1

Use of Hydrocolloids to Control Food Size and Shape

1.1 Introduction

Appearance – one of the four quality factors of foods – comprises color, shape, size, gloss, and visual appeal. In general, foods' physical properties include size and shape, and number, nature, and conformation of constituent structural elements. During mastication, the size and shape of food particles and their surface roughness are sensed, becoming inseparable attributes of the overall textural sensation. The ability to use hydrocolloids to control food shape and size is common knowledge. This chapter begins by defining size and shape. Round and spherical shapes are emphasized, along with the means to estimate/calculate roundness and sphericity. Other shapes, geometrical and irregular, are also illustrated. Explanations of how to obtain different food shapes using different molds for setting and other techniques, such as flow of a preset gel through silicone tubes and simultaneous cooling of an agar–agar or other gelling agent solution to obtain a noodle (spaghetti) shape, are described. This chapter also includes a description of cutting techniques for gels or foods that are created with the help of hydrocolloids, as well as spherification to produce spherical and ellipsoid shapes (e.g. artificial salmon eggs), and different illustrations of these foods' appearance (https://www.amazingfoodmadeeasy.com/info/modernist-techniques/more/gelification-technique).

1.2 The Attractive Shape of Foods

1.2.1 Triangular and Prism-Shaped Foods

Consumers consistently associate a diversity of tastes and flavors to food shape. The shape of a product/food might affect the consumer's sensory and hedonic responses to it. Many foods are triangular in shape (i.e. a polygon with three edges and three vertices, one of the basic shapes in geometry). Samosa is a fried or baked pastry with a savory filling such as spiced potatoes, onions, peas, chicken and other meats, or lentils (Figure 1.1). Aside from its triangular shape, it might appear as a cone or half-moon shape, depending on the region

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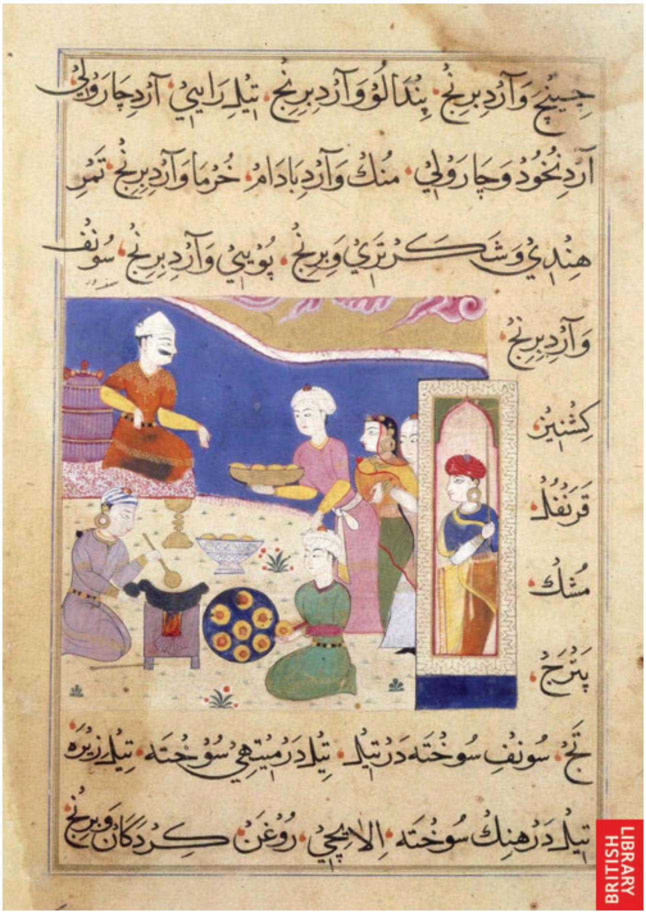


Figure 1.1 Medieval Indian Persian manuscript Nimatnama-i-Nasiruddin-Shahi [The Book of Recipes], c. 16th century, showing samosas being served. Date: 1495–1505. *Source:* The British Library.

from which it originates (Mudireddy 2019). The outer deep-fried crust remains pretty much the same, whereas the filling changes (Reza 2015; Duggal 2021). Nachos are a regional Mexican dish consisting of heated tortilla chips or *totopos* (i.e. a flat, round, or triangular corn product similar to a tortilla) covered with melted cheese or a cheese-based sauce, often served as a snack or appetizer (Figure 1.2) (Mudireddy 2019). Borek, or burek, is a filled pastry made of a thin flaky dough such as filo with a variety of fillings, for instance, cheese, meat, potatoes, or spinach (https://en.wikipedia.org/wiki/B%C3%B6rek). In Albania, it is called *byrek*, and is traditionally prepared from a number of dough layers rolled out by hand. The final form can be small, individual triangles (https://en.wikipedia.org/wiki/B%C3%B6rek). In Armenia, *byorek* consists of dough folded into triangles and stuffed with different spiced fillings. In Tunisia, the local deep-fried variant, called *brik*, is a triangular-shaped pastry pocket with chopped onion, tuna, harissa (i.e. hot chili pepper paste) and parsley (Field and Field 1970). Pizza, perhaps the most popular fast food in the

Figure 1.2 Nachos with beef and beans. *Source:* Renee Comet.

Figure 1.3 A single slice of pizza with sausage and cheese. *Source:* Renee Comet.

world, was originally a food for the poor in 18th century Naples. It is a source of national and regional pride in Italy, as well as of cultural identity (Mudireddy 2019). It consists of a flat base of leavened dough topped with tomatoes, cheese, and various other ingredients and baked at high temperatures, traditionally in a wood-fired oven (Helstosky 2008). Pizza is generally round and usually cut into triangular slices (sectors) (Figure 1.3). A sector is a region bounded by two radii of a circle and the intercepted arc of the circle (Figure 1.4). The angle formed by the two radii is called the central angle. A sector with a central angle less than 180° is called a minor sector. Which Wich sells customizable submarine sandwiches called "Wiches" – there are 10 categories and 60 topping options (https://www.whichwich.com/menu/) – that can be cut into

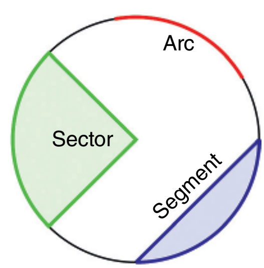


Figure 1.4 A circle showing the arc, segment and sector. *Source:* Limane/ Wikimedia Commons/ Public domain.

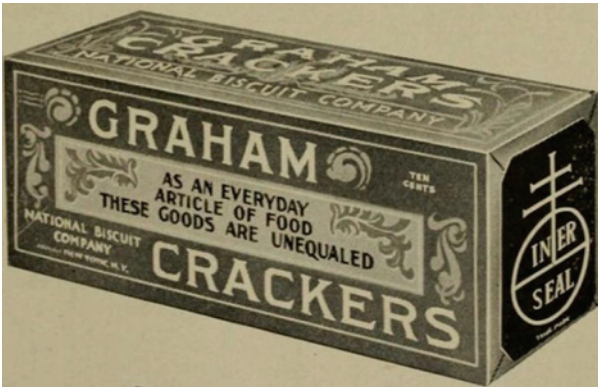


Figure 1.5 A box of National Biscuit Company graham crackers, c. 1915, which was priced at 10 cents. *Source:* Internet Archive Book Images/Wikimedia Commons/Public Domain.

little triangles. Toblerone is a chocolate bar produced in Bern, Switzerland, with a distinctive triangular shape and packaging, the bar being composed of a series of joined triangular prisms. The decision to space out the distinctive triangular chocolate chunks in two sizes of Toblerone bars sold in the UK upset its fans, who say that they mind the gap (https://www.bbc.com/news/uk-37904703). A waffle is a food item prepared from leavened batter or dough that is cooked by sandwiching it between two hot plates that are decorated to provide a distinct size, shape, and surface impression. Many places serve them in miniature triangular patterns with remarkable toppings (https://en.wikipedia.org/wiki/Waffle).

1.2.2 Rectangular and Cube-Shaped Foods

A rectangle is a special case of a parallelogram in which each pair of adjacent sides is perpendicular (https://en.wikipedia.org/wiki/Rectangle). De Villiers defined a rectangle more generally as any quadrilateral with axes of symmetry through each pair of opposite sides (De Villiers 1996). Many foods have a rectangular shape (https://thingsthatarerectangles.wordpress.com/category/food/). A few examples include toast, which is a rectangular breakfast treat, and graham crackers (Figure 1.5), a classical rectangular snack (https://thingsthatarerectangles.wordpress.com/category/food/) used to sandwich roasted marshmallows and a piece of chocolate in the traditional campfire treat *s'more*. A saltine or soda cracker is a thin, usually square cracker made from white flour, yeast, and baking soda, with most varieties lightly sprinkled with coarse salt (https://en.wikipedia.org/wiki/Saltine_cracker). Brisket is a cut of meat from the breast or lower breast of beef or veal which can have a rectangular shape. Rice provides an example of a food that can be shaped into cubes.

1.2.3 Circular and Spherical-Shaped Foods

A circle is a shape consisting of all points in a plane that are at a given distance from a given point, the center; accordingly, it is the curve traced out by a point that moves in a plane such that its distance from the center point is constant (https://en.wikipedia.org/wiki/Circle). A sphere is a geometrical object in a three-dimensional space likened to the surface of a ball. Similar to the circle in a two-dimensional space, a sphere is defined mathematically as the set of points that are all at the same distance *r* from a given point (center) in a three-dimensional space (https://en.wikipedia.org/wiki/Sphere). The circle is a highly symmetrical shape: every line through the center forms a line of reflection symmetry, and it has rotational symmetry around the center for every angle. As a result of this beautiful geometry, many foods have a circular shape. A few examples are: cut hard-boiled eggs, pizza, burgers, crepes, savory and sweet pies, pancakes, doughnuts, okonomiyaki, scones, tacos, meatballs, pork buns, cupcakes, cob loaf dip, tart, cookies, sushi, wheels of cheese, bagels, and cakes (https://www.taste.com.au/articles/proof-circular-foods-are-the-best/ecugi02b). Other web sources provide more examples of spherical foods. For example, buffalo chicken cheese balls, spinach balls, fried macaroni and cheese balls, kicked-up cheese balls, salmon croquets, Oreo balls, cheesy fried-chicken farm balls, puff balls, jello popcorn balls, sausage balls, cookie dough balls, pickled green cherry tomatoes, Italian meatballs, sauerkraut balls, peanut butter balls, Mexican rice balls, no-bake granola balls, ham and cheese arancini, cake balls, popcorn balls, rum balls, shrimp balls, Braunschweiger balls, sun-dried tomato and mozzarella rice balls, potato rice balls, strawberry balls, and cheesy artichoke chicken balls, to name a few (https://www.food.com/ideas/on-a-roll-ball-shaped-snacks-sweets-6350#c-379847). It is essential to note that the terms "sphere" and "ball" can be used interchangeably, although in mathematics, a distinction is made between a *sphere* – a two-dimensional closed surface set in a three-dimensional Euclidean space (Figure 1.6), and a *ball* – a three-dimensional shape that comprises the sphere and everything *inside* the sphere (a *closed ball*) or, more often, just the points inside the sphere (an *open ball*) (https://en.wikipedia.org/wiki/Sphere).

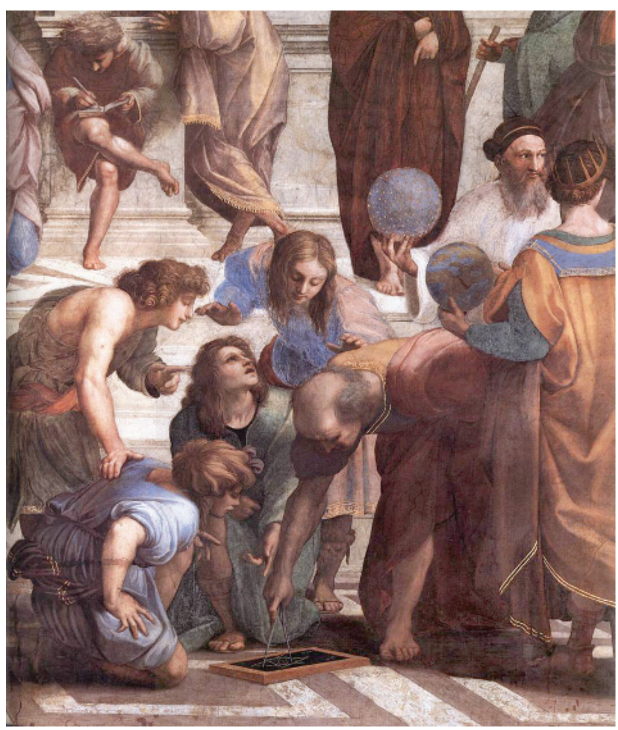


Figure 1.6 Detail from Raphael's *The School of Athens* featuring a Greek mathematician – perhaps representing Euclid or Archimedes – using a compass to draw a geometric construction. *Source:* Raffaello Sanzio/Wikipedia Commons/ Public Domain.

1.3 Selected Geometrical Properties of Foods

1.3.1 Size

The textural characteristics of foods include mechanical, geometrical, and other primary parameters. Under the heading of geometrical characteristics, we include particle size and shape (e.g. gritty, grainy, coarse); and particle shape and orientation (e.g. fibrous, cellular, crystalline) (Szczesniak 1963). Size and shape are always part of a physical object, and are essential to adequately defining that object. In defined uses, both size and shape affect the process (Mohsenin 1970). This connection can be revealed using a two-dimensional system such as:

$$I = f\left(\text{sh}, s\right) \tag{1.1}$$

where I is the index influenced by both shape, sh, and size, s. In further uses, the index I may be a function of not only size and shape but also of other parameters, such as orientation, o, packing index, p, firmness, f, and so on.

$$I = f\left(\text{sh}, s, o, p, f, \ldots\right) \tag{1.2}$$

A good illustration of this relationship would be determining the number of specified objects to fill a container. If I is substituted by Y, with X_1 for shape, X_2 for size, X_3 for orientation, X_4 for packing and X_5 for firmness, the equation in multiple regression form will be:

$$Y = b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 \tag{1.3}$$

This relationship can be evaluated by assessing a set of specimens, where the magnitude of the contribution of each x to the variation in y can be estimated by means of analysis of variance and multiple correlation (Quenoville 1952; Mohsenin 1970). This methodology was used to define the correlation between permeability of a reservoir and the petrographic properties of sediments, such as shape, size, mineral composition, arrangement, and orientation (Griffiths 1958).

The size and shape of an agricultural commodity, or of any item for consumption, not only affect the degree of consumer approval; in numerous cases, they also affect packaging, distribution of stresses when forces are applied, and processability (Szczesniak 1983). In the area of food powders, such as soluble coffee manufacturing, the existence of fines could clog extraction columns and in a similar manner fines might block filters in home brewing equipment. Particle size and, specifically, particle size distribution in porous media control permeability to water and impact extractability and solubility characteristics (Szczesniak 1983).

1.3.2 Characterization of Size

Size is frequently characterized by determining whether a whole or ground product can be passed through a sieve or screen of defined mesh size. This method is widely used for grading agricultural commodities; however, it has substantial disadvantages, such as the fact that sieving only divides the product in relation to its smallest dimension. It is, however, appropriate for products that are close to spherical in shape. Slit screens are used for oblong materials (i.e. the vertical diameter of the screen hole is greater than the horizontal diameter), such as rice (Szczesniak 1983). Sieve analysis refers to the practice of assessing a material's particle size distribution by passing it through a sequence of sieves of progressively smaller mesh size (i.e. the number of openings in 1 sq. inch of screen) and weighing the quantity of material that remains in each sieve as a portion of the full mass (https://fintec1.com/wp-content/uploads/2020/07/FF-24.0101-Determing-Screen-Mesh-Size.pdf).

Additional applied methods for defining the size of fruit and vegetables are length or diameter measurements, and count per volume or weight. For fruit, larger size is generally crucial for the fresh market, whereas for vegetables, which are preferred at immaturity, a smaller size is desirable (Szczesniak 1983). The size and shape of food powders affect aerodynamic and hydrodynamic features, as well as mixing, segregation, and other characteristics that influence both processing and quality. Average size and particle size distribution are very important parameters for powders. The size and shape of dry particles may be determined by microscopic examination. A particle size analyzer uses the resultant photographs to estimate the size and distribution of the particles. The size of particles suspended in a fluid food product can be determined microscopically, by wet-sieving technique or by Coulter Counter particle size analyzer (Szczesniak 1983). When particles are distributed in a liquid or semi-liquid food, their size and shape influence the rheological parameters of the system. In fruit juices, particles of increasing size increase viscosity, whereas with globules in an emulsion, decreasing size leads to increasing viscosity. In commercial tomato juice, particle shape and size (diameter) influence viscosity (Surak et al. 1979). Elongated particles in tomato juice contribute more to viscosity than spherical ones (Kattan et al. 1956).

1.3.3 Size Reduction

It is often necessary to reduce the size of foods, both in the industry and in the kitchen. Size control is frequently needed to speed up transfer of both heat and mass. Size is also controlled for mixing purposes and to obtain uniformity in cooking, during consumption and on the plate. Size reduction continues on the plate as the bite is portioned out, and then in the oral cavity during mastication (Chen 2009). Essential unit operations in nearly all food processes include size reduction and mixing. These are used to manufacture specific formulations, to assist in processing, or to adjust sensory features of foods to the required quality (Fellows 2000). Size-reduction operations expose the cut surfaces to air (i.e. oxygen), leading to further oxidation of the food. A reduction in size/increase in area also increases hot-air drying rates or the action of oxidative enzymes, such as lipoxygenase or peroxidase (Fellows 2000). In engineering, size reduction is one of many "unit operations" or actions that must be taken as part of the material's processing. Size reduction is divided into two major categories depending on whether the material is a solid (grinding and cutting) or a liquid (emulsification or atomization) (Earle 1983). Technically, forces acting on a body produce fracturing or shearing of the material. While engineers are mostly concerned with the energy involved in grinding, cooks appreciate the effects of size reduction in cooking (i.e. color, flavor, and texture).

1.3.4 Energy Requirements for Size Reduction of Solid Materials

Theoretical considerations propose that the energy dE necessary to yield a slight change dx in the size of a unit mass of material can be expressed as a power function of the size of the material (Brennan et al. 1990):

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{K}{x^n} \tag{1.4}$$

A number of researchers have used this equation. Peter von Rittinger was an Austrian pioneer of mineral processing (Figure 1.7), whose work included the early scientific study of comminution, and his theory on the relations of work and power in when breaking rocks, sometimes referred to as Rittinger's law (Lynch and Rowland 2005). Rittinger's inventions and mathematical descriptions of unit operations established mineral processing as a modern technology (Steiner 1991). He was the first to provide a sound mathematical basis for the physics of wet-classification and gravity-separation processes, and the first to discuss the quantitative relationship between energy consumed and size reduction achieved in crushing and grinding (Steiner 1991).

For the grinding of solids, Rittinger considered that the required energy should be proportional to the newly produced surface, with a factor of 2. Then

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{K}{x^2} \tag{1.5}$$

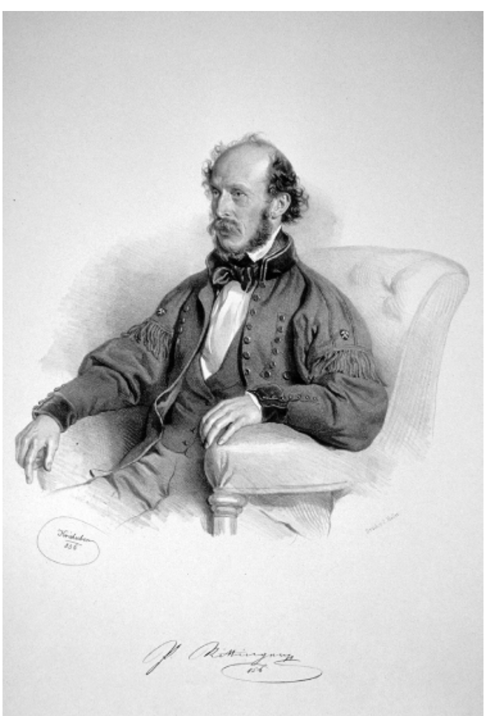


Figure 1.7 Peter von Rittinger, lithograph by Josef Kriehuber, 1856. *Source:* Peter Geymayer/ Wikimedia Commons/Public Domain.

or, integrating

$$E = K\left[\frac{1}{x_2} - \frac{1}{x_1}\right] \tag{1.6}$$

where x_1 is the average initial feed size, x_2 is the average final product size, E is the energy per unit mass required to create this new surface and is generally measured in horsepower hour per ton, and K is Rittinger's constant for a specific machine and material. Rittinger's law is applicable mostly to that part of the process during which the new surface is being created and holds most accurately for fine grinding, where the increase in surface per unit mass of material is large (Richardson et al. 2002). Due to the inaccuracy of the assumptions on which it is based, and the difficulty in determining its parameters, Rittinger's law is only approximate (Berk 2009).

Friedrich Kick was a professor at the Technical University in Vienna from 1892 to 1910. He became well-known for his experiments on material properties and his development of test equipment to measure those properties. Kick's experiments led him to hypothesize a link between energy and size reduction (Lynch and Rowland 2005): "For any unit weight of ore particles the energy required to produce any given reduction ratio in the volumes is constant no matter what may be the original size of the particles" (Richards and Locke 1940). Kick considered that the energy required for a given size reduction was proportional to the size-reduction ratio, which requires $n = 1$ (Kick 1883). Then

$$\frac{dE}{dx} = -\frac{K}{x} \tag{1.7}$$

or

$$E = K \ln\frac{x_1}{x_2} \tag{1.8}$$

with $\frac{x_1}{x_2}$ being the size-reduction ratio.

Kick's law has been found to hold more accurately for coarser crushing, where most of the energy is used to create fractures along existing fissures. It gives the energy required to deform particles within the elastic limit. For numerous crushing operations, the energy prerequisite suggested by Kick's law appears to be too low, whereas that required by Rittinger's equation appears to be excessive (Brennan et al. 1990).

Fred Bond was the engineer who did much to define the relationship between ore hardness, tonnage processed, size reduction achieved, and power required (Lynch and Rowland 2005). Throughout the late 1930s and 1940s, Bond dedicated much of his time to understanding the energy–size reduction correlation. He advanced the concept that the energy needed for grinding was the total energy needed to make the grinding mill product minus the energy needed to make the feed (Lynch and Rowland 2005). In Bond's work, n takes the value 3/2 giving

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{K}{x^{3/2}} \tag{1.9}$$

or

$$E = 2K\left[\frac{1}{(x_2)^{1/2}} - \frac{1}{(x_1)^{1/2}}\right] \tag{1.10}$$

where x_1 and x_2 are measured in micrometers and E in kWh short per ton (907.16 kg),

$$K = 5Ei \tag{1.11}$$

where Ei is the bond work index – the energy required to reduce the unit mass of a material from an infinite particle size to a size at which 80% of it passes a 100-μm sieve. The bond work index is obtained from laboratory crushing tests on the feed material. The third theory holds reasonably well for a variety of materials undergoing coarse, intermediate, and fine grinding (Bond 1952; Brennan et al. 1990).

1.4 Size Enlargement and Reduction Processes

1.4.1 Definition of Forming and Its Aims

Forming is a size-enlargement process in which foods that have a dough-like consistency are molded into a variety of shapes and sizes, frequently following a mixing operation. Forming is used to intensify the range and accessibility of baked goods, confectionery, and snack foods (Fellows 2000). Controlling the size of a formed food piece is important to ensuring identical rates of heat transfer into the center of the baked product, to guarantee the weight of the food piece, and to confirm the standardization of smaller food items for the subsequent control of fill weights. Extrusion also has a forming function (Fellows 2000).

1.4.2 Confectionery Molders

Confectionery depositing–molding equipment is comprised of separate molds of the required shape and size for a particular product, associated with a specific conveyor. The depositor has a piston filler that places a precise specified volume of hot sugar mass into each mold. Depositors can place food of a single type, layered foods, or center-filled foods. In the case of chocolate paste, the food is then cooled in a cooling tunnel. When it has hardened satisfactorily, separate sweets are ejected and the molds restart the cycle (Fellows 2000).

1.4.3 Pie-Casing Formers

Pie casings are shaped by putting a portion of dough into aluminum foil containers or refillable pie molds and pressing it with a die. Then a filling is placed into the casing and a continuous layer of dough is positioned over the top. The lids are then cut by countering blades (Fellows 2000). Hayashi (1989) and Rheon (2016) described equipment for forming and encasing balls of dough with other materials. Throughout this process, the inner and outer materials are coextruded, distributed and shaped by two “encrusting discs”

(Fellows 2000). The comparative thickness of the outer layer and the diameter of the inner sphere are determined by the separate materials' flow rates (Fellows 2000). The comparative thicknesses of the inside and external layers can therefore be modified by merely fine-tuning the flow rates, allowing a high degree of flexibility for the manufacturer of various consumable items. Such equipment is used in Japan for manufacturing cakes with an outer layer of rice dough and filled with adzuki bean paste. It can also be applied to produce doughnuts, fish filled with vegetables, hamburgers filled with cheese, meat pies, and sweet-breads filled with jam (Fellows 2000).

1.4.4 Hydrocolloids in Food Fillings

Hydrocolloids are frequently used in fruit pie filling (Saha and Bhattacharya 2010). Fruit preparations for baked goods are used as toppings or fillings for biscuits, cakes, pies or rolls. Methylcellulose and hydroxypropyl methylcellulose (HPMC) are used to control boil-out of bakery fillings and of hot structures in potato croquettes, meat analogues, processed meat, or fish products. Boil-out occurs when during the baking or microwaving process, the viscosity of the filling decreases, causing it to boil and be expelled from the dough product. Carboxymethylcellulose (Figure 1.8) stabilizes and thickens waffle fillings with a high sugar content (Onyango et al. 2009; Correa et al. 2010; Gómez et al. 2010). Addition of 2–5% inulin (Figure 1.9) inhibits the phase separation of pasta fillings. Inulin creates and maintains a soft, velvety filling with a diminutive bite that does not disintegrate during ingestion. κ- and ι-carrageenan, and their mixtures, can be used in pie fillings and ready-to-eat desserts (Soukoulis et al. 2008). In addition, the synergistic gelling between high-guluronate alginate and highly esterified pectin may be used in fruit fillings (Toft et al. 1986). Inclusion of xanthan gum to fruit pie fillings increases consistency, stability, flavor release and syneresis control.

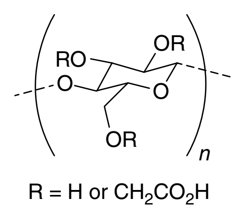
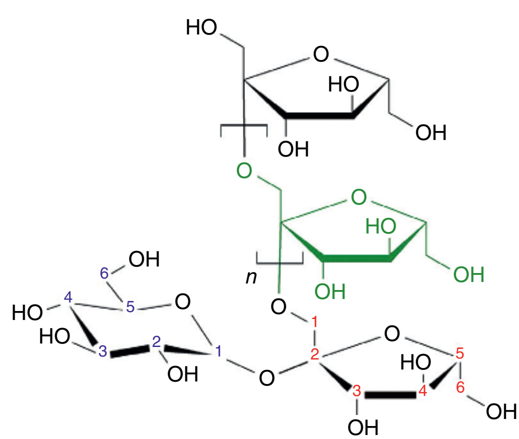


Figure 1.8 Chemical structure of carboxymethylcellulose. *Source:* Edgar181/Wikimedia Commons/Public domain.

Figure 1.9 Structural formula of inulin (fructan). Additional features (carbon numbers and repeated fructosyl unit) are highlighted with colors. *Source:* Florian Fisch/Wikimedia Commons/Public domain.



1.4.5 Cutting and Shaping Spherical Edible Products

For cutting and shaping spherical edible products, specialized companies and machines are essential. For instance, Rheon Automatic Machinery Co. manufactures unique food-processing machines. The company develops technologies to automate food-production systems in processing and baking. Rheon Automatic Machinery operates branches in the United States and Germany, with Yasunori Tashiro serving as its current chairperson (https://www.bloomberg.com/profile/person/3232015). One of their inventions relates to a method for shaping a spherical body consisting of a dough crust and filling. A continuously fed cylindrical body, consisting of dough crust and filling, is constricted by at least three slidable members, which form an opening, or close it. The members slide one along the other to constrict the cylindrical body. The contact area of the members with the surface of the cylindrical body gradually decreases as the opening is closed, thereby constricting the cylindrical body and shaping the spherical body (Tashiro 1989). Another patent deals with an improved apparatus for cutting and shaping a spherical body of sticky material. The apparatus is particularly useful for processing a substantially round food product consisting of soft, very sticky material while avoiding problems of dough adhesion or clogging, or of protruding filling (Tashiro 1993).

1.5 Shape – Definition and Implications

1.5.1 Shape of a Food Commodity

"To define the shape of a body fully, one must specify the location of all points on the external surface" (Medalia 1980). This is a time-consuming process. In addition, it can raise mathematical difficulties, particularly in the case of powders/agglomerated powders (Szczesniak 1983). As a result, qualitative shape descriptions of, for example, fruit and vegetables have been prepared (Mohsenin 1970).

1.5.2 Roundness and Sphericity

Roundness is defined as the degree of sharpness of the corners of a solid (Curray 1951; Mohsenin 1970).

$$\text{Roundness} = \frac{A_\text{p}}{A_\text{c}} \tag{1.12}$$

where A_p is the largest projected area of an object in its natural resting position (m^2) and A_c is the area of the smallest circumscribing circle (m^2) (Mohsenin 1970).

Roundness can also be estimated by:

$$\text{Roundness} = \sum_i^n \frac{r}{NR} \tag{1.13}$$

where r is the radius of the curvature of a corner of the particle surface, R is the radius of the maximum inscribed circle in the longitudinal section of the particle, and N the number of corners. If the corners are worn down, then r approaches R, and roundness = 1 (when $r \to R$) (Mohsenin 1970).

Furthermore:

$$\text{Roundness ratio} = \frac{r}{R} \tag{1.14}$$

where R in this case is the mean radius of the object and r is the radius of the curvature of the sharpest corner (Mohsenin 1970).

Sphericity is a measure of how spherical (round) an object is. Sphericity can be estimated by different methods. For instance:

$$\text{Sphericity} = \frac{d_e}{d_c} \tag{1.15}$$

where d_e is the diameter of a sphere of the same volume as the object, and d_c is the diameter of the smallest circumscribing sphere or, usually, the longest diameter of the object (Curray 1951; Mohsenin 1970). The advantages of using such an expression are that it relates the shape of the solid to that of a sphere of the same volume.

The volume of a solid can be equal to the volume of a *triaxial ellipsoid* which has diameters equivalent to those of the sample. This ellipsoid is a type of quadric surface that is a higher-dimensional analogue of an ellipse. The equation describing a standard axis-aligned ellipsoid body in an xyz-Cartesian coordinate system is:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \tag{1.16}$$

where a and b are the equatorial radii (along the x and y axes) and c is the polar radius (along the z axis), all of which are fixed positive real numbers determining the shape of the ellipsoid. If all three radii are equal, the solid body is a sphere; if two radii are equal, the ellipsoid is a spheroid (Weisstein 2003). In other words: $a = b = c$ (sphere); $a = b > c$ (oblate spheroid, i.e. disk-shaped); $a = b < c$ (prolate spheroid, i.e. like a rugby ball) (Figure 1.10). Finally, if $a > b > c$, the solid is a scalene ellipsoid (i.e. it has three unequal sides).

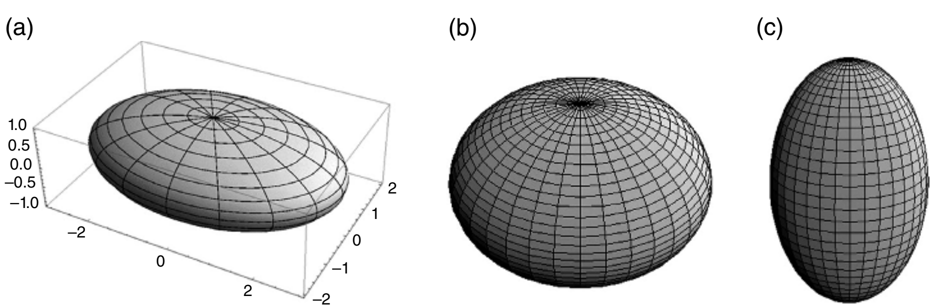


Figure 1.10 (a) Ellipsoid, (b) Oblate and (c) prolate spheroids. *Source:* Adapted from Wikimedia Foundation.

Scalene ellipsoids are frequently called "triaxial ellipsoids" the implication being that all three axes need to be specified to define the shape (Weisstein 2003).

As stated, if the volume of the solid is equal to the volume of a triaxial ellipsoid with intercepts *a, b, c,* and in addition, the diameter of the circumscribed sphere is the longest intercept *a* of the ellipsoid, then the degree of sphericity can be calculated as:

$$\text{Sphericity} = \sqrt[3]{\frac{\text{Volume of solid}}{\text{Volume of circumscribed sphere}}} = \frac{\sqrt[3]{abc}}{a} \tag{1.17}$$

or, the geometric mean diameter divided by the major diameter, where a is the longest intercept, b is the longest intercept normal to a, and c is the longest intercept normal to a and b (Mohsenin 1970). It is important to note that the intercepts need not intersect at a common point. Another definition of *sphericity* is given by $\frac{d_i}{d_c}$, where d_i is the diameter of the largest inscribed circle and d_c is the diameter of the smallest circumscribed circle (Mohsenin 1970).

Sphericity can also be defined as the ratio of the surface area of a sphere having the same volume as the object to the actual surface area of the object (Sahin and Sumnu 2006):

$$\phi = \frac{\pi D_p^2}{S_p} = 6\frac{V_p}{D_p S_p} \tag{1.18}$$

where ϕ is the sphericity, D_p is the equivalent or nominal diameter of the object (m), S_p is the surface area of the object (m^2), and V_p is the volume of the object (m^3) (Sahin and Sumnu 2006). The equivalent diameter is regarded as the diameter of a sphere that has the same volume as the spherical object before (Sahin and Sumnu 2006).

Another approach to estimating sphericity is:

$$\phi = \frac{\sum\left(D_i - D_{ave}\right)^2}{\left(D_{ave}N\right)^2} \tag{1.19}$$

where D_i is any measured dimension (m), D_{ave} is the average dimension or equivalent diameter (m), and N is the number of measurements (an increase in N increases the accuracy of the result; Sahin and Sumnu 2006). In accordance with this formula, if the sample sphericity value is close to zero, it can be considered spherical (Sahin and Sumnu 2006).

1.5.3 Average Projected Area and Sphericity of Hydrocolloid Beads

Another method of approximating the degree of sphericity of a convex body was established nearly 65 years ago when sizing machines were developed for fruit (Houston 1957). A novel criterion for size, the average projected area, was suggested, based on the theories of convex bodies. For such bodies:

$$\frac{V^2}{S^3} \geq \frac{1}{36\pi} \tag{1.20}$$

where V is the volume and S is the surface area of the convex body. A_c, the average projected area of the convex body, is one-fourth of the surface area. Substituting $4A$ for S in Eq. (1.20), and after some manipulation, we get:

$$A \le KV^{2/3} \tag{1.21}$$

In the case of a sphere, $K = \dfrac{9\pi}{16} = 1.21$, when equality in Eq. (1.21) is achieved. In other words, this method enables evaluating the degree of sphericity of a bead and checking how K changes when the bead is not spherical. A few further conclusions can be derived: the dimensionless K constant varies with the characteristic dimensions of the object; the variation of A_c for unrestricted orientation is too great for a satisfactory measure of volume, but this variation can be reduced to an acceptable level (Houston 1957).

A small number of manuscripts have dealt with roundness and sphericity of hydrocolloid beads. Indeed, they are in most cases small items; consequently, axial dimension measurements can be derived from the outlined projections of the bead. Tracings need to be made of both the maximum and minimum projected areas, and the axis dimensions can be derived from those drawings (Nussinovitch and Gershon 1996). Identical results can be achieved by shadowgraph (Mohsenin 1970). An approximation of the deviations of hydrocolloid beads from sphericity is essential in studies of mass and heat transfer. The sphericity of alginate beads was estimated by two techniques (Nussinovitch and Gershon 1996): a method initially developed for quartz grains, which expresses the shape character of a bead relative to that of a sphere of the same volume, and a method formerly established for convex bodies, which determines a dimensionless constant that relates surface area to volume. Deviations from sphericity were easily estimated by the former method. The difference between the two measures of bead sphericity was not more than 5%. Deviations from perfect sphericity were ~7% for the tested alginate beads under the examined conditions (Nussinovitch and Gershon 1996).

1.5.4 How Are Gels Shaped?

Gelling agents are used to produce different food product shapes. Cubes, spheres and noodle shapes are very common, and add visual charm to the dishes. It is preferable to set soft gels directly in the platter in which they will be served, as they are prone to tearing upon unmolding. It is also possible to set harder gels in serving dishes which might provide much visual appeal, particularly if glass serving dishes are used. It is easy to form gels by setting them in a block and then cutting them into the desired shapes. For this purpose, the container can be filled with gel to the final height and then the gel is cut into cubes with a knife. If harder gel is preferred, a cookie cutter (i.e. a tool to cut cookie/biscuit dough into a particular shape) can be used for a wide range of shapes. Sheets of elastic gels can set in a thin layer of not more than 3 mm thickness on a smooth plastic surface. This creates flexible sheets that can be wrapped over or around foods. Another common way to set artistically shaped gels is to use silicone or plastic molds. Ice cube trays that can be purchased in a wide variety of shapes and sizes might be used. For instance, hemispherical and spherical molds of dissimilar sizes can be utilized to manufacture interesting shapes. An additional remarkable option is the preparation of gel noodles, usually used as a garnish (see Section 1.9.1 for a detailed description of such a dish). Another shape with marked visual appeal is rounded gel pearls, or beads. There are numerous procedures to prepare these. The methodologies and more details about such shapes are provided in this section and Section 1.6 (see also https://www.amazingfoodmadeeasy.com/info/modernist-techniques/more/gelification-technique).

1.5.5 Silicone Molds to Modify Gel Shapes and Sizes

Siloxanes, frequently called silicones, are molecules with an oxygen–silicon backbone (Si-O-Si) in which each Si atom carries two organic groups (Rücker and Kümmerer 2015). Fluid siloxanes are used to form silicone elastomers or silicone rubbers through vulcanization, with the addition of crosslinking agents to link the linear polymers (Lassen et al. 2010). Silicone elastomers can be used in consumer goods such as diving masks and other scuba equipment, protective masks, earplugs, baking tins, consumer product packaging, showerhead membranes, soft-touch products (e.g. pencils), spatulas, etc., and for food packaging (fruit labels, bakery papers, wrappers for candy, chewing gum, meat and frozen food) (Lassen et al. 2010). Silicones can safely contact foods, as is the case with kitchenware such as baking molds, dough scrapers, or food packaging (Gross 2015).

Linear and cyclic volatile methyl siloxanes (VMSs) are chemicals with no natural source. VMSs are ubiquitous anthropogenic pollutants that have recently come under suspicion for potential toxicity and environmental persistence (Alton and Browne 2020). They have been extensively used in cosmetics, personal care products and coatings, among many others. As a result of their wide use, VMSs can be found in different environmental media, as well as in the human body (Fromme et al. 2019). The topic of siloxane in baking molds, emission to indoor air and migration to food during baking in an electric oven was studied (Fromme et al. 2019). Fourteen new silicone baking molds and three commercial metallic molds were used in different baking experiments. VMSs were measured in the indoor air throughout the baking process and at the edge and center of the finished cakes using gas chromatography–mass spectrometry. In addition, particle number concentration (PNC) and particle size distribution were measured in the indoor air. The conclusions of that study demonstrated that the silicone molds with the highest concentrations of cyclic VMSs were associated with distinctly higher concentrations of the compounds in indoor air. Using a mold for more than one baking cycle decreased the indoor air concentrations markedly. Samples collected from the edge of the cake had higher concentrations than samples from the center. The overall impression was that as a general rule, silicone molds should be used only after precleaning while strictly following the producers' temperature guidelines (Fromme et al. 2019).

Used as bakeware, silicone cooking molds do not need to be coated with oil; in addition, their flexibility allows easy removal of the baked foods from the mold. Silicone molds are microwave-safe, freezer-safe, and oven-safe. In 1979, the FDA declared that silicone was safe for use in cooking and everyday use. Changes in temperature do not cause food-grade silicone to leach into foods, despite common consumer concern (https://www.mindbodygreen.com/articles/is-silicone-toxic). The non-stick, bendable molds are available in numerous shapes and sizes. It is recommended to first check the molds with water to determine how much volume they will hold. Using this technique, it is possible to mold gels with suspended solids. To accomplish this, only a portion of the gel is cast. Then it is left to set until a soft texture is achieved, and the solid is carefully laid upon the soft gel and the remaining gelling fluid is cast. Thick gel sheets can be cast using a mold formed from pastry bars (Myhrvold et al. 2011). Silicone molds can be used to achieve differently shaped products. For example, spaghetti is a thin, long, round type of pasta, whereas linguine is thin, long and flat. To make gel "linguine," a thin gel sheet is cast in a mold. Once the gel has set, a pasta cutter can be used to cut the sheet into strips. Although, perfect gel spheres can be challenging to manufacture, silicone molds can be used to create them in various different sizes. To obtain gel spheres, the hot gel fluid formulation is poured into the cavities of the chosen silicone mold and allowed to set. Some gels require refrigeration, others set at room temperature after just a few minutes. The set spheres are then popped out of the mold (Myhrvold et al. 2011).

1.6 Miscellaneous Shapes and Sizes of Edible Hydrocolloid Products

1.6.1 Edible Hydrocolloid Gel Beads

Agar is a mixture of at least two polysaccharides –agarose (Figure 1.11), a neutral polymer, and agaropectin, a sulfated polymer (Nussinovitch 1997, 2010). Firm gel beads can be prepared by dropping, for example, an agar/agarose solution from a syringe into a cold oil bath. The gel solution is obtained by boiling in water for at least 1.3 minutes. In the kitchen, oil can be easily chilled by placing it in a bowl over ice water. The oil should be very cold, but not congealed. The dropping must be quick enough to eliminate setting of the fluid in the syringe. The droplets form spherical beads because oil and the water-based/hydrophilic gel do not mix. Thus, solid gel beads are produced. The set/gelled beads are then removed from the oil with a perforated spoon. To remove the oily residue from the surface of the gel beads, they should be rinsed with cold high-proof alcohol (Myhrvold et al. 2011). Agarose beads can be successfully manufactured in a single stirred vessel by emulsification of hot agarose solution and subsequent freezing/gelling of the aqueous drops into soft solid particles. The particle size and size distribution can be controlled by selecting an appropriate energy dissipation rate and/or surfactant concentration (Mu et al. 2005). Despite the fact that flow in a stirred vessel is transitional, the relationship between drop/particle mean size and energy dissipation rate is similar to that for turbulent flow (Baldyga et al. 2000). A different technique to make small frozen spherical beads is to dispense the gel base drop by drop into liquid nitrogen. This only works well for gels that remain stable after thawing (Myhrvold et al. 2011). Cold-set gel beads that have the flattened shape of lentils or split

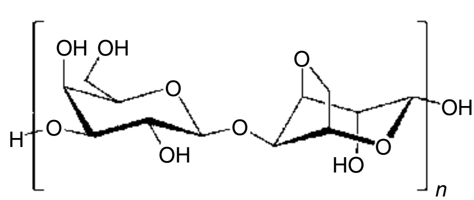


Figure 1.11 The structure of the repeating unit of an agarose polymer. *Source:* Yikrazuul/ Wikimedia Commons/Public domain.

peas can be prepared by dispensing gel droplets onto the chilled surface of a pan. Once they set, water is poured over the solidified gel droplets and they are easily dislodged using a silicone spatula; the water is drained, leaving these cold-set semisolid moieties (Myhrvold et al. 2011).

A widespread and simple method for producing beads is to crosslink an alginate solution. It is not surprising that this is the model system of choice for numerous encapsulations and for bead manufacturers. The manufacture of different alginates, and their chemical and physical properties have been reviewed in many textbooks and manuscripts (among them Davidson 1980; Nussinovitch 1997; Phillips and Williams 2000), and the reader is referred to these for further details. The vibrating nozzle technique can be used to produce a monodispersion of beads that are larger than 200 μm in diameter, depending on the application (Serp et al. 2000). Furthermore, their manufacture can be scaled up. In particular, reasonably high production rates, between 1 and 15 mL/min depending upon the desired bead size and polymer solution rheology, can be achieved, producing an alginate bead-size distribution of less than 5% (Brandenberger et al. 1997; Seifert and Phillips 1997).

1.6.2 Parameters to Be Considered Upon Formation of Beads Through Capillary Jet Breakage

The breakup of a liquid jet by applying vibration was proposed by Savart in 1833 and interpreted by Lord Rayleigh in 1878 as a resonance effect (Savart 1833; Lord Rayleigh 1878). A liquid jet preferentially breaks into droplets at a defined frequency which is a function of the jet diameter and the linear jet velocity. If all vibrations are eliminated except for the optimum frequency, quasi-monodispersed droplets are produced. Droplets as small as a few hundred micrometers and yields of liters per hour may be achieved. Lord Rayleigh (Figure 1.12) showed that the breakage takes place when the length of the jet is longer than its circumference (Lord Rayleigh 1878). For Newtonian and low-viscosity liquids, the optimum breakup wavelength, λ_{opt}, to obtain monodispersed droplets is given by:

$$\lambda_{\mathrm{opt}} = \pi\sqrt{2}\,d_{\mathrm{j}} \tag{1.22}$$

where d_{j} is the jet diameter. The frequency, f_{opt} to be applied is equal to:

$$f_{\mathrm{opt}} = \lambda_{\mathrm{opt}} U_{\mathrm{j}} \tag{1.23}$$

where U_{j} is the linear velocity of the jet corresponding to the flow rate:

$$F = \frac{\pi}{4} d_{\mathrm{j}}^2 U_{\mathrm{j}} \tag{1.24}$$

The volume of the droplets may be predicted by:

$$v = \frac{F}{f_{\mathrm{opt}}} = \frac{\pi}{6} d^3 \tag{1.25}$$

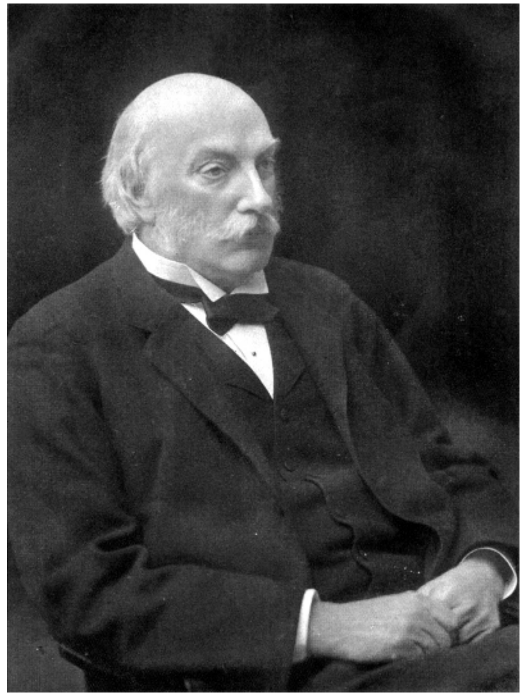


Figure 1.12 John William Strutt, 3rd Baron of Rayleigh, British physicist. *Source:* Unknown author/Wikimedia Commons/Public Domain.

and by combining these equations, one obtains:

$$d = \sqrt[3]{v\frac{6}{\pi}} = 1.89d_{\mathrm{j}} \tag{1.26}$$

Equation (1.26) predicts that the droplet size must be 1.89 times the jet diameter and independent of the frequency. Weber extended Eq. (1.22) to viscous liquids (Weber 1931):

$$\lambda_{\mathrm{opt}} = \pi\sqrt{2}\,d_{\mathrm{j}}\sqrt[2]{1 + \frac{3\eta}{\sqrt{\rho\sigma d_{\mathrm{j}}}}} \tag{1.27}$$

where η is the fluid viscosity, ρ is the liquid density, and σ is the surface tension. However, for usual encapsulation solutions (i.e. alginate solution, melts), the theoretical droplet size is affected by less than 1%. On the other hand, the jet diameter, d_{j}, is generally assumed equal to the internal nozzle diameter, d_{n} (Schneider and Hendricks 1964). However, at the exit of the nozzle, the jet is subjected to pressure relaxation, leading to jet expansion that can be expressed by (Brandenberger et al. 1997):

$$\frac{d_{\mathrm{j}}}{d_{\mathrm{n}}} = 4.33W_{\mathrm{e}}^{-0.337} \tag{1.28}$$

with

$$W_{e_{\mathrm{n}}} = \frac{\rho d_{\mathrm{n}} u^2}{\sigma} \tag{1.29}$$

where W_e is the Weber number and W_{e_n} is the Weber number related to flow inside the nozzle. Recent experiments recorded droplet formation and jet breakup using a fast camera. The experimental data well fit Lord Rayleigh's equation if the jet expansion at the exit of the nozzle was considered. In addition, it appeared that good transmission of the vibration (i.e. by a metallic membrane) is needed to guarantee low dispersion (Chevallier et al. 2017).

1.6.3 Bead Shape and Its Improvement

The shape of an object in a space is the part of that space occupied by the object, as determined by its external boundary. Another definition of shape is the geometrical information from an object that remains when location, scale and rotational effects are filtered out (Kaye 1993). The sphere is one of the most common shapes in nature (Musser and Burger 1997), probably due to its ability to enclose the greatest volume for a given surface area. Most beads are produced in a sphere-like shape. Archimedes (287–212 BCE) found that the surface area (volume) of a sphere is two-thirds the surface area (volume) of the smallest cylinder containing that sphere. Figure 1.13 shows a sphere of radius r contained within a cylinder with radius base r and height $2r$. The surface area of the cylinder is $2\pi r^2 + 2\pi r(2r) = 6\pi r^2$. Based upon Archimedes' observation, the formula for the surface area of a sphere of radius r is $\frac{2}{3}\left(6\pi r^2\right) = 4\pi r^2$. The volume of the sphere is $\frac{2}{3}\left(2\pi r^3\right) = \frac{4}{3}\pi r^3$. Of course, the r in $4\pi r^2$ is squared, a unit of area, whereas the r in $\frac{4}{3}\pi r^3$ is cubed, a unit of volume (Musser and Burger 1997). The shape of a bead can be described by borrowing terms from different fields. These include: round – approaching spheroid; oblong – vertical diameter greater than the horizontal diameter; ovate – egg-shaped; obvate – inverted ovate;

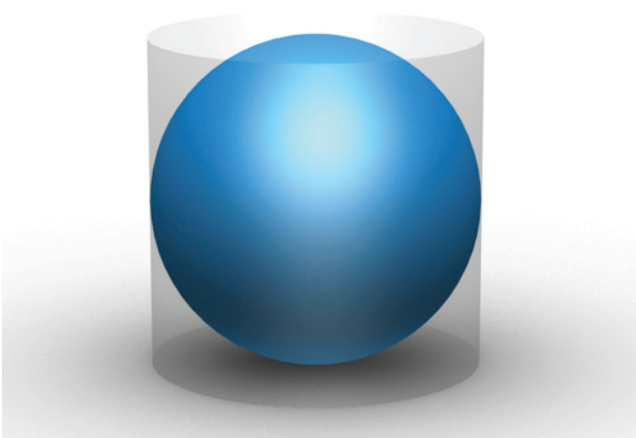


Figure 1.13 A sphere of radius r contained within a cylinder with radius base r and height $2r$. *Source:* André Karwath aka/Wikimedia Commons/CC BY-SA 2.5.

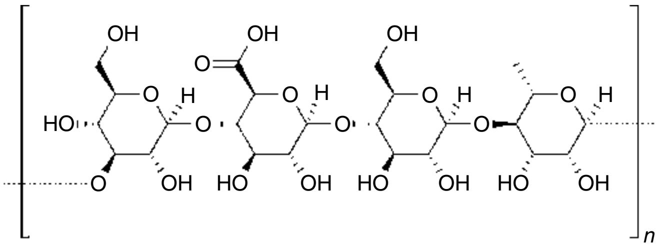


Figure 1.14 Chemical structure of gellan gum. *Source:* Edgar181/Wikimedia Commons/ Public domain.

elliptical – approaching ellipsoid; truncate – having both ends squared or flattened; ribbed – in cross section, sides are more or less angular; regular – horizontal cross section approaches a circle; irregular – horizontal cross section departs considerably from a circle (Mohsenin 1980).

Gelling agents [i.e. agar–agar, alginate, carrageenan, gellan, and low-methoxyl pectin (LMP)] can be used to create various gel shapes. For instance, κ-carrageenan's property of being easily induced into a gel form by contact with metal ions, amines, amino acid derivatives, and water-miscible organic solvents was used to tailor the gel into various shapes, such as beads, cubes and membranes (Tosa et al. 1979). Numerous bead manufacturers want to generate beads in a spherical or sphere-like shape. For instance, gellan beads can be formed in a spherical shape, enabling mathematical modeling studies of their spherical geometry. To manufacture such shapes, a dispersion of gellan gum (Figure 1.14) was extruded into a solution containing a mixture of calcium and zinc ions (counterions). By changing the experimental variables, for instance pH, of the counterion solution, process variables could be optimized to achieve control over the bead size and morphology (Agnihotri et al. 2004). Different bead shapes sometimes result from the ingredients used in the manufacturing process, as well as the entrapped moieties. Dropping a 3.5% κ-carrageenan-containing papain solution into 0.5 M potassium chloride using the ionotropic gelation method, with a hardening time of 20 minutes, it was possible to obtain beads characterized by a spherical disc shape with a collapsed center, and an absence of aggregates (Sankalia et al. 2006a). Dissimilar combinations of water-soluble polymers and production techniques can lead to control of bead size, shape and other parameters (Agrawal et al. 2004). For instance, beads containing chitosan, fine-particle ethylcellulose, HPMC and caffeine were manufactured. Spherical beads with good mechanical properties could be created without microcrystalline cellulose. Furthermore, beads with high sphericity could be obtained with high chitosan content, and low HPMC content, water content, spheronizer speed and extruder speed (Agrawal et al. 2004).

A study on shape improvement of prepared alginate beads described injection of an aqueous solution of 2% alginate into a novel solvent consisting of layers of hexane and *n*-butanol, *n*-butanol with 1% $CaCl_2$, or *n*-butanol with 2% $CaCl_2$ in water. Beads of up to 3.5 mm in diameter obtained with this method had a roundness which was similar or up to 5% better than comparable beads prepared by just dropping alginate solution into a $CaCl_2$ hardening bath (Buthe et al. 2004). In addition, the novel solvent-based method allowed for highly reproducible preparation of alginate beads with precisely predictable sizes.

The biggest beads obtained with this method were 9 mm in diameter. Thus, with the solvent-based preparation of alginate beads, it was possible to obtain beads of exactly the type needed for specific analytical purposes (Buthe et al. 2004). Another study described the production of alginate hydrogel microbeads of various shapes with narrow size distributions (94–150 μm) in non-silanized/silanized poly(dimethylsiloxane) devices (Tan and Takeuchi 2007). The method combined an internal gelation method with T-junction droplet formation in a microfluidic device (Okushima et al. 2004). The use of calcium-carbonate nanoparticles enabled an internal gelation method for microscale production. The method allowed easy control over bead size by varying flow parameters, and better monodispersity and control of the shape of the hydrogel beads compared to conventional external gelation methods performed in microfluidic devices (Tan and Takeuchi 2007). Modifications to the design (e.g. shortening the channel length) or switching to devices that can withstand higher pressures or silicon glass-based devices may enable the production of smaller hydrogel beads (Takeuchi et al. 2005). Another report claimed that the optimal conditions for calcium-alginate bead sphericity were a concentration of 2.24% sodium alginate, a flow rate of 0.059 mL/s for the sodium-alginate solution, and a 459 rpm rotation for the calcium-chloride solution. The predicted and experimental bead sphericities under optimal conditions were 94.5 and 96.7%, respectively, showing close agreement (Woo et al. 2007). Immersion in hot water slightly decreased bead size and rupture strength. Sodium-chloride treatment increased bead size and decreased rupture strength. While the pH of the calcium-chloride solution had little effect on bead sphericity, bead size and gel strength decreased with longer times in each solution with different pH. Beads coated with pectin and glucomannan showed no significant changes in sphericity, but their sizes decreased with time. The coated beads showed higher rupture strengths than the non-coated ones (Woo et al. 2007).

Elongation ratio (ER) – the quotient of the bead's length to width (Wong and Nurjaya 2008) – can be calculated to characterize bead shape. An ER of unity represents a perfect sphere, while higher values represent greater elongation or more divergence from a spherical shape (Das and Ng 2010). Almost all of the tested calcium-pectinate beads (except the dried beads prepared with 3% pectin), which included the following parameters: crosslinking with calcium chloride at a concentration of 2.5–20.0%, crosslinking pH of 1.5–5.5, crosslinking time of up to 24 hours, pectin concentration of 3–6%, and a pectin-to-drug ratio of 1 : 1 to 4 : 1, were spherical in shape (i.e. $ER < 1.25$) (Das and Ng 2010). In the case of κ-carrageenan, the sphericity of the formed beads was calculated as the ratio of the surface area of an equivalent sphere to the surface area of the bead, which in the case of oblate spheroids can be measured (Keppeler et al. 2009). When the conventional bead manufacturing method of dripping was used, highly spherical beads with a homogeneous surface were observed within a carrageenan concentration range of 1–6% (w/w). Higher carrageenan concentrations did not produce spherical beads, probably due to the high viscosity of the dropping solution. By adjusting the dripping rate (10 drops/min), the carrageenan solution temperature (50 ± 4 °C) and the distance between the syringe tip and the hardening solution (optimal at 2 cm), a constant bead size could be obtained for the entire range of carrageenan concentrations, with a diameter of 3.1 ± 0.1 mm and excellent sphericity. An increase in carrageenan concentration led to a significant increase in dropping solution viscosity and to larger beads (Sankalia et al. 2006b). Nevertheless, the bead size was not significantly different among concentrations used, in agreement with a previous report (Sipahigil and Dortunc 2001). The explanation for this phenomenon is probably the constant surface tension of the dripping solution, which leads to homogeneous bead drops independent of carrageenan concentration in the solution (Keppeler et al. 2009).

1.6.4 Shape and Size of Hydrocolloid Beads and Their Estimation

Precise assessments of shape and size are vital in the study of hydrocolloid beads. Most of them are produced in a spherical shape. However, deviations from sphericity occur, with spheroid and ellipsoid beads being quite common (Nussinovitch 2010). Size is a measure of how big or small a bead is. It is easier to specify the size of a spherical or ellipsoid-shaped bead; for irregularly shaped beads, the term size must be arbitrarily defined (Nussinovitch 2010). Beads can be formed in the millimeter, micrometer or nanometer size ranges. Overall, particle size can be determined by sieve analysis, passage through an electrically charged opening or settling rate (Sahin and Sumnu 2006). Numerous techniques have been developed for bead manufacture. These techniques include dripping (Walsh et al. 1996; Romo and Perez-Martinez 1997), emulsification and coacervation (Poncelet et al. 1993, 1994; Green et al. 1996), rotating-disc atomization (Bégin et al. 1991; Ogbonna et al. 1991), air jet (Klein et al. 1983; Levee et al. 1994), atomization (Siemann et al. 1990), electrostatic dripping (Bugarski et al. 1994; Halle et al. 1994; Poncelet et al. 1994), mechanical cutting (Prüsse et al. 1998), and the vibrating nozzle technique (Ghosal et al. 1993; Brandenberger et al. 1997; Seifert and Phillips 1997). Another common technique for manufacturing spherical polymer beads is suspension polymerization. In this process, minute droplets of monomer stabilized by small amounts of surface-active polymers are suspended in a continuous non-solvent medium, most commonly water, and polymerization is carried out by the addition of monomer-soluble initiators (O'Connor and Gehrke 1997). Suspension-crosslinking technique was used to yield thermally responsive gels of HPMC in a spherical form. The spherical beads had diameters ranging from 500 to 3000 μm. Bead size commonly decreased with the use of a larger impeller, swinging at high stirring speeds, or a lower phase ratio. As bead size decreased, the size distribution also narrowed (O'Connor and Gehrke 1997). Some of these methods suffer from limitations, particularly with respect to difficulties in achieving the simultaneous production of beads at a high production rate with a satisfactory level of material utilization under mild and non-toxic conditions, or under completely sterile conditions, in the ability to scale up the process, and in particular, in obtaining beads with a narrow size distribution (Nussinovitch 2010).

1.7 Assorted Specially Shaped and Sized Hydrocolloid Foods

1.7.1 Ham Consommé with Alginate Melon Beads

Melon juice beads are an example of a crosslinked gel product that can be included in a consommé. This recipe was created by Ferran Adrià i Acosta, the head chef of El Bulli restaurant and considered one of the best chefs in the world (https://en.wikipedia.org/wiki/Ferran_Adri%C3%A0). To produce melon juice beads, 500 g of melon juice (extracted from

800 g of fresh melon) were mixed with 0.4% sodium alginate, until the hydrocolloid dissolved. The blend was vacuum-sealed to remove trapped air and transferred into a syringe. For the crosslinking solution, calcium-chloride salt (2.5 g) was dissolved in 500 g water. The melon–alginate fluid was dropped into the calcium-chloride bath. The resulting beads were removed from the bath after three minutes. Then, the crosslinked beads were rinsed in a clean water bath and 10 g was added to champagne flutes that included 50 g each of cold ham consommé. The beads remained suspended in the product (Myhrvold et al. 2011, p. 48).

1.7.2 Extruded Gel Noodles

Ferran Adrià's revolutionary cooking has made El Bulli the most famous restaurant in the world (McInerney 2010). One of his achievements is extruded gel noodles. In general food-grade tubing is filled with liquid gel and after setting by placing the tubing in a cold bath, air (or gas) is used to push out the spaghetto (i.e. the singular form of spaghetti). For this, a bicycle pump, whipping siphon charged with nitrous oxide and the like can be used (Myhrvold et al. 2011). The reader is also referred to Section 1.9.

1.7.3 Cold Gels

Cold gels can have different shapes. Hydrocolloids for manufacturing such gels could be vegetative-originated gums, such as agar, carrageenan, gellan and LMP, and gelatin, which originate from animals. To prepare a cold gel, selection of texture and firmness is important, ranging from elastic to brittle or rubbery, and from very soft to very firm. Then the gelling agent needs to be chosen. Many of these formulas use a mixture of two or more gelling agents. The quantities of the gelling agents are measured relative to the weight of the liquid, followed by dry blending of the gelling agents, and dispersing them into the cold flavorful liquid. Hydration is fully achieved by blending while heating to ensure that the gelling agents are evenly distributed during hydration. The gel is then cast in a mold (Myhrvold et al. 2011).

1.7.4 Knot Foie

The Ashley Book of Knots, an encyclopedia of knots written and illustrated by the American sailor and artist Clifford W. Ashley, was first published in 1944. This book was written over 11 years, and contains thousands of numbered entries and about 7000 illustrations. It remains one of the leading wide-ranging books on knots (Ashley 1944). Sixty years later, Wylie Dufresne discovered that knots (Figure 1.15) can also be used in foods. Wylie Dufresne is a leading American proponent of molecular gastronomy, and the creator of the magnificent dish knot foie (https://en.wikipedia.org/wiki/Wylie_Dufresne). In 2007, Dufresne stated that the addition of hydrocolloid gums to numerous products can create products such as fried mayonnaise and foie gras that can be tied into a knot (Chang 2007). He also mentioned that his reading material included "Water-Soluble Polymer Applications in Foods" and "Hydrocolloid Applications: Gum Technology in the Food and Other Industries," both written by A. Nussinovitch, one of the authors of this book (https://www.starchefs.com/about_us/press_kit/images/NewYorkTimes110607.pdf; https://blog.ideasinfood.com/

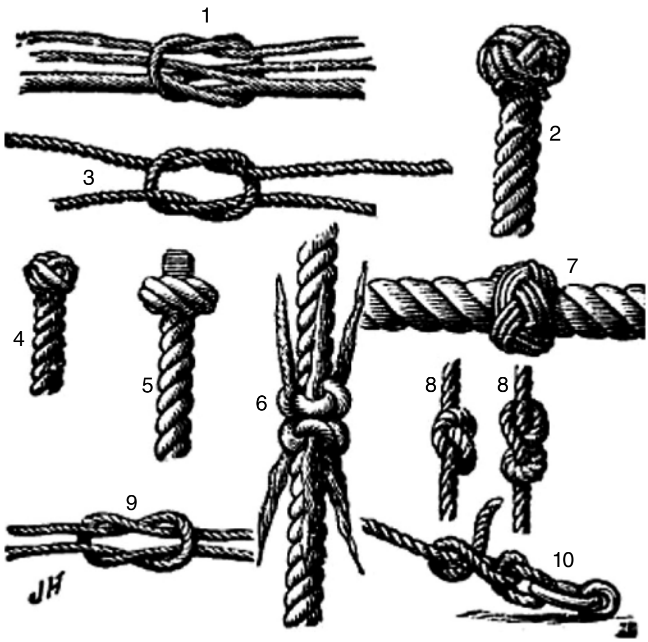


Figure 1.15 Some knots. *Source:* Nordisk Familjebok/Wikimedia Commons/Public Domain.

ideas_in_food/2007/07/not-our-idea.html). In this recipe, the hydrocolloids konjac mannan, agar and xanthan are used. The hydrocolloids are dry blended with the warm foie gras which was first heated to 82 °C to melt the torchon fat and split the terrine. Then water heated to 80 °C and a beaten egg yolk are added to the foie gras, and the mixture is blended until fully incorporated. The mixture is poured into a non-stick mold and refrigerated for about three hours to set. The set product is cut into strips which are tied carefully into a knot, paying attention not to break them. The full recipe and instructions for garnishing can be found in Myhrvold et al. (2011, p. 144).

1.7.5 Shapes of Gummy Worms

Fishermen use mold systems to produce artificial lures from liquid plastic. These molds come in numerous shapes and sizes, and are suitable for casting gels. If metal molds are used, they require a covering (sprayed or wiped) of a very thin film of cooking oil (Myhrvold et al. 2011).

1.7.6 Gel Films

Gel films can be created by casting the gel solution on an acetate sheet, petri dish or silicone mat. Acetate sheets are a flexible, transparent, ultra-versatile material with an extensive variety of purposes that are also suitable for chocolate and confectionery work. Very thin gel layers can be used to mimic other foods, e.g. a cloudy gel that includes coconut milk can mimic a slice of cheese; and by using skill, creativity and technique, it is possible to create films that look like lacy veils, or fruit-based gels that resemble stained glass (Myhrvold et al. 2011).

1.8 Foods for the Elderly

Hydrocolloids are used to control and adjust food texture. It is essential to identify how these polysaccharides affect swallowing behavior when planning foods for the elderly. Since the texture of foods is influenced by aroma and taste, and vice versa, a familiarity with the relationship between texture and flavor release is critical in manipulating foods to diminish the risk of aspiration (Nishinari et al. 2016). The difficulty in tailor-making foods for the elderly is the fact that knowledge in various research fields, such as food rheology, oral physiology, processing and psychology, is required to make any significant contribution to this endeavor (Nishinari 2006; Chen 2009). The number of elderly suffering from difficulties in chewing and deglutition (i.e. the action or process of swallowing) is growing. As a result, pneumonia due to aspiration is currently the third largest cause of death in Japan (Nishikubo et al. 2015). Dysphagia (i.e. difficulty or discomfort in swallowing, as a symptom of disease) also results in undernourishment, and conversely, malnutrition causes dysphagia (Via and Mechanick 2013; Carrión et al. 2015).

Enzyme technology was used to develop more or less soft foods, easily crushed between the tongue and palate (Nakatsu et al. 2014; Takei et al. 2015). Appearance, flavor and texture were chief attributes (Delwiche 2012; Spence et al. 2016) for the palatability of these food products, as their shape, size and color needed to be attractive to increase the elderly's desire for food, thereby improving their undernourishment and quality of life. Variety is also essential for good taste (Nishinari et al. 2016).

Milled foods are commonly used for the elderly and/or individuals with trouble masticating. Heated and pressurized gels were found to be appropriate for this purpose since they are deformable and adaptable for dysphagic patients (Tokifuji et al. 2012). For such meat gels, the transit time in the vallecular area was short. The epiglottic vallecula is a depression just behind the root of the tongue in the medial and lateral glossoepiglottic folds (i.e. a mucous membrane fold that extends from the margin of the epiglottis to the pharyngeal wall and base of the tongue on each side, forming the lateral boundary of the epiglottic valleculae) in the throat. Very little food residue was found in the oropharynx (i.e. the part of the throat at the back of the mouth behind the oral cavity) (Tokifuji et al. 2012, 2013). Not much mastication effort is required for minced foods; nevertheless, food fragments disintegrate, and the establishment of a coherent bolus becomes difficult, leading to the possibility of aspiration (Nishinari et al. 2016). It was remarkably demonstrated that for thinly sliced cucumber, cutting into smaller parts does not automatically cause a decrease in chewing time (Kohyama et al. 2003). For agar gel cubes, the size distribution was more important than the actual dimensions of the gel pieces for bolus formation (Kitade et al. 2013). Furthermore, the gel bolus was easier to assemble with gel pieces of various sizes than with those of similar sizes. It was also demonstrated that the mastication effort was not necessarily less for smaller gels (Kitade et al. 2014), and that the elapsed time from the end of mastication to swallowing as a function of chewing time indicated that structural breakage by mastication was effective for the gel cubes that were up to 20 times larger than gels with smaller sizes in the initial stage of mastication (Kitade et al. 2014).

1.8.1 Effects of Hydrocolloid Addition on the Mastication of Minced Foods

The effects of xanthan gum, locust bean gum and guar gum on the mastication of boiled minced carrots or mackerel fish were studied (Yoshimura et al. 2003, 2004). Addition of these thickening agents reduced both the time and number of chews of the minced foods. The age of the panel influenced the results. The young panel favored minced food with 0.6% xanthan gum, while those with 2.0% xanthan were not highly rated due to the marked residual that had to be swallowed. The minced foods fortified with the thickening agents were judged by the elderly panel as viscous, easy to swallow and tasty. Thus, the viscoelasticity of the thickening agents enhanced the palatability of the minced foods, particularly for the elderly panel (Yoshimura et al. 2003, 2004). The effect of xanthan gum with different intrinsic viscosities on the mastication properties of minced (0.5 cm) and cubed (1.0 cm) steamed carrots was studied (Yoshimura et al. 2005). With young panelists, the number of chews and the duration of chewing for these carrots were not considerably different; nevertheless, the inclusive evaluation of the carrots mixed with xanthan at the highest intrinsic viscosity was lowest (Yoshimura et al. 2005). Another report (Ichimura et al. 2000) described that patients who suffer from aspiration (i.e. when something you swallow "goes down the wrong way" and enters your airway or lungs) favored thickened fluid foods, whereas individuals without this problem preferred less viscous liquid foods (Ichimura et al. 2000). Xanthan gum with the lowest intrinsic viscosity was also used with cooked carrots served to an elderly panel (Yoshimura et al. 2005). They found that the addition of xanthan gum improved mouthfeel and made the carrots easy to swallow. If members of this panel had their natural teeth or partial dentures, they suggested that minced carrots (0.5 cm) with the addition of xanthan gum were easier to chew. Those members with full dentures were suggested that cut carrots (1.0 cm) were best for chewing, the minced carrots being too small. It was concluded that the condition of the teeth was important in the mastication of minced foods for the elderly panel members (Yoshimura et al. 2005).

The effects of mixed polysaccharides – xanthan/high acyl gellan – as viscosity-forming agents to control the consistency of steamed minced carrots was also studied. The young panel favored the addition of xanthan gum on its own. The elderly panel members preferred mixed hydrocolloids because they felt that they decreased the number of chews and duration of chewing; they felt that use of these mixed thickening agents results in a more coherent bolus. In addition, the number of chews increased with deteriorating dental condition, meaning that they had to invest extra effort (Yoshimura et al. 2008). In brief, addition of viscosity formers to minced foods can lessen the number of chews and chewing duration, convert the minced foods into a more coherent mass and make the mastication more effective. For more efficient mastication, the size of each fragment should not be too small (Yoshimura et al. 2008).

1.8.2 Hydrocolloids for the Design of Food for the Elderly

Starch is largely used as a viscosity-forming agent in numerous commercial items for consumption (Nishinari et al. 2016). Since dispersed starch can exhibit thixotropic behavior (i.e. the apparent viscosity decreases with time of shearing but the change is reversible) and its viscosity changes throughout storage, it is difficult to use it for handling the viscosity of products for treatment of dysphagia. Solutions of guar gum and xanthan do not retrograde (like the starch dispersion) and therefore could serve for such thickening purposes (Nishinari et al. 2016).

A xanthan-based solution (4.1% w/w) demonstrated shear-thinning behavior over a wide range of experimental shear rates, i.e. between 0.03 and 1000 per second. The xanthan solution showed the highest viscosity at the lowest shear rate and the lowest viscosity at the highest shear rate. Similarly, solutions of guar gum (2.0 and 2.6% w/w) exhibited shear thinning (Nishinari et al. 2016). These solutions also demonstrated identical steady shear viscosity at 50 per second but dissimilar shear-thinning performance. A shear rate 50 per second was chosen because it was strongly believed to be the shear rate in the oral cavity, despite much debate on this value (Nishinari et al. 2016). Shear-thinning occurrence depended on the polydispersity Mw/Mn. Mn is the number averaged MW (molecular weight), and Mw is the weight averaged MW of the hydrocolloid (Nishinari et al. 2016). Those solutions served in a videofluorographic (VF) observation of 32 patients swallowing different liquids (Nishinari et al. 2016). The objectives of VF swallowing studies (VFSSs) are both diagnostic and therapeutic (Palmer et al. 1993). A comprehensive narrative of the VFSS method includes the position of the patient, the foods offered, the views achieved, amendments of ordinary feeding and swallowing behavior, a standardized set of interpretations, and reporting the results (Palmer et al. 1993). The VFSS does not automatically conclude when a patient aspirates. In fact, the purpose of the test is an overall assessment of aspiration, and the effects of maneuvers designed to reduce it. Modifications of feeding and swallowing are tested empirically throughout the VFSS. The amendments consist of therapeutic and compensatory techniques that may advance the patient's well-being and swallowing efficacy (Palmer et al. 1993). The results of the VFSS (Nishinari et al. 2016) demonstrated that for 32 performed observations, the ratio of aspirations was 4/32 for 4.0% xanthan, 5/32 for 2.0% guar gum and 7/32 for 2.6% guar gum solutions. The viscosity at the lower shear rate appeared to be more important rather than that at 50 per second or higher shear rate. The likelihood of aspiration seemed to decline with growing viscosity at lower shear rate. The authors also concluded that the number of observations was not sufficiently high, and that this hypothesis should be confirmed by a larger number of data in the future (Nishinari et al. 2016).

1.9 Demonstrating the Use of Hydrocolloids in Controlling Food Size and Shape

The use of hydrocolloids in controlling the shape and/or size of various products is demonstrated by a few examples and photographs. Pasta is a food that comes in various different shapes and sizes (roughly 350 different types of pasta worldwide). Chefs use these different shapes and sizes for diverse purposes, as some pasta shapes hold some types of sauce better than others. Spaghetti is America's favorite pasta shape. It can be used with nearly any variety of sauce in pots or stir-fried dishes. Spaghetti is a long, thin, solid, cylindrical pasta (https://www.dictionary.com/browse/spaghetti). It is a main food in traditional

Italian cuisine. Similar to other pasta, spaghetti is prepared from milled wheat and water, sometimes supplemented with vitamins and minerals. Italian spaghetti is characteristically prepared from durum wheat (Chihak 2020). Due to its popularity, it is not surprising that chefs have tried to use gelling agents to mimic the shape and size of spaghetti (http://lilrizzos.blogspot.com/2015/01/why-does-pasta-come-in-so-many.html).

Figure 1.16 demonstrates the preparation of agar spaghetti. The gelling cooks at the restaurant ElBulli, who create appetizing gels in noodle form, designed this procedure. Briefly, food-grade tubing is filled with a fluid gel composition and then left to set. Once ready to serve, air is forced into one end of the tube, extruding a long strand of spaghetti. A peristaltic pump can accelerate the process and increase the yield (Myhrvold et al. 2011). Agar was chosen as a gelling agent for this recipe due to its high gelling hysteresis, that is, the difference between gelling (~38 °C) and melting (~85 °C) temperatures (Nussinovitch and Hirashima 2014). This difference allows mixing the ingredients into the gelling solution before it sets. In addition, there is a marked dependence of gel melting point and sol setting point on the concentration of different agars, raising the importance of choosing a suitable agar type and concentration for a well-defined task (Davidson 1980; Kojima et al. 1960).

Being one of the most common shapes in nature (https://www.mathnasium.com.hk/2015/01/math-in-nature-perfect-spheres), ball-shaped foods are very popular and many

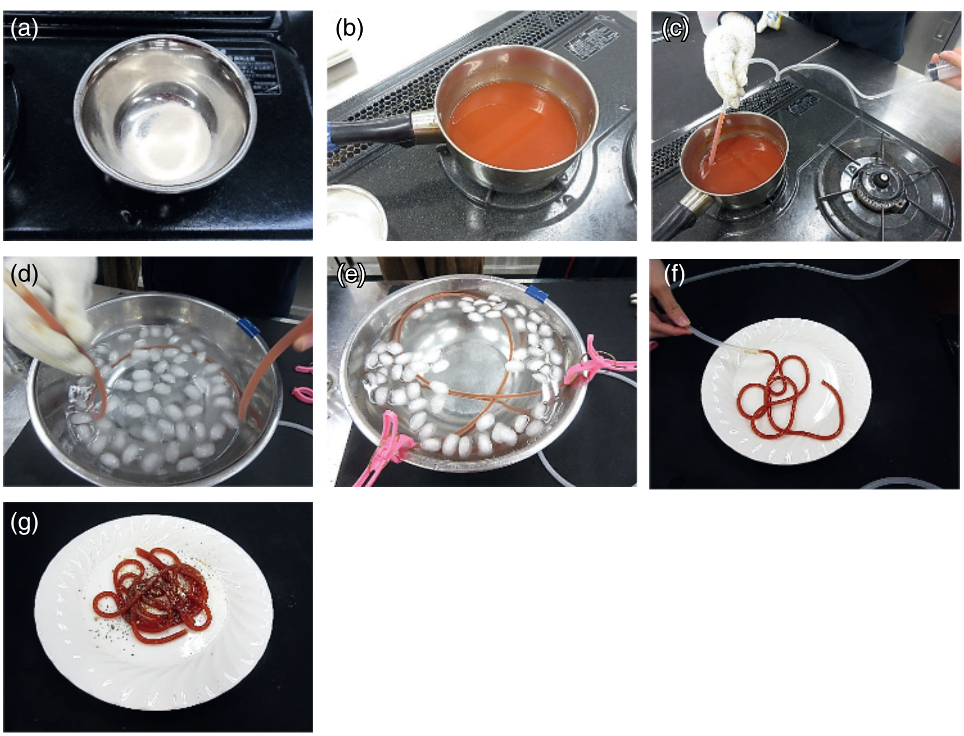


Figure 1.16 Agar spaghetti. (a) Agar–agar powder. (b) Tomato soup. (c) Drawing tomato soup by syringe into attached silicone tube, (d) cooling the silicone tube filled with the tomato soup, (e) cooling the silicone tube using clothespins, (f) extruding the jelly. (g) Serve.

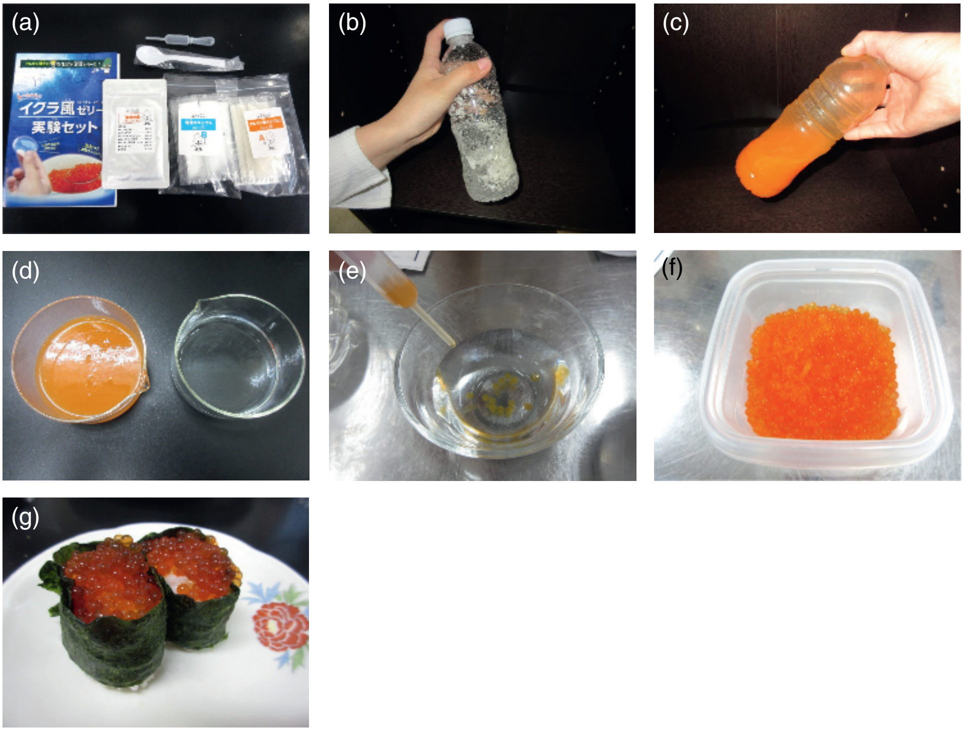


Figure 1.17 Comercial experimental set for producing artificial salmon roe. (a) Ingredients in commercial set. (b) Shaking the sodium alginate aqueous dispersion, (c) adding orange food coloring. (d) The two solutions. (e) Dropping the sodium-alginate solution into the calcium-lactate solution. (f) Artificial salmon roe. (g) Artificial salmon roe sushi.

foods are spherical. A few examples of spherical foods are eggnog popcorn balls, feta-stuffed falafel, boudin balls, cake pops, cinnamon-oat truffle treats, the turducken of cheese balls, tomato–basil arancini, chevré truffles, and brigadeiros, to name a few (https://www.chowhound.com/food-news/179944/have-a-ball-spherical-food-we-love/). Therefore, it is not surprising that chefs have tried to mimic the shape, size, hue and texture of the spherical salmon roe (i.e. salmon eggs). Figure 1.17 demonstrates the preparation of artificial salmon roe using an experimental set that is marketed in Japan by the Kimica Corporation. Alginate was chosen for this preparation because it forms a gel with a number of divalent cations (McDowell 1960). Calcium is particularly suited to food purposes because it is non-toxic. Spontaneous crosslinking takes place via carboxyl groups by primary valences and via hydroxyl groups by secondary valences (Nussinovitch 1997). It is important to note that when the colored alginate drops fall into the setting bath (which usually includes calcium chloride or calcium lactate), their surface starts to gel (i.e. becomes crosslinked). Rapid removal of the formed spheroids from the calcium setting bath leaves us with droplets of liquid surrounded by a membrane. If the formed spheres are left for a longer time in the setting bath, the whole bead solidifies. Obtaining "real" liquid-core beads requires another technique (Peschardt 1946), eventually dubbed reverse spherification (Myhrvold et al. 2011).

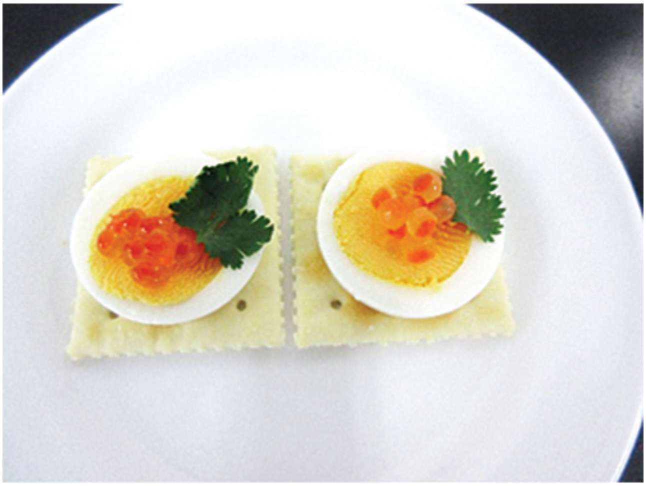


Figure 1.18 Real salmon roe (left) and commercial artificial salmon roe (right).

Figure 1.18 presents the similarities between real and artificial salmon roe. The shape, size and appearance of the products are the same, and the artificial roe are quite appealing, as well as costing much less.

1.9.1 Agar Spaghetti

(Serves 5)

3 g agar–agar powder (Figure 1.16a)
250 g tomato soup (Figure 1.16b, *Hint 1*)
Syringe (50 mL), silicone tube (4 mm diameter, 1–2 m length)
Cheese powder, herbs (optional)
pH = 3.98

For preparation, see Figure 1.16

1) Add agar–agar powder to tomato soup, and heat at 90–100 °C until completely dissolved.
2) Attach silicone tube to the syringe, and fill it with the agar tomato soup mixture (Figure 1.16c).
3) Remove the silicone tube from the syringe, and put it in a bowl of ice water for 10 minutes (Figure 1.16d and e, *Hint 2*).
4) Fill the syringe with air, attach the cold tube with the set agar jelly and extrude the jelly (Figure 1.16f).
5) Garnish with cheese powder and herbs (Figure 1.16g).

Preparation hints:

1) If there are solid lumps in the soup, strain them out. You can make tomato soup using soup stock, salt, pepper, sugar, etc.
2) Use clothespins to prevent the tube ends from sinking (Figure 1.16e).

1.9.2 Commercial Experimental Set to Produce Artificial Salmon Roe

(1 experimental set) (Figure 1.17a, *Hint 1*)

2 g sodium alginate (Figure 1.17a, right, orange package A)
2 g calcium lactate (Figure 1.17a, second from right, blue package B)
Orange food coloring (Figure 1.17a, third from right)
Dropper, spoon
Tap water

For preparation, see Figure 1.17

1) Put 200 mL tap water in a plastic bottle, add sodium alginate, close the lid, and shake the bottle (Figure 1.17b) until the lumps disappear.
2) Add orange food coloring to the sodium-alginate solution (1), shake the bottle (Figure 1.17c), and pour the solution into a bowl (Figure 1.17d).
3) Pour 200 mL tap water into another plastic bottle, add calcium lactate, close the lid, and shake it.
4) Pour the calcium-lactate solution (3) into another bowl (Figure 1.17d).
5) Suck the sodium-alginate solution (2) with a dropper, and drop one by one into the calcium-lactate solution (4) (Figure 1.17e).
6) Scoop out the artificial salmon roe (Figure 1.17f, *Hint 2*).

Preparation hints:

1) Made by Kimica Corporation (https://kimica-algin.com/, https://www.kimica.jp/ikurajelly/).
2) Eating suggestion: marinate the artificial salmon roe in soy sauce and sugar, and use for sushi (Figure 1.17g).

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