Swelling of couscous grains under saturated conditions[⋆,⋆⋆]

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Abstract

The article presents a grain-scale experimental approach for the study of a model that swells granular food material. During the swelling phase, both the evolution of particle size using image analysis and the spatially resolved field of diffusion coefficient of water inside the grains were studied using MRI measurements. A concentrically penetration of water in the cross section of the grains was shown on images.The experimental results were compared to classical models from the literature used to predict the swelling of polymeric materials. A simple first-order kinetic equation was shown to be adequate to describe the size evolution during swelling. Thus, the results suggested that the swelling dynamics was a water uptake-limiting mechanism because of the existence of a gelatinous layer at the grain surface formed during the manufacturing process, as previously reported in the literature.

1. Introduction

The swelling of a granular particle is a spontaneous increase in its volume to restore the equilibrium between the solid phase and the surrounding fluid[1, 8, 12]. The initial out-of-equilibrium condition originates from a change in the particle environment or a change in the chemical conditions of the interstitial fluid (composition, salinity, etc.). This phenomenon is associated with a complex hydro-mechanical coupling where the evolution of the solid matrix modifies the distribution of the liquid in the pores, which in turn modifies the swelling rate[10, 30, 39]. Therefore, the absorption of a single particle depends on a number of parameters such as molecular structure, inner surface, porosity, hydrophobicity or crosslinking of the solid matrix.

Swelling in saturated conditions occurs in many industrial processes and environmental phenomena. For example, the swelling of clays that modifies the stability of soils[4, 27, 32], or the swelling of hydrogel in hygienic products[9]. In addition, this phenomenon is a key step in food engineering[41, 43, 44] because it influences many mechanisms, such as powder reconstitution, agglomeration or frying[41]. In practical conditions, the reconstitution of food powders involves a number of steps that often overlap: wetting, sinking, swelling, dispersion, and solubilization[13, 15, 26, 34], making it difficult to characterize each step individually. It is then impossible to give a general rule for the influence of both the hydro-mechanical coupling and physicochemical properties of powders on the reconstitution process. A

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better understanding of the basic physical mechanisms involved in the swelling of food granular media is therefore necessary.

Among granular media in food, couscous grains have the advantage of being well controlled in size, shape and composition[2]. In particular, this grain allows the study of swelling as it limits the dispersion of its solid matrix during its reconstitution. This makes it a model system for studying the swelling of granular food materials. Moreover, couscous powders are of major industrial interest since they are one of the most common food products made from durum wheat[17]. Couscous grains are obtained after wet agglomeration, rolling-sieving, steam cooking, and drying [3]. The wet agglomerates are formed by mixing durum wheat semolina and water together to induce the wet agglomeration of the native semolina particles. These wet agglomerates are rolled in a rotating screen drum to homogenize the structure and size of the grains (between 1 and 2 mm). To strengthen the structure, the rolled agglomerates are then cooked. Finally, they are dried to reduce their water content and to maintain their stability during storage.

Couscous particles are thus mainly composed of starch granules bound by a gluten matrix[16], sometimes including aleurone cells with an alveolar structure[18]. These particles are millimetric in size, are almost spherical and begin to absorb water by capillary diffusion when poured into a liquid. Water diffusion into particles induces particle swelling due to the relaxation of polymer chains[31, 36], which softens the particle, increases its size and decreases its mechanical resistance to shear stresses[14, 28, 35]. Wetting is generally improved for large particles and agglomerates, as well as for more spherical particles[19, 24], as they offer lower particle-solvent contact angles than small particles. Highly porous particles are also known to display a better wetting behavior, as water mass transfer into the particle is enhanced by water uptake in the pores[16, 22].

A range of studies have been performed to model the swelling of granular particles[8, 33, 45]. Most of them are semi-empirical[11, 29] and show evidence that swelling properties depend on particle size and composition. Recently, Sweijden et al.[39] proposed a physical model to predict the swelling of Super Absorbent Polymer (SAP) particles. This model is based on a free diffusion of water in particles and has been generalized to take into account irregular particle shape and water uptake on the surface[25]. This model successfully predicts the swelling of pharmaceutical particles[37] or SPA particles[39] under saturated conditions, but has never been applied to food powders. Particle swelling mainly depends on the water diffusion coefficient D and the maximum absorption ratio Q_{max}, defined as the ratio between the mass of the hydrated and the dry particles. An open question is how these two parameters depend on the size, morphology and chemical composition of the particles. Although Q_{max} can be measured experimentally using simple weighing methods, in many situations the direct determination of the value of D is much more difficult; nonetheless, it is crucial since it is considered as constant in many models.

To summarize, there is currently no physical model to predict the swelling of granular food materials from the mechanical and physicochemical properties of the grains and their environment. The swelling mechanism is complex

Table 1
Chemical composition of couscous grains used in this study.

Ingredient	Composition (% of dry matter)
Carbohydrates	72 %
Proteins	12 %
Fat	1.8 %
Fibers	2.4 %
Minerals	0.04 %

because of the coupling between the evolution of the liquid flow properties on the one hand and the evolution of the chemical nature and mechanical properties of the solid matrix on the other. Yet, predicting the swelling of couscous grain and of any granular grain for food processing is important, for at least two reasons. First, to achieve the precise nutritional, physical, chemical and sensorial properties of couscous products, it is particularly important to deepen knowledge of the structure-function relationship between the grains and water. Secondly, via the swelling process, these particles can take up water and thus open up a variety of new formulation applications for valuable products.

In this article, time-resolved optical measurements of the swelling dynamics of couscous particles under saturated conditions were combined with spatially resolved Magnetic Resonance Imaging (MRI) measurements at the grain scale to evaluate the diffusing properties of water. To the best of the authors' knowledge, little use has been made of MRI in food products to date, and even less on food powders such as couscous grains[23]. However, MRI offers numerous opportunities for monitoring water uptake and water distribution in these products. The results were then directly compared with the theoretical predictions from the literature related to the swelling of SAP particles. The relevance of such an approach to predict the swelling of granular media in food was then discussed.

2. Materials and methods

2.1. Materials

In this study, couscous powder made of industrial durum wheat semolina (Comptoir du Grain, Arles, France) was used (see Tab. 1). The bulk density value, measured in triplicate with a pycnometer, was $\rho_s = 1380 \pm 5$ kg.m^{-3} at 20 °C. The surface structure of the grains was obtained using Scanning Electron Microscopy, SEM type JEOL JSM-7100F133 supplied with a hot (Schottky) electrongun (JEOL Ltd., Tokyo, Japan) from ×600 to ×9000 magnification in a partial vacuum using 3 kV accelerating voltage. Prior to analysis, the samples were coated with carbon in a sputter coater (Polaron SC7640, Thermo VG Scientific, East Grinstead, United Kingdom). Particle size distribution was determined[1] using a laser diffraction granulometer (Mastersizer 3000, Malvern Instruments, UK) in the range $0.1 - 3500$ μm.

Fig. 1 shows the SEM images and the particle size distribution. The median size of the couscous particle was

[1]Classical granulometric parameters were determined: d_{10}, d_{50}, and d_{90}, corresponding to the diameters for which 10 %, 50 %, and 90 % of the particle population have smaller sizes, and the span, a polydispersity indicator defined as the width of the distribution normalized by its median: $span = \frac{d_{90}-d_{10}}{d_{50}}$

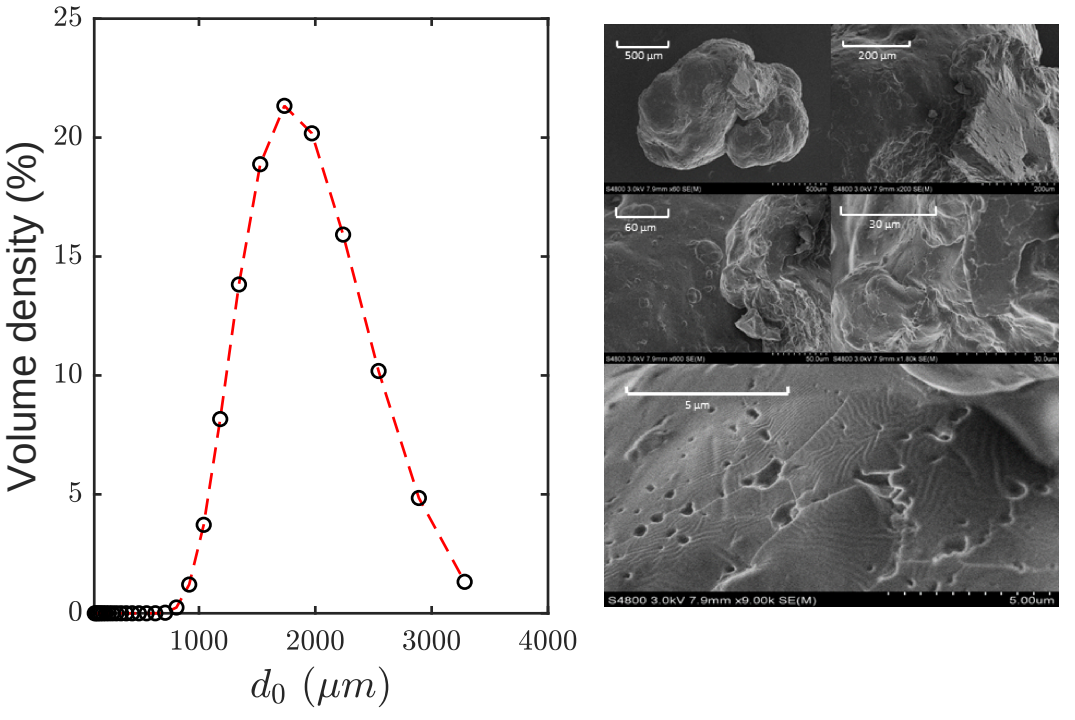

Figure 1: Left: Particle size distribution of couscous grains. The volume density defined in terms of equivalent sphere diameter (%) is shown as a function of particle diameter d_0. Right: SEM images from ×600 to ×9000 magnification in a partial vacuum using 3 kV accelerating voltage.

d_{50} = 1700 μm, and the size distribution was slightly polydisperse ($span$ = 0.7). The maximum absorption ratio of single particles (Q_{max}), defined as the ratio between the mass of the swollen particle and the mass of the dry particle, was estimated after two hours by vacuum filtration. In deionized water at 20 °C ($\rho_w = 10^3$ kg.m^{-3}), the value of Q_{max} was found to be equal to $Q_{max} = 3.54 \pm 0.41$. The sphericity and aspect ratio results suggested that the particles of couscous powders had quasi spherical shapes. Since the grains only differ by their median size, as shape parameters, chemical compositions, water activities, maximum absorption ratio, densities, and surface appearance (porosity, roughness), all the grains were used in the distribution, with no preliminary sieving, in the subsequent phases.

2.2. Methods

2.2.1. Optical measurements and image analysis

A CCD camera (Lumenera Lw235M 2.0 Megapixel, 1616 × 1216 pix^2), placed at the bottom of a transparent PMMA vessel, recorded the swelling dynamics of single particles through a 45° tilted mirror. The acquisition frequency

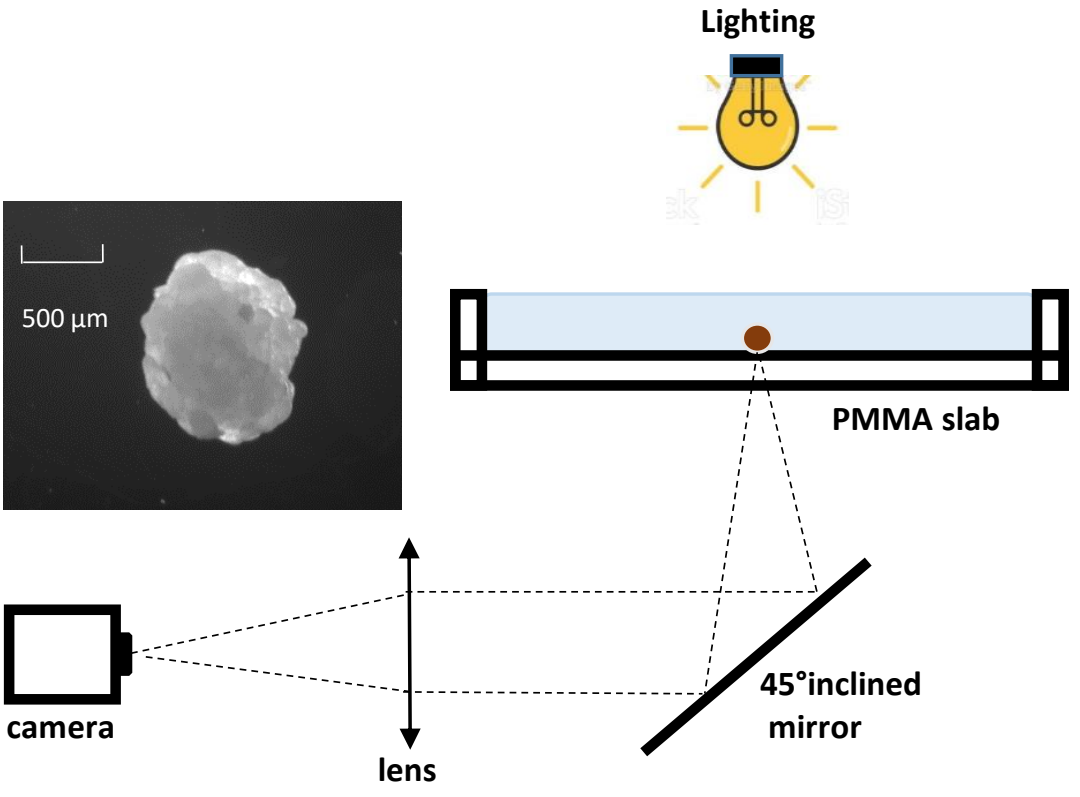

Figure 2: Sketch of the experimental setup used to follow the swelling of a single couscous grain.

of the camera was 30 Hz and the grain was illuminated from above with a LED projector. A sketch of the experimental setup and a typical image are given in Fig. 2. From the recorded images, data processing using the ImageJ software [20] was applied to analyze and quantify the swelling of single particles. The images were first binarized by thresholding to obtain grains that appeared as white spots on a dark background. The edge and centroid of the particles were then detected. A calculation of the distance between the centroid and the edge of the particles returned object properties (area, perimeter, minor axis, major axis of fitted ellipsoid). In the following, particle diameter $d(t)$ denotes twice the mean distance between the centroid and the edge of the particle at time t during swelling.

2.2.2. Magnetic Resonance Imaging measurements

To map the diffusion coefficient D of water molecules in the grains during swelling, a magnetic resonance imaging (MRI) technique was used [38, 42]. This spectroscopy technique is non-intrusive, and is used to see through opaque materials and monitor dynamic phenomena by direct marking (no tracer injection). The swelling was tracked by direct detection of the water protons at the grain scale. The MRI experiments were carried out with a Bruker Avance III 600 wide bore spectrometer (14.1 T, 600 MHz proton resonance frequency, Bruker, Germany). The sample temperature

was regulated to 20 ± 0.1 °C. The micro-imaging probe (MicWB40) was a 25 mm quadrature resonator manufactured by Bruker, with a 150 G.cm^{-1} gradient system. Although MRI is a unique technique in providing information on the changes in distribution of water within and outside the couscous grains, assigning the relaxation times remains a major difficulty regarding the signal to noise ratio if the swelling dynamics at short time scales has to be captured. In fact, the measured single relaxation time, T1, in couscous grains after swelling was of the order of 2 s. This value makes it very difficult to obtain proton weighted images at short times during swelling. Thus, in this study, proton density images were only used to qualitatively illustrate the evolution of the particle size over time as well as the position of the liquid interface during water penetration at the beginning of the swelling. To extract quantitative data, a diffusion-weighted sequence based on a signal difference was used, which allowed the extraction of the diffusion coefficient value minimizing the relaxation effects. The acquisition of proton density images was performed using a standard spin-echo sequence with an echo time of 14 ms and a repetition time[2] of 500 ms. The geometric parameters were as follows: the field of view (FOV) was 2.5 cm×2.5 cm, the thickness slide was 500 μm, and the image size was 256×256 pix^2. The acquisition of each point lasted about 2 min and the images obtained had a spatial resolution of about 98 μm. The apparent diffusion coefficient (mean of D at the voxel scale) can be measured by MRI using a diffusion-weighted sequence (PFGSE for pulsed field gradient spin echo). The PFGSE sequence consisted of the application of two gradients of short and intense magnetic fields. The first one gave the proton precession a phase advance according to their position, and the second compensated for this advance. Thus, only immobile protons underwent a zero phase shift. With this sequence, the spin-echo attenuation S was related to the intensity of the magnetic field gradient G, via Eq.1:

$$S = A \exp\left[-\gamma^2 \delta^2 \left(\Delta - \frac{\delta}{3}\right) D G^2\right] \tag{1}$$

where γ is the nuclear gyro-magnetic ratio, $\delta = 6$ ms is the duration of the diffusion gradient, A the amplitude of the signal and $\Delta = 11$ ms is the evolution time (delay between the two gradients). S was fitted to Eq.1 for each swelling time point to extract a mapping of the self-diffusion coefficient D for ten gradient values (see fig.6 (b)). The geometric parameters were then as follows: the field of view (FOV) was 2.5 cm×2.5 cm, the thickness slide was 500 μm, and the image size was 128×128 pix^2. The acquisition of each point lasted about 2 min and the images obtained had a spatial resolution of about 200 μm. To validate our protocol, it has been checked for each experiment that the diffusion coefficient of pure water was found outside the grains showing that the T1 and T2 relaxation times were not limiting.

[2]The value of the repetition time was a compromise between the duration of the experiments and the signal to noise ratio to ensure both good image quality and good time resolution.

3. Results and discussions

3.1. Evolution of particle diameter

In the following, all swelling experiments were performed in deionized water at 20 °C. Working at room temperature allowed swelling to take place over long periods of time and was particularly well suited to the low time resolution of the MRI methods.

The swelling typically lasts 3 hours in the experimental conditions presented in this study (Fig. 3), and the ratio between the final and the initial diameters is constant ($d_{max}/d_0 = 1.6 \pm 0.1$), as shown in Fig. 4, left. It can be seen in the inset of Fig. 3 that the shape remains globally identical, as confirmed by the measurements of the sphericity coefficient e, defined as $e = 4\pi S_g/p^2$ where S_g and p are the area of the grain and its perimeter at time t, respectively (see Fig. 4, right). A value of e close to 1 confirms the hypothesis of the grains being almost spherical in the rest of the analysis.

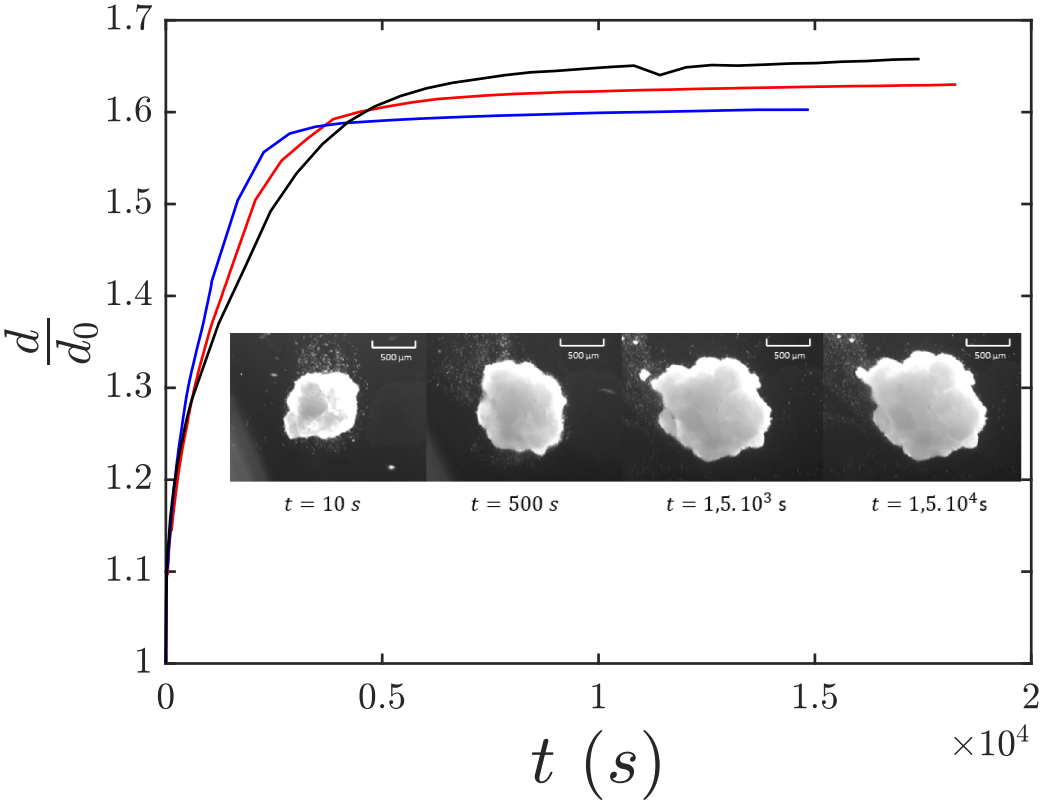

Figure 3: Typical time evolution of the normalized diameter d/d_0. The curves correspond to different initial diameter d_0. $d_0 = 1.37$ mm, 1.63 mm and 1.90 mm for the blue, red and black curves, respectively. Inset: typical images of a couscous particle at different times during swelling, recorded with a CCD camera.

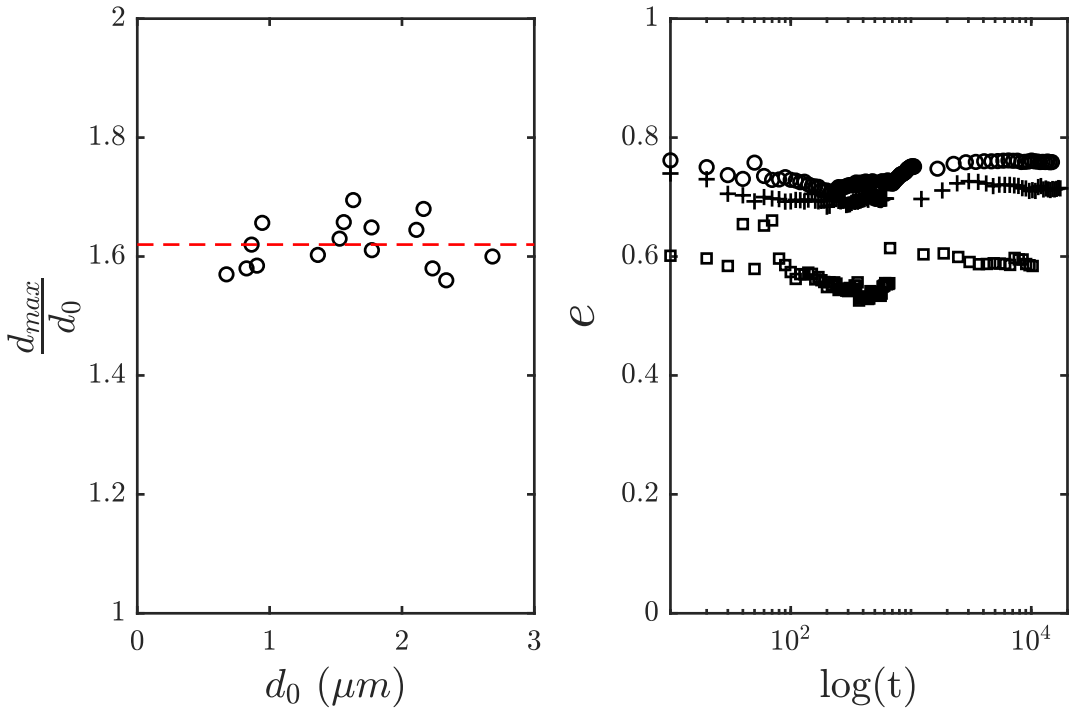

Figure 4: Left: Evolution of the normalized maximal diameter d_{max}/d_0 as a function of the initial diameter d_0. Right: Typical time evolution of the circularity parameter e during swelling for four independent experiments.

3.2. Water diffusion in grains

The distribution of water inside the grains was followed using Magnetic Resonance Imaging (MRI) of proton density and linked to the evolution of their diameter. Fig. 5 shows the long-time swelling dynamics of five couscous grains over a total period of 30 hours. As expected, the water diffuses from the edges towards the center of the grains during the swelling period, which is about 3 hours. Swelling occurs when water is not able to penetrate to the center of the aggregates and disrupts the structure by hydration of the sub-particles. After this time, the grain size no longer changes but the amount of water continues to slowly increase inside the grains until, after 30 hours, the signal is almost identical to the pure water signal.

This behavior over a long time is due to the presence of air pockets trapped in the porous matrix of the grain, which slowly dissolves in the surrounding water. As estimated by image analysis, the characteristic size of these air bubbles is ~ 100 μm, and the volume fraction is ~ 6 % of the total volume of the grain once it has reached its maximum radius. The typical dissolution time of all these bubbles is of the order of $\sim$ 15 hours, which is much greater than the time calculated from the Epstein Plesset equations (of the order of 100 s). One explanation is the fact that the trapped air

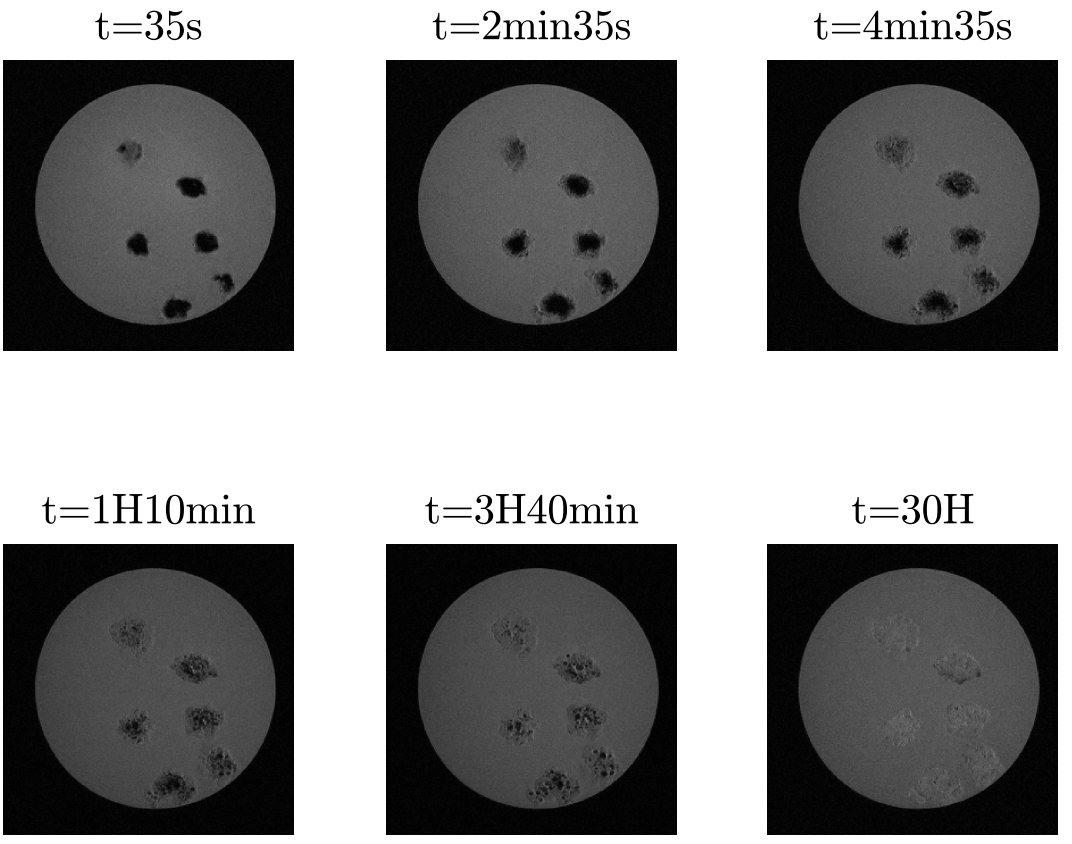

Figure 5: MRI intensity images showing the long-time swelling dynamics of six couscous grains. The image resolution is 98 μm.pix^{-1}.

has to diffuse through the gel matrix of the swollen grain, which changes the spatial scale of diffusion and increases the final dissolution time. This phenomenon of air dissolution does not influence the dynamics of swelling as such and will not be analyzed here in detail, but deserves to be mentioned.

From the MRI spin-echo procedure, the evolution of the attenuation signal S with the magnetic field gradient G was obtained and fitted to Eq. 1 for each pixel (see Fig. 6(a) and (b)). In Fig. 6(c), as the solid or partially wet parts of the sample returned weak signals, those pixels for which the fit model was poor ($R^2 < 0.9$) were eliminated. Then, the signal background coming from the surrounding water was also eliminated (Fig. 6(d)) making crowns appear at each time inside the particles. The mean diffusion coefficient $\bar{D}$ was obtained by averaging the local diffusion coefficient D in the crown over all the pixels.

$\bar{D}$ decreases over time during the swelling process and stabilizes when the diameter reaches its final value ($\bar{D} =$

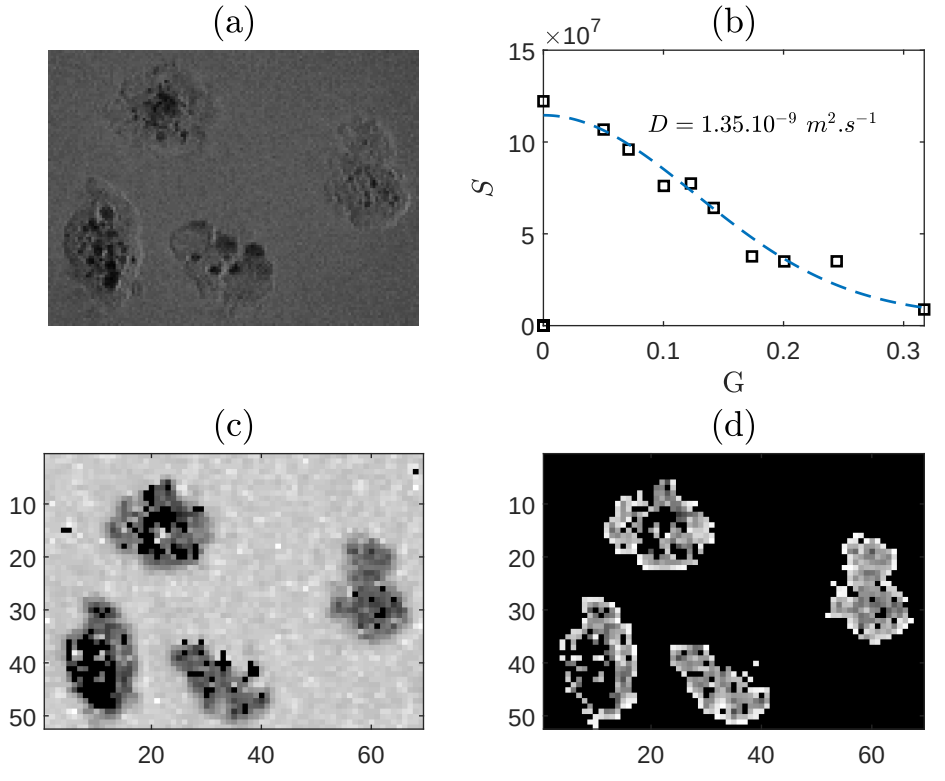

Figure 6: (a) MRI intensity image of four swollen particles at time $t = 10^3$ s. (b) Example of spin-echo attenuation at a given pixel. Data are adjusted to Eq. 1. (c) Diffusion map extracted from spin-echo attenuation of all pixels in the image. Black points correspond to pixels for which the fit model is $R^2 < 0.9$. (d) Final diffusion map by suppressing the background signal coming from the surrounding water.

1.4 10^{-9} $m^2.s^{-1}$), as shown in Fig. 7. The mapping of the diffusion fields shows that this time evolution is due to the existence of a diffusion coefficient gradient near the surface of the particles over a thickness of the order of 200 μm. At any given time, the diffusion coefficient is higher in the outer ring near the surface than in the bulk of the particle.

3.3. Swelling models

In this part, the swelling dynamics extracted from experimental measurements is compared to models extracted from the literature. The swelling of individual particles is driven by the difference in chemical potential between the core of the particle and the liquid medium (deionized water in this study) [21]. It is assumed that two processes can occur during the swelling [39]: water uptake at the surface and diffusion of the liquid in the particle. These two processes may take place at the same time, or one of the two may be dominant depending on the associated characteristic times. Several works in the literature propose empirical or semi-empirical models to account for these phenomena and predict the evolution of particle diameter with time. In the following, to compare our experimental data with results from the literature, a re-scaled time is introduced (see Sweijen et al.[39]): $t^* = 4\alpha\bar{D}t/d_0^2$, where

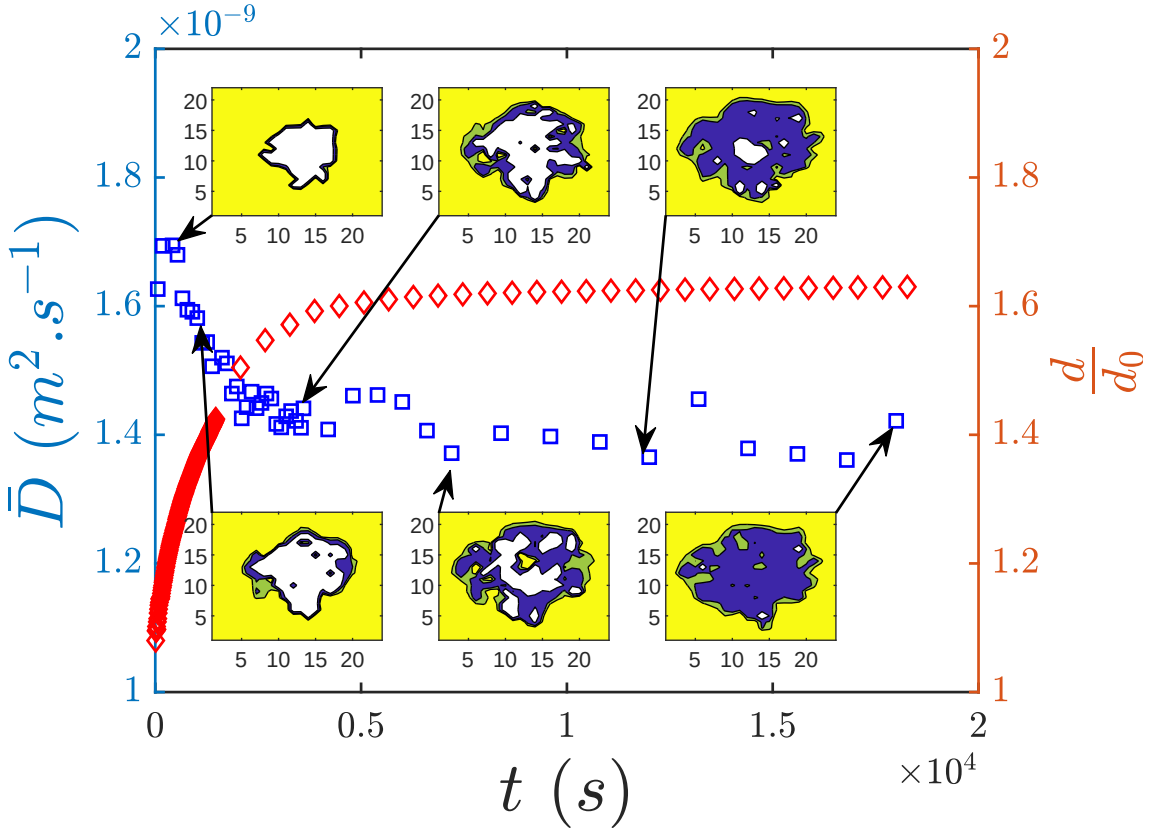

Figure 7: Time evolution of the mean diffusion coefficient $\bar{D}$ and the normalized diameter d/d_0 during a swelling event. Images correspond to diffusion coefficient maps at different times. Each color is associated with a range of diffusion coefficients: $\bar{D} > 1.8\times10^{-9}$ m^2.s^{-1} (yellow), $1.5\times10^{-9} < \bar{D} < 1.8\times10^{-9}$ m^2.s^{-1} (green), $0.8\times10^{-9} < \bar{D} < 1.5\times10^{-9}$ m^2.s^{-1} (blue), $\bar{D} < 0.8\times10^{-9}$ m^2.s^{-1} (white).

$d_0^2/\bar{D}$ is the characteristic timescale for diffusion of water through the particle and α^{-1} the ratio between particles and water densities ($\alpha = 0.7246 \pm 0.05$ in our experiments). The evolution of the re-scaled particle diameter is given by $d^* = (d(t) - d_0)/(d_{max} - d_0)$, where d_0 and d_{max} are the initial and the final diameters of the particle, respectively, and are extracted from experimental data. Comparisons between the experimental data and the usual models used in the literature (see Tab. 2) are presented in Fig. 8.

The models of Buchholz et al. (1998) and Sweijen et al. (2017a) are purely diffusive models, without any free parameters in our case. These two models predict a much faster swelling than that observed experimentally. In fact, the characteristic swelling time in these models is related to the diffusing time $d_0^2/4\bar{D} \approx 10^3$ s, which is an order of magnitude smaller than what is measured experimentally. This result suggests that swelling is influenced by water uptake at the surface of the grain and not only by diffusion, as evidenced by the best quality of fit for Sweijen et al. (2017b) and Omidian et al. (1998) models. The only free parameter of these models, k, corresponds to the inverse of a characteristic absorption time at the surface of the grains, whose values are $k = 3.29\ 10^{-4}$ s^{-1} and $k = 2.15\ 10^{-4}$

Table 2
Swelling models from the literature used for comparison with experimental data. $\alpha = \rho_w/\rho_s$ is the ratio between the water and particle densities.

Models	Parameters	References
$\frac{d(t)}{d_0} = \frac{d_{max}}{d_0 - 1}(1 - e^{-kt})$	k free parameter	Omidian et al. (1998)[29]
$\frac{d(t)}{d_0} = \left[1 - \theta_{max}(e^{-kt} - 1)\right]^{-1/3}$	$\theta_{max} = 1 - \left(\frac{d_0}{d_{max}}\right)^3$, k free parameter	Sweijen et al. (2017b)[40]
$d'(t) = \frac{4\pi^2 d_0 \bar{D}}{3\alpha d^2(t)}\left[Q_{max} - \alpha\left(\frac{d(t)}{d_0}\right)^2 + \alpha - 1\right]$	$\alpha = 0.7246$, $Q_{max} = 3.62$, $\bar{D} = 1.4\ 10^{-9}$ m^2.s^{-1}	Buchholz et al. (1998)[5]
$d'(t) = \frac{4\bar{D}}{\alpha d(t)} \frac{Q_{max} - \alpha\left(\frac{d(t)}{d_0}\right)^3 + \alpha - 1}{\alpha(d(t)/d_0)^3 - \alpha + 1}$	$\alpha = 0.7246$, $Q_{max} = 3.62$, $D = 1.4\ 10^{-9}$ m^2.s^{-1}	Sweijen et al.(2017a)[39]

s^{-1} for the Sweijen et al. (2017b) and Omidian et al.(1998) models, respectively.

In our case, $K = kd_0^2/4\bar{D} \ll 1$ is the only dimensionless group of the problem and is related to a water uptake-limiting swelling behavior. This can be explained by the existence of a layer near the surface of the particles where the diffusion properties are largely modified. This hypothesis is supported by the observation of an inhomogeneity of the diffusion properties in a crown of thickness ≈ 300 μm (see Fig. 7) and by recent works on the internal structure of couscous [16], where the authors show that the kinetics of the changes to the physicochemical characteristics of the grains during the cooking and the drying stages can contribute to generating heterogeneities in the couscous grains. In fact, the internal structure of agglomerates results from the spatial arrangement and the agglomeration of the primary particles induced by capillary forces and starch gelatinization at the surface, which in turn modify diffusion properties. The chemical composition of the powder, as well as the production process, need to be highlighted to understand the complexity of the swelling mechanisms occurring in this "real" food powder:

- According to Debet and Gidley (2006) [7], the presence of surface components (i.e. residual proteins, lipids) impacts the granular swelling of starch (rate and extent), particularly for two of the most commonly used starches (maize and wheat). The presence of these components is far from negligible in couscous powders (see table 1) and may enhance the intricacy of the powder swelling.

- During industrial production, a cooking stage inducing partial melting and merging of the particles is performed in order to transform wet agglomerates into more plastic and stable grains. During this step, a part of the starch (i.e. the main component of couscous) is gelatinized, amylose-lipid complexes are created and proteins (i.e. gluten) are insolubilized. These very complex phenomena are not identical throughout the particle, meaning that some parts of the grain may be more modified than others. This may be particularly true at the particle surface, explaining disparities observed between mathematical models and our observations. Also, the extent of starch gelatinization after the cooking stage was found to vary in the ratio from one (Debbouz and Donnelly (1996)[6]) to two (Bellocq et al. (2018)[3]) and may also impact particle swelling behavior.

It is important to note that the Omidian et al.(1998) model was initially interpreted in the literature as a purely

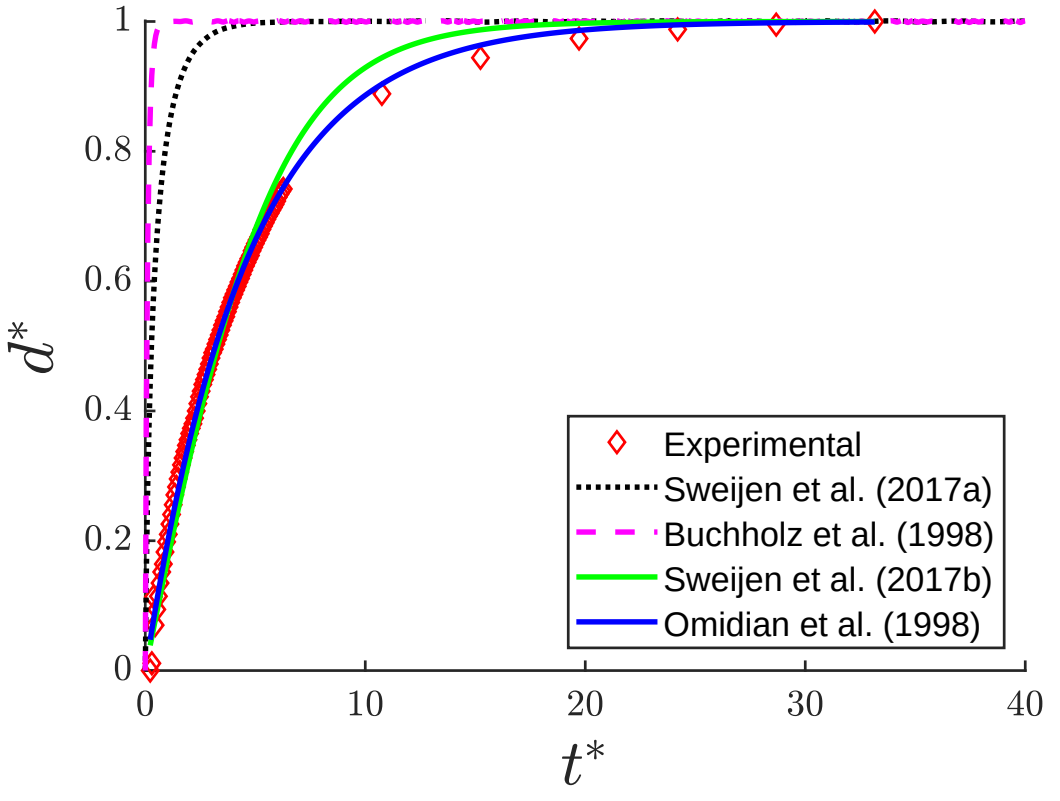

Figure 8: Evolution of the normalized diameter d^* as a function of the normalized time t^*. Experimental data are compared to different swelling models extracted from the literature. Experimental data are the mean out of 10 independent experiments. The Omidian et al. (1998) and Sweijen et al. (2017b) models are fitted to experimental data with only one free parameter ($R^2 = 0.9809$ and 0.9652, respectively). There is no free parameter for the other models presented.

diffusing model. Authors have related it to a Voigt rheological model that accounts for the immediate elastic and delayed viscous strain responses due to gelatinization within the grain. Our result shows that this model also captures the swelling dynamics of couscous grains well in our experiments and can be employed as a law for water uptake at the particle's surface, as suggested in the recent works of Sweijen et al.[39, 40].

4. Conclusions

In this paper, the swelling properties of couscous grains under liquid saturation conditions at ambient temperature have been studied. It has been shown that a recent time-resolved MRI technique can be an efficient tool to investigate water penetration inside granular materials in food.

The majority of swelling models proposed in the literature are based either on the assumption of a diffusive dynamics with an assumed constant diffusion coefficient, or on water uptake-limiting dynamics via absorption at the particle surface.

By monitoring both the evolution of the particle diameter and the apparent diffusion coefficient of the liquid within the grain, it has been shown that a first-order kinetic model accounting for the dynamics of water capture at the surface of the particles allows to describe the growth of the particle size over time. The results suggest that the swelling dynamics is a water uptake-limiting mechanism because of the existence of a gelatinous layer at the grain surface formed during the manufacturing process, as previously reported in the literature.

MRI offers new perspectives for in situ monitoring of the water intake and water distribution of couscous grains. This technique may be generalized to others steps occurring during couscous formulation, for example to assess starch gelatinization or retrogradation phenomena.

5. Bibliography

CRediT authorship contribution statement

Sébastien KIESGEN DE RICHTER: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original draft, Supervision, Funding acquisition. **Naïma GAUDEL:** Methodology, Validation, Investigation, Writing - Original draft, Visualization. **Claire GAIANI:** Resources, Writing - Original draft, Supervision, Funding acquisition. **Arthur PASCOT:** Software, Writing - Original draft. **Maude FERRARI:** Methodology, Software, Validation, Investigation, Visualization. **Mathieu JENNY:** Software, Formal analysis, Investigation.

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Swelling of couscous grains under saturated conditions

Sébastien KIESGEN DE RICHTER,Naïma GAUDEL,Claire GAIANI,Arthur PASCOT,Maude FERRARI,Mathieu JENNY

- MRI is an effective tool to investigate water distribution in granular food materials
- Water diffusion coefficient in grains is heterogeneously distributed in space
- Classical diffusive models from the literature cannot predict swelling dynamics
- Results suggest that the swelling dynamics is a water uptake-limiting mechanism

Dear Editor,

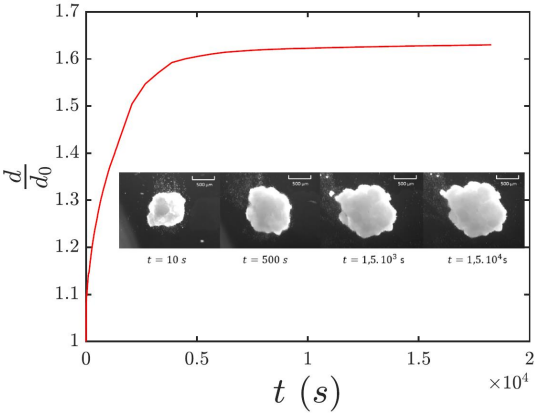
This manuscript has not yet been published elsewhere and it is not under consideration by another journal. All authors have approved the manuscript and have agreed to submit it to Journal of Food Engineering. All authors have also read and adhered to the Statement of Ethical Standards for manuscript submitted to Journal of Food Engineering.

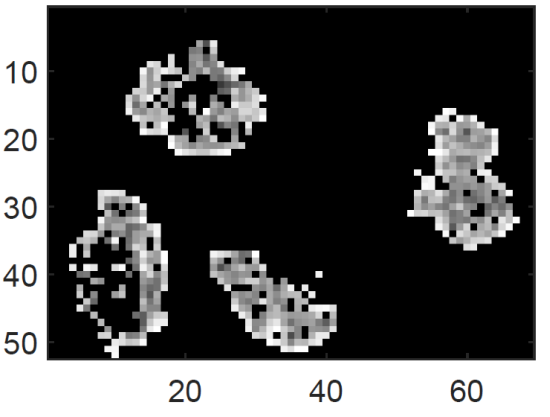
Finally, the authors have no known conflicts of interest.

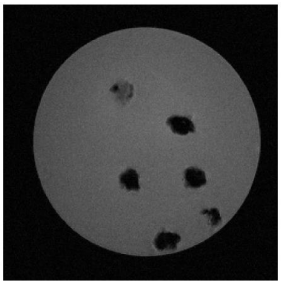
Graphical Abstract

Swelling of couscous grains under saturated conditions

Sébastien KIESGEN DE RICHTER,Naïma GAUDEL,Claire GAIANI,Arthur PASCOT,Maude FERRARI,Mathieu JENNY







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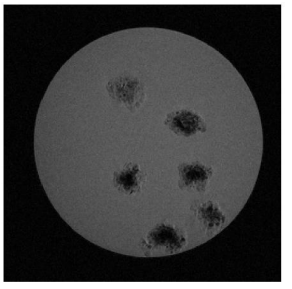

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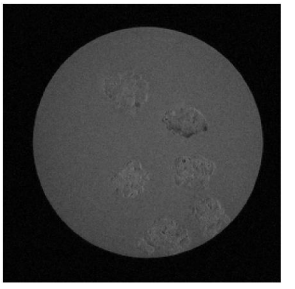

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