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Reconstruction of food microstructure via statistical correlation functions. The use of lineal-path distribution functions

A. Derossi *, C. Severini, T. De Pilli

Department of Science of Agriculture, Food and Environment, University of Foggia, Italy

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ABSTRACT

The reconstruction of microstructure of biological and synthetic materials is of great importance for theoretical and practical application. The obtaining of this purpose through limited statistical information is a challenge at which some pioneering researchers are focusing their efforts. For the first time, a reconstruction method was used to rebuild bread microstructure by using the information of lineal-path distribution function (LPF). The method was a powerful tool to reconstruct bread microstructure; a perfect match between lineal-path function of reference and reconstructed images were obtained. The reconstructed images progressively improve, compared to the reference, increasing the number of LPFs used during reconstruction. The use of LPFs in different direction did not allowed to obtain a perfect match between the bread and the reconstructed images because, LPF did not contain sufficient microstructure information however, the essential features of bread were captured proving the possibility to reconstruct food microstructure.

1. Introduction

Random heterogeneous materials are ubiquitous in nature and in synthetic systems. Examples are soil, porous media, biological tissues, sandstone, fiber, rock formations, tree patterns in forests, cosmological structure, etc. (Lu and Torquato, 1992a; Jiao et al., 2009). The precise understanding of the microstructure of these systems is of crucial importance for practical application due to the strict relation between microstructure information and the bulk properties of materials such as conductivity, permeability, mechanical and electromagnetic properties, heat and mass transfer (Lee and Torquato, 1989; Lu and Torquato, 1992a; Torquato and Lu, 1993; Russ, 2005; Baniassadi et al., 2012; Li et al., 2012). Most of heterogeneous materials may be considered as two-phase random systems composed from two different phases or from one phase in different states. In food science a lot of product may be considered as two-phase systems in which a void phase (pores) and a solid matrix phase (cell membranes, proteins, crystals, globules, etc.) exists. A typical examples are bread characterized from pores and solid matrix (crumb), and sausages, composed by fat globules (discontinuous phase) and protein elements (continuous phase), or emulsions composed by water and oil phases. The importance of microstructure on the quality of food is not a new idea (Aguilera, 2005; Parada and Aguilera, 2007; Datta, 2007). Aguilera (2005) was the first scientist who highlighted as all macroscopic properties of food are governed from elements in the range of 10–100 μm. In an interesting paper, he clearly analyzed as food microstructure greatly affects nutritional values, sensorial properties, transport phenomena as well as microbial stability. Later, Datta (2007) who studied the food as porous media, showed as the intrinsic permeability, *k*, which is a parameter strictly related with pore connectivity, significantly affects the mass transfer during processing. Furthermore, Parada and Aguilera (2007) showed the importance of microstructure on the bioavailability of several nutrients. In light of above considerations, one of the most important challenge is to ascertain what is the essential information to obtain the quantitative characterization of food microstructure, its exact theoretical and experimental quantification and its relation with the macroscopic properties. With this aim some authors, on the basis of a rigorous theory, developed a series of statistical correlation functions able to extract microstructure information from two-phase random systems (Torquato et al., 1988; Lu and Torquato, 1992b; Torquato and Lu, 1993; Torquato, 2002; Quintavalla, 2006). One of these basic functions is *the n-point correlation function* $S_n(x_1, x_2, \ldots x_n)$, which is the probability to find n points at position $x_1, x_2, \ldots x_n$ all in one of the two phases of the system (Coker and Torquato, 1995). However, since infinite n-point functions are not attainable in practice, low-order version, such as

* Corresponding author. Address: Department of Science of Agricultural, Food and Environment, University of Foggia, Via Napoli 25, Italy. Tel.: +39 0881 589245; fax: +39 0881 589222.

E-mail address: antonio.derossi@unifg.it (A. Derossi).

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a *two-point correlation* $S_2(x_1, x_2)$ and *three-point function* $S_3(x_1, x_2, x_3)$, are commonly used (Smith and Torquato, 1988; Quintavalla, 2006; Jao et al., 2007). The *lineal-path distribution function*, $L^i(z)$ is another interesting statistical descriptor, which refers the probability that a segment of length z completely falls in the phase i (Lu and Torquato, 1992a, 1992b; Torquato, 2002; Singh et al., 2008). This function contains important connectedness information along a straight line and also it gives some information in stereology. Further correlation functions such as *chord-length distribution function*, $p(z)$, *pore size distribution function*, $P(z)$, *two-point cluster function*, $C_2(x_1, x_2)$, have been developed and validated for several digitized model systems (identical hard disks, identical overlapping disks, periodic rods, Debye overlapping disks, etc.) and for some materials such as sandstone, magnetic gels, Boron modified Ti-alloys (Rintoul et al., 1996; Singh et al., 2008; Chan and Govindaraju, 2004) while very few papers showed the use of these functions to obtain microstructure information of food (Derossi et al., 2012, 2013a, 2013b). The reconstruction of microstructure of random heterogeneous systems from limited microstructure information is an interesting inverse problem. If achieved, this result should enable to generate an accurate bi- or three-dimensional structure of any material from which should be possible to estimate their macroscopic properties. Moreover, the study of reconstruction will give light on the type of microstructure information contained into the statistical correlation functions. Although different approaches to reconstruct random media have been proposed (Joshi, 1974; Quiblier, 1984; Adler et al., 1990; Berk, 1991) we focus our attention on the simulated annealing method proposed from Rintoul and Toruato (1997). The method is based on the finding of a state of minimum 'energy' by interchanging the phase of two the pixels in a digitized random model system (simulated), having the same porosity fraction of the reference material (Yeong and Torquato, 1998). The 'energy' is defined as the sum of square of the difference between the correlation functions of simulated and reference systems. Although this method has been used for several digitized model systems showing a good ability in the reconstruction of two-phase random systems (Rintoul et al., 1996; Rintoul and Toruato, 1997; Li et al., 2012; Baniassadi et al., 2012) this problem is still understudied and never it was used for the reconstruction of food microstructure. On the basis of these considerations, the aim of this paper was to study the reconstruction of bread microstructure by using the information contained in the *lineal-path distribution function* extracted, from 2D images, in several direction.

2. Material and methods

2.1. Theoretical background

A random medium is a domain of space $V(\omega)\ \varepsilon\ R^3$ (the realization ω is taken from some probability space Ω) where the volume V is characterized from two-phases: phase 1 in the region γ_1 with a volume fraction Φ_1, and phase 2 in the region γ_2 with a volume fraction Φ_2. For a given realization ω, the characteristic function $I_{(x)}$ of phase 1 may be reported as:

$$I_{(x)} = \begin{cases} 1, & \text{if } x \text{ falls in the phase } 1(\epsilon_i) \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where i is the region occupied by phase i (Equal to 1 or 2) (Lu and Torquato, 1992a, 1992b). Also, a useful system to study heterogeneous material is a two-phase fully penetrable spheres which is obtained adding polydispersed spheres of radius R until a specific porosity fraction is reached. Lu and Torquato (1992a), based on a rigorous theory, showed that for these systems the lineal-path distribution function is defined as

$$L_{(z)} = \phi_1^{\,1+\frac{2z(m+1)}{[\pi R(m+2)]}} \quad (2)$$

where R is the average radius of the disks, z is the length of the segment (pixels or mm) and m is the parameter of Schultz size distribution which is equal to:

$$f(R) = \frac{1}{\Gamma(m+1)}\left[\frac{m+1}{\langle R\rangle}\right]^{m+1} R^m \exp\left[\frac{-(m+1)R}{\langle R\rangle}\right] \quad (3)$$

where Γ is the gamma function.

2.2. Raw material and images acquisition

Bread was chosen as model because their structure may be considered as a two-phase systems in which the void (pores) is the phase 1 and the solid matrix (crumb) is the phase 2. Also, since the position of pores produced during yeast fermentation is extremely affected from several random variables such as air incorporation, dough preparation, bread structure may be considered a random system. Particularly, we used "Altamura" bread (Oropan s.p.a., Italy), purchased locally because of the large diffusion of bread in the south Italy. The loaves were cut to obtain slices with a thickness of 1 cm and the images were acquired by using a flat scanner mod. Hp 3600 (Hp, Scanjet) covering the samples with a black box to obtain a good contrast between the background and the samples, and to guarantee constant lightness conditions. The images were acquired by positioning the top of the slice sample parallel with the light of scanner (x axis) with the aim to avoid the effect of sample's position on lineal-path distribution function. A resolution of 600 dpi = 0.004233 mm/pixels was used and the images were saved in TIFF format. Binary image were obtained by applying the Otsu's method (Sezgin and Sankur, 2003; Jiao et al., 2010), choosing the threshold through the functions "rgb2gray" and "graytresh" available in the image analysis Toolbox of Matlab R2012b (Mathworks, USA).

2.3. Computation of lineal-path distribution function

The binary images of bread may be represented by a common two-dimensional arrays:

$$I = \begin{matrix} I_{1,1} & I_{1,2} & I_{1,3} \\ I_{2,1} & I_{2,2} & I_{2,3} \\ I_{3,1} & I_{3,2} & I_{i,j} \end{matrix} \quad (4)$$

where $I_{i,j}$ ($i = j = 1, 2, 3, 4, \ldots, n$) only assumes value 0 (black pixels) or 1 (white pixels); black pixels refer to the pores of bread (phase 1), while the white pixels refer to the crumb (phase 2). Lineal-path distribution function (LPF) was extracted in four directions: (1) LPF_0 along horizontal direction (x axis, 0°); (2) LPF_{90} along vertical direction (y axis, 90°); (3) LPF_{45} along diagonal direction (45°); (4) LPF_{135} along diagonal direction (135°). The extraction of LPF in horizontal and vertical direction was obtained by using the algorithm developed and validated by Derossi et al. (2012, 2013a, 2013b). In addition, a modified version of the these algorithms was developed to extract LPF function along diagonal directions (45° and 135°).

2.4. Reconstruction procedure

For simplicity, we consider the reconstruction procedure of a general two-phase random system carried out by using the microstructure information provides from a general statistical correlation function, $f(r)$. Also, we defined the correlation function of the phase j (equal to 1 or 2) of our "reference" systems as $f_0(r)$ and the lineal-path function of the reconstructed model system as