprised $y \times z = 1920 \times 1080$ pixels. Videos were stored in `.mp4` format for offline processing. The camera was held in position along the y-axis by a bipod. The timer of the audio recorder was in the field of view, for synchronisation purposes. A line drawing of the acoustic part of the setup is shown in Figure 1.

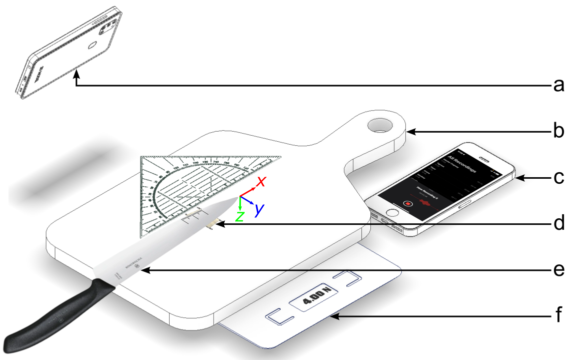

Fig. 1: Line drawing of the acoustic part of the experimental setup, consisting of a video-recording device (a), a board (b), an audio-recording device (c), a cheese sample (d), a wetted blade (e), and scales (f). Note that the positive x-axis was defined as the direction of shear in the horizontal xy-plane from the point of view of the operator.

2.3 Micro-computed tomography

The cylinder with the cheese sample was positioned on a rotating plate inside the imaging chamber inside a MicroXCT-400 device (Carl Zeiss AG, Oberkochen, Germany) such that the central axis of the cylinder coincided with the rotational axis of the plate. Tomographic imaging was performed using a procedure similar to those previously published [26, 27].

The X-ray source operated at a 10-W power and a 60-kV peak voltage. The exposure time was 1 s per image. A detection scintillator with a 4× objective was used. In total, 1601 projections were acquired, evenly distributed over 360°. This scanning process had a 2.5-h duration. The resulting voxel size corresponded to $5.64 \times 5.64 \times 5.64\,\mu\mathrm{m}^3$.

Three-dimensional images were reconstructed from the raw data using XMRe-constructor 8.1.6599 software (Zeiss). Digital cutting was done using Avizo 2020.2 software (Thermo Fisher Scientific, Waltham, MA, USA). The resulting three-dimensional reconstruction was sliced per voxel height, perpendicular to the z-axis. These slices were stored in `.tif` format for offline processing.

2.4 Processing

Audio and video files were transferred to a laptop computer for processing in MATLAB® (The Mathworks, Inc., Natick, MA, USA). The audio data were divided and cropped into four

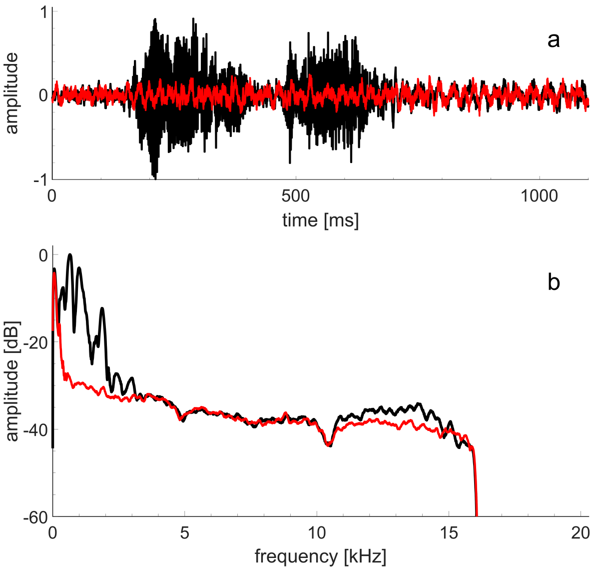

Fig. 2: Normalised audio signal as a function of time of a single mozzarella squeak (a) and the Fourier amplitude spectrum thereof (b). Controls are represented by red lines.

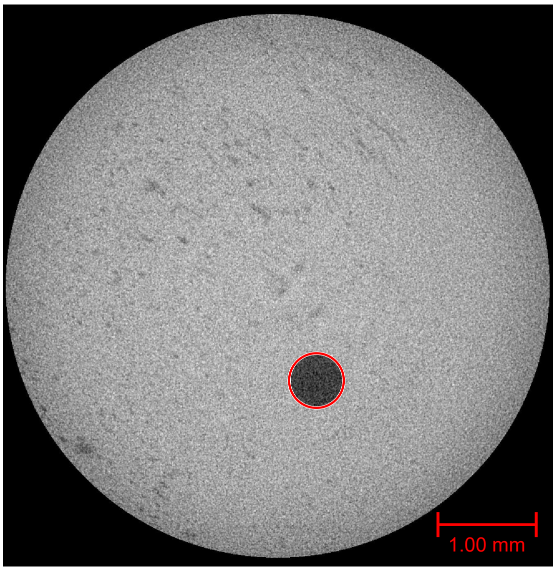

Fig. 3: Micro-computed tomography slice of thickness 5.64 μm, showing a gas bubble of 0.56-mm diameter indicated by a red circle.

1100-ms segments, each starting at blade movement. Each segment was converted to the frequency domain using the `fft` function, filtered using a 501-points fifth degree Savitzky-Golay filter using the `sgolayfilt` function, after which the frequencies corresponding to the most prominent peaks were determined.

Micro-computed tomographic slices were processed using the `onan` function to measure bubble dimensions. From these, the bubble concentration was computed. In addition, the bubble resonance frequencies were computed using the empirical relation for gas bubbles in watery media [22]:

$$f_\mathrm{r} \approx \frac{6.5\,[\mathrm{m\,s^{-1}}]}{d}, \tag{1}$$

where d is the bubble diameter and f_r is the Minnaert resonance frequency.

The total number of audio segments analysed was 804. The total number of μCT slices measured was 993.

3 Results and discussion

Figure 2 demonstrates a representative squeak recording and its Fourier spectrum. Ignoring responses below -20 dB with respect to the AC component, the peak responses corresponded to frequencies up to 1.9 kHz. These peaks were absent in the control signal.

Under our measurement conditions, mozzarella was forced to squeak in 10% of the experiments, at fundamental squeak frequencies up to 2 kHz. According to (1), this frequency corresponds to a resonant cavity diameter greater than 3 mm. The presence of bubbles of such diameters is unrealistic in mozzarella. Consequently, our audio measurements indicate, through negative deduction, that the acoustics must come from a resonating porous structure, rather than from resonating bubbles.

From the μCT slices, the mean bubble diameter was measured to be 0.30 ± 0.13 mm, with bubbles ranging from 0.21 mm to 0.56 mm. The diameters measured from μCT correspond to Minnaert frequencies greater than 13 kHz, which is more than six times the fundamental squeak frequencies recorded. Therefore, in analogy to the audio measurements, bubbles may be ruled out as the primary source for the acoustic response in squeaky mozzarella cheese.

Figure 3 shows an example of a gas bubble entrapment inside a mozzarella cheese sample. Other, much smaller gaseous entities can be observed in the same slide, but these did not appear to be spherical. Those entities might be explained by the presence of microscopic channels described in literature [20, 21]. Given the low squeak frequencies recorded, we presume that these channels are connected to each other, creating a resonating porous structure [23]. Since the procedure of μCT scanning takes several hours and involves rotation of the sample, minute transportation of fluid components might have obfuscated the observation of components of less than 0.2-mm diameter, which may have included connecting pores. The μCT slices showed a bubble density of 51 $\mathrm{cm^{-3}}$. This low bubble density may account for the absence of a high-frequency component in the spectra analysed.

4 Conclusions

Cheese is an attractive multi-phase material, that is not yet ripe for mimicking tissue. Our results confirm the presence of small bubbles in squeaky mozzarella. However, these are not responsible for the audible acoustic responses recorded.

Author Statement

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