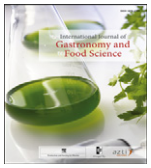

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Sous vide cooking: A review

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Abstract

Sous vide is a method of cooking in vacuumized plastic pouches at precisely controlled temperatures. Precise temperature control gives more choice over doneness and texture than traditional cooking methods. Cooking in heat-stable, vacuumized pouches improves shelf-life and can enhance taste and nutrition. This article reviews the basic techniques, food safety, and science of sous vide cooking.

Keyword: Sous vide cooking

Introduction

Sous vide is French for "under vacuum" and sous vide cooking is defined as "raw materials or raw materials with intermediate foods that are cooked under controlled conditions of temperature and time inside heat-stable vacuumized pouches" (Schellekens, 1996).

Food scientists have been actively studying sous vide processing since the 1990s (cf. Mossel and Struijk, 1991; Ohlsson, 1994; Schellekens, 1996) and have mainly been interested in using sous vide cooking to extend the shelf-life of minimally processed foods—these efforts seem to have been successful since there have been no reports of sous vide food causing an outbreak in either the academic literature or outbreak databases (Peck et al., 2006). Chefs in some of the world's top restaurants have been using sous vide cooking since the 1970s but it was not until the mid-2000s that sous vide cooking became widely known (cf. Hesser, 2005; Roca and Brugués, 2005); the late-2000s and early-2010s have seen a huge increase in the use of sous vide cooking in restaurants and homes (cf. Baldwin, 2008; Keller et al., 2008; Blumenthal, 2008; Achatz, 2008; Norén and Arnold, 2009; Baldwin, 2010; Potter, 2010; Kamozawa and Talbot, 2010; Myhrvold et al., 2011).

Sous vide cooking differs from traditional cooking methods in two fundamental ways: the raw food is vacuum-sealed in heat-stable, food-grade plastic pouches and the food is cooked using precisely controlled heating.

Vacuum-sealing has several benefits: it allows heat to be efficiently transferred from the water (or steam) to the food; it increases the food's shelf-life by eliminating the risk of recontamination during storage; it inhibits off-flavors from oxidation and prevents evaporative losses of flavor volatiles and moisture during cooking (Church and Parsons, 2000); and reduces aerobic bacterial growth—this results in especially flavorful and nutritious food (Church, 1998; Creed, 1998; García-Linares et al., 2004; Ghazala et al., 1996; Lassen et al., 2002; Schellekens, 1996; Stea et al., 2006).

Precise temperature control has more benefits for chefs than vacuumized packaging does: it allows almost-perfect reproducibility (Keller et al., 2008; Blumenthal, 2008; Achatz, 2008); it allows greater control over doneness than traditional cooking methods (Baldwin, 2008; Norén and Arnold, 2009; Baldwin, 2010; Myhrvold et al., 2011); food can be pasteurized and made safe at lower temperatures, so that it does not have to be cooked well-done to be safe (Baldwin, 2008, 2010); and tough cuts of meat

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(which were traditionally braised to make them tender) can be made tender and still be a medium or a medium-rare doneness (Baldwin, 2008, 2010; Myhrvold et al., 2011).

This paper first reviews the importance of time and temperature in sous vide cooking in Section 2. Section 3 discusses the basic techniques of sous vide cooking. Food safety principles important for sous vide cooking are detailed in Section 4. Some conclusions are drawn in Section 5. Finally, Appendix A briefly discusses the mathematics of sous vide cooking.

Temperature and time

Cooking is the application of heat to change food for eating: some of these changes happen quickly and others happen slowly. Most traditional cooking is only concerned with fast changes because it is hard to hold food at a temperature (below boiling) with traditional heat sources for long enough that these slow changes become important. The precise temperature control in sous vide cooking lets you control both the fast and the slow changes.

To illustrate fast and slow changes, let us consider the cooking of eggs and meat. In both eggs and meat, it is the change or denaturing of proteins that is important: in eggs, the tightly bundled proteins unfold when they denature and cause the white or yolk to thicken and gel; in meat, the proteins shrink, solubilize, or gel when they denature and change the texture of the meat.

Effects of heat and time on eggs

The fast changes happen quickly when the temperature of the food exceeds a certain threshold. For example, if you heat a shelled chicken egg until the temperature equalizes (say, for 30–60 min) then at

- 61.5 °C/143 °F: the protein conalbumin denatures and causes the egg white to form a loose gel;
- 64.5 °C/148 °F: the protein livetin denatures and causes the egg yolk to form a tender gel;
- 70 °C/158 °F: the protein ovomucoid denatures and causes the egg white to form a firm gel (the egg yolk also coagulates around this temperature); and
- 84.5 °C/184 °F: the protein ovalbumin denatures and causes the egg white to become rubbery (Belitz et al., 2004; Charley and Weaver, 1998).

Fig. 1 shows how even small changes in temperature visibly change the texture of the yolk in eggs cooked for 1 h.

Similar changes can be achieved if the shelled egg is held for logarithmically different times at a particular temperature. Fig. 2 shows a similar change in texture from doubling the heating time as Fig. 1 shows for small changes in temperature; see Vega and Mercadé-Prieto (2011) for a model of yolk viscosity as a function of time and temperature.

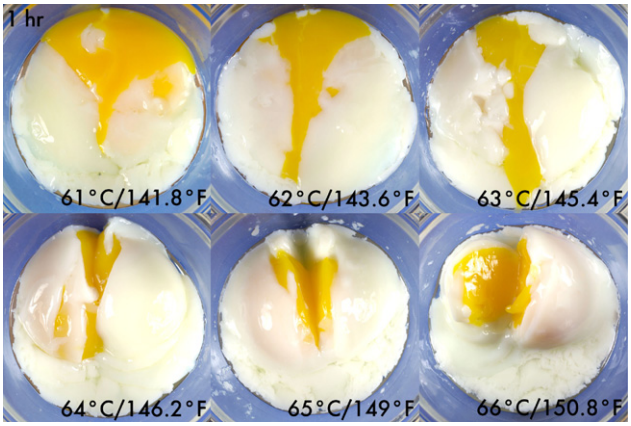

Fig. 1. Large, AA-grade, shelled chicken eggs cooked for 60 min at 61 °C/141.8 °F, 62 °C/143.6 °F, 63 °C/145.4 °F, 64 °C/147.2 °F, 65 °C/149 °F, and 66 °C/150.8 °F.

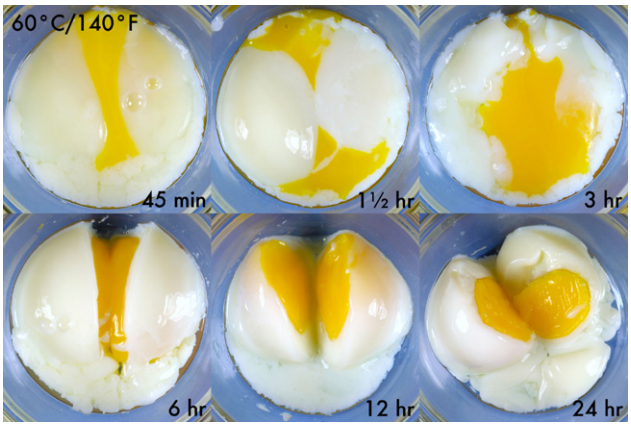

Fig. 2. Large, AA-grade, shelled chicken eggs cooked at 60 °C/140 °F for 45 min, 90 min, 3 h, 6 h, 12 h, and 24 h. The texture of the 3-h-egg's yolk was noticeably thicker than the 90-min-egg's yolk, which was thicker than the 45-min-egg's yolk.

Effects of heat and time on muscle meat

Meat is roughly 75% water, 20% protein, and 5% fat and other substances. When we cook, we are using heat to change (or denature) these proteins. Which proteins and how much we denature them mainly depends on temperature and to a lesser extent on time. Many divide the proteins into three groups: myofibrillar (50–55%), sarcoplasmic (30–34%), and connective tissue (10–15%). The myofibrillar proteins (mostly myosin and actin) and the connective tissue proteins (mostly collagen) contract when heated, while the sarcoplasmic proteins expand when heated. For a non-technical discussion of muscle meat, see McGee (2004, Chapter 3); for a more technical discussion of muscle meat, see Lawrie (1998), Charley and Weaver (1998), and Belitz et al. (2004); for an excellent review article on the effects of heat on meat see Tornberg (2005).

During heating, the muscle fibers shrink transversely and longitudinally, the sarcoplasmic proteins aggregate and gel, and connective tissues shrink and solubilize. For the fast

changes: the muscle fibers begin to shrink at 35–40 °C/95–105 °F and shrinkage increases almost linearly with temperature up to 80 °C/175 °F. The aggregation and gelation of sarcoplasmic proteins begins around 40 °C/105 °F and finishes around 60 °C/140 °F. Connective tissues start shrinking around 60 °C/140 °F but contract more intensely over 65 °C/150 °F. The slow changes mainly increase tenderness by dissolving collagen into gelatin and reducing inter-fiber adhesion.

These fast changes lead to the idea that the doneness of meat is determined by the highest temperature that it reaches: 50 °C/125 °F is rare, 55 °C/130 °F is medium-rare, 60 °C/140 °F is medium, and 70 °C/160 °F and above is well done. Note that while two similar cuts cooked to the same internal temperature will have a similar plumpness and juiciness, their color may be different. The color of meat cooked to the same temperature depends on how quickly it reaches that temperature and on how long it is held at that temperature: the faster it comes up to temperature, the redder it is; the longer it is held at a particular temperature, the paler it becomes (Charley and Weaver, 1998); see Fig. 3 for meat cooked at 55 °C/131 °F for 90 min up to 48 h and note how the meat cooked for 48 h is noticeably paler than the meat cooked for 3 h.

Myofibrillar proteins

While there are about 20 different myofibrillar proteins, 65–70% are myosin or actin. Myosin molecules form the thick filaments and actin the thin filaments of the muscle fibers. The muscle fibers start to shrink at 35–40 °C/95–105 °F and the shrinkage increases almost linearly up to 80 °C/175 °F. The water-holding capacity of whole muscle meat is governed by the shrinking and swelling of myofibrils. Around 80% of the water in muscle meat is held within the myofibrils between the thick (myosin) and thin (actin) filaments. Between 40 °C/105 °F and 60 °C/140 °F, the muscle fibers shrink transversely and widen the gap between fibers. Then, above 60–65 °C/140–150 °F the muscle fibers shrink longitudinally and cause substantial water loss and the extent of this contraction increases with temperature.

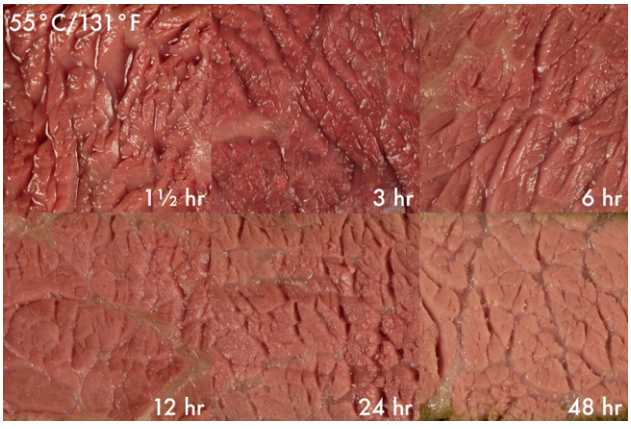

Fig. 3. USDA-choice beef chuck roast cooked at 55 °C/131 °F for 90 min, 3 h, 6 h, 12 h, 24 h, and 48 h. Note how the connective tissue has broken down enough in the 24 h and 48 h pictures that the primary bundles of muscle fibers are readily recognizable.

Sarcoplasmic proteins

Sarcoplasmic or soluble proteins are made up of about 50 components, but mostly enzymes and myoglobin. Unlike the myofibrillar proteins and connective tissue, sarcoplasmic proteins expand when heated. The aggregation and gelation of sarcoplasmic proteins begins around 40 °C/105 °F and finishes around 60 °C/140 °F. Before these enzymes are denatured they can significantly increase the tenderness of the meat. The ratio of myoglobin (Mb), oxymyoglobin (MbO2), and metmyoglobin (MMb+) also determines the color of the meat; see Belitz et al. (2004) or Charley and Weaver (1998) for more details on meat color.

Connective tissue

Connective tissue (or insoluble proteins) holds the muscle fibers, bones, and fat in place: it surrounds individual muscle fibers (endomysium) and bundles of these fibers (perimysium) and bundles of these bundles (epimysium); the perimysium and epimysium bundles are readily seen in the 48-h picture in Fig. 3. Connective tissue consists of collagen and elastin fibers embedded in an amorphous intercellular substances (mostly mucopolysaccharides). Collagen fibers are long chains of tropocollagen (which consist of three polypeptides wound about each other like a three-ply thread). Collagen fibers start shrinking around 60 °C/140 °F but contract more intensely over 65 °C/150 °F. Shrinking mostly destroys this triple-stranded helix structure, transforming it into random coils that are soluble in water and are called gelatin. Elastin fibers, on the other hand, do not denature with heating and have rubber-like properties; luckily, there is much less elastin than collagen—except in the muscles involved in pulling the legs backward. There is not one temperature above which the collagen is denatured but the rate of denaturing increases exponentially with higher temperatures; for safety reasons, we usually use 55 °C/130 °F as the lowest practical temperature for denaturing collagen.

Tenderness

Tenderness is very highly prized—the tenderest cut of beef, the tenderloin, is also the most expensive cut of beef. When chewing, you deform and fracture the meat. The mechanical forces include shear, compressive, and tensile forces; most studies use a Warner–Bratzler (W–B) shear test perpendicular to the muscle fibers and this seems to correlate well with taste tests. Typically, W–B shear decreases from 50 °C/120 °F to 65 °C/150 °F and then increases up to 80 °C/175 °F. While this increase in tenderness used to be attributed to a weakening of connective tissue, most now believe it is caused by the change from a viscoelastic to an elastic material: raw meat is tougher because of the viscous flow in the fluid-filled channels between the fibers and fiber bundles; heating up to 65 °C/150 °F increases tenderness because the sarcoplasmic proteins aggregate and gel and makes it easier to fracture

the meat with your teeth; over 65 °C/150 °F and up to 80 °C/175 °F, the meat is tougher because the elastic modulus increases and requires larger tensile stress to extend fractures (Tornberg, 2005).

Both the intramuscular connective tissue and the myofibrillar component contribute to toughness. In many cuts, connective tissue is the major source of toughness, but the myofibrillar component is sometimes dominant and referred to as actomyosin toughness.

For connective tissue toughness, both the collagen content and its solubility are important. Muscles that are well worked have connective tissue that makes them tougher than muscles that were exercised comparatively little or that are from young animals. The more soluble the collagen, the more tender the meat is and collagen from younger animals tend to be more soluble and soluble at lower temperatures.

Actomyosin toughness can be a major contributor to toughness in young animals and in relatively little used muscles; see Charley and Weaver (1998) and Lawrie (1998) for more detail. Immediately after slaughter, the warm flesh is soft and pliable. In a few hours, the meat goes into rigor and becomes rigid and inelastic. Cross-links form between the myosin and actin filaments where they overlap – where the muscles are allowed to contract or shorten – and are locked in place during rigor. After rigor has passed, the meat again becomes soft and elastic. (If pre-rigor meat is chilled to below 15 °C/60 °F, then cold-shortening of the muscles may occur and significantly increase toughness.)

Enzymes

Recall that enzymes make up a significant portion of the sarcoplasmic proteins. The sarcoplasmic calpains and lysosomal cathepsins are especially important in aging or conditioning. These enzymes catalyze the hydrolysis of one or more of the proteins—calpains the Z line proteins and cathepsin the myosin, actin, troponin, and collagen proteins. Dry aging is usually done at 1–3.3 °C/34–38 °F with about 70% humidity for 14–45 days. Higher temperature aging is also possible, see Lawrie (1998, pp. 239–240); Myhrvold et al. (2011) found that even 4 h at 45 °C/113 °F can significantly improve tenderness. Lawrie (1998) notes that at 49 °C/120 °F that tenderness is particularly increased but that it has a somewhat undesirable flavor. At sous vide cooking temperatures between 55 °C/130 °F and 60 °C/140 °F, many of the enzymes have been denatured but some of the collagenases are active and can significantly increase tenderness after about 6 h (Tornberg, 2005).

Basic techniques

Sous vide cooking typically takes two forms: cook-hold or cook-serve and cook-chill or cook-freeze. Cook-hold or cook-serve sous vide cooking consists of preparing for packaging, vacuum packaging, heating or pasteurizing, finishing, and serving. Cook-chill or cook-freeze sous vide cooking consists of preparing for packaging, vacuum packaging, pasteurizing, rapid chilling, refrigerating or freezing, reheating or rethermalizing, finishing, and serving. See Fig. 4 for a flow diagram of the main types of sous vide cooking; the food safety reasons behind these steps are discussed in detail in Section 4.

In this section, the cooking of meat is discussed in detail and then the cooking of poultry, fish and shellfish, and plants is briefly discussed.

Meat

Meat has been an important part of our diets for 100 000 years, and we have raised animals for food for at least 9000 years; the last few decades, however, have seen dramatic changes in the meat we eat; today's meat is from younger and leaner animals, which might have traveled halfway across the world to reach our tables (McGee, 2004). Since traditional cooking methods were not designed for today's leaner and younger meat, they often produce dry and flavorless results. Sous vide cooking lets chefs cook almost any cut of meat so that it is moist, tender, and flavorful (Baldwin, 2010).

Preparing for packaging

Tougher cuts of meat are frequently marinated, tenderized, or brined before vacuum packaging; see Myhrvold et al. (2011) for extensive discussions of marinating, mechanical tenderizing, and brining.

Most marinades are acidic and contain either vinegar, wine, fruit juice, buttermilk or yogurt. It is recommended that alcohol is minimized in the marinades because the lower vapor pressure of alcohol will tend to cause the vacuumized pouch to balloon during cooking.

Mechanical tenderizing has become quite common and is accomplished by inserting hundreds or thousands of thin blades into the meat to cut some of the internal fibers. This typically does not leave any obvious marks on the meat and reduce moisture lose by cutting internal fibers that would have contracted with heating. The greatest concern with mechanical tenderizing is that it can push surface pathogens into the interior of the whole muscle and so mechanically tenderized meat needs to be pasteurized to be safe.

Brining and curing has become increasingly popular in modern cooking, especially when cooking pork and poultry. There are two methods of brining, traditional brining and equilibrium brining. In traditional brining, the meat is put in a 3–10% salt solution for a couple of hours, then rinsed and cooked as usual. In equilibrium brining: the meat and water are weighted together; then 0.75–1.25% of the weight of the meat and water of salt is added for a brine (or 2–3% for a cure); the meat is then held in the solution for hours or days until the salt concentration in the meat and the water has equalized; then the meat is rinsed and cooked as usual (Myhrvold et al., 2011). Brining has two effects: it dissolves some of the support

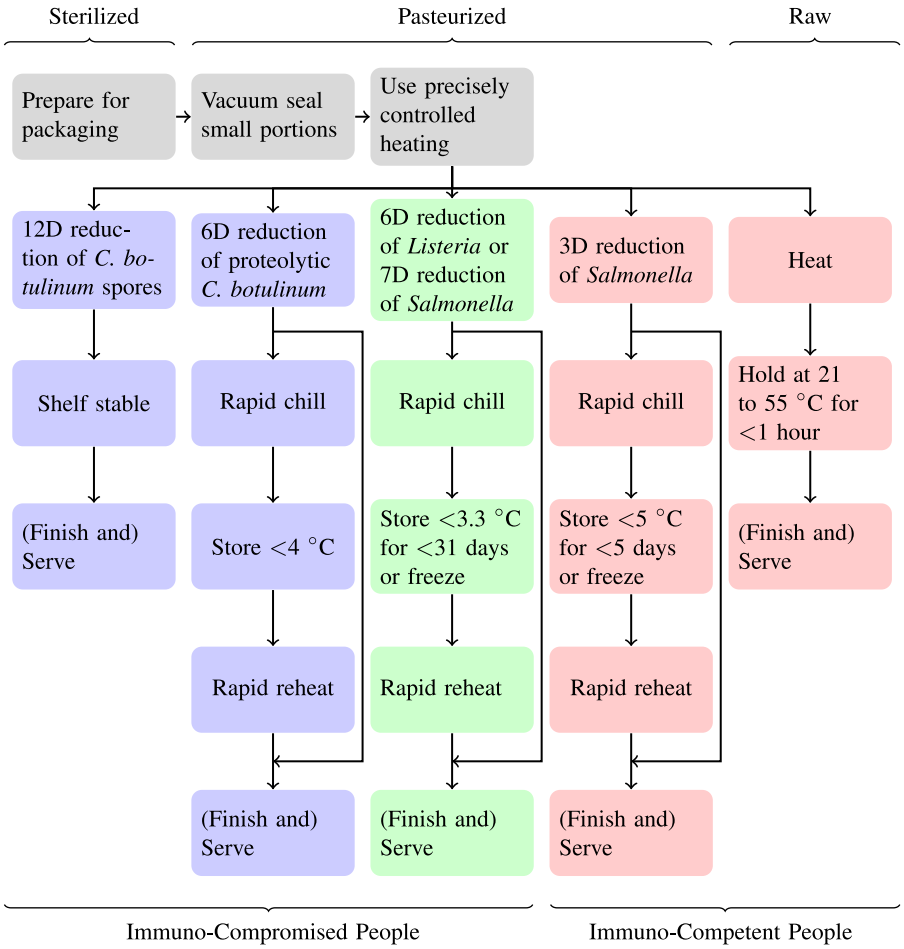

Fig. 4. A flow diagram of sous vide cooking. The branches in red and green (the rightmost three) are common in both restaurant and home kitchens while industrial food processors only use the branches in blue and green (the leftmost three). The branches in red (the rightmost two) should only be served to healthy, immuno-competent people and, in the rightmost branch, they should understand and accept the risks.

structure of the muscle fibers so they cannot coagulate into dense aggregates and it allows the meat to absorb between 10% and 25% of its weight in water (which may include aromatics from herbs and spices) (Graiver et al., 2006; McGee, 2004).

Vacuum packaging

Vacuum-sealing's main benefit is that it allows heat to be efficiently transferred from the water bath or steam oven to the meat. For cook-chill or cook-freeze sous vide cooking, vacuum packaging eliminates the risk of recontamination during storage and inhibits off-flavors from oxidation. It has been generally recommended that the strongest vacuum possible (typically 10–15 mbar for firm food and 100–120 mbar for liquids) should be used to reduce the ballooning of the pouches during cooking and to reduce aerobic bacterial growth, but Norén and Arnold (2009) found that pulling a 10–15 mbar vacuum significantly degraded the taste and texture of fish and poultry. It is not currently known why pulling a stronger vacuum degrades the texture of the food. If the food is below 10 °C/50 °F, so the vapor pressure of water is below 12 mbar/0.2 psi, then Baldwin (2010) recommends using a 90–95% vacuum when using a chamber vacuum sealer and Myhrvold et al. (2011) recommend vacuum-sealing at a pressure of 30–50 mbar/0.4–0.7 psi; these vacuum sealing pressures seem to keep the texture of the food from being damaged and usually prevent the vacuum-sealed pouches from floating during cooking. Both Norén and Arnold (2009) and Baldwin (2010) also recommend using the water-displacement-method for sealing food in Ziploc® (or similar quality re-sealable storage) bags; this has the advantages of not damaging the texture of food or requiring expensive equipment. Many home cooks use clamp-style vacuum-sealers and these sealers have problems sealing pouches with liquid in them but do not pull a strong enough vacuum to damage the texture of foods.

Cooking

In almost all cases, the cooking medium is either a water bath or a convection steam oven. Convection steam ovens allow large quantities of food to be prepared, but do not heat uniformly enough to use (Table 1 or Table 2). Indeed, Sheard and Rodger (1995) found that none of

Table 1
Approximate heating times for thawed meat to 0.5 °C/1 °F less than the water bath's temperature. You can decrease the time by about 13% if you only want to heat the meat to within 1 °C/2 °F of the water bath's temperature. These calculations assume that the water bath's temperature is between 45 °C/110 °F and 80 °C/175 °F; the thermal diffusivity is about 1.4×10^{-7} m^2/s; and the surface heat transfer coefficient is 95 W/m^2-K. For thicker cuts and warmer water baths, heating time may (counter-intuitively) be *longer* than pasteurization time.

Thickness (mm)	Slab-like	Cylinder-like	Sphere-like
5	5 min	5 min	4 min
10	19 min	11 min	8 min
15	35 min	18 min	13 min
20	50 min	30 min	20 min
25	1¼ h	40 min	25 min
30	1½ h	50 min	35 min
35	2 h	1 h	45 min
40	2½ h	1¼ h	55 min
45	3 h	1½ h	1¼ h
50	3½ h	2 h	1½ h
55	4 h	2¼ h	1½ h
60	4¾ h	2½ h	2 h
65	5½ h	3 h	2¼ h
70	–	3½ h	2½ h
75	–	3¾ h	2¾ h
80	–	4¼ h	3 h
85	–	4¾ h	3½ h
90	–	5¼ h	3¾ h
95	–	6 h	4¼ h
100	–	–	4¾ h
105	–	–	5 h
110	–	–	5½ h
115	–	–	6 h

Table 2
Time sufficient to pasteurize meat, fish, or poultry in water baths from 55 °C/131 °F to 66 °C/150.8 °F. This table is based on the internationally accepted and generally conservative 2 min at 70 °C/158 °F with $z = 7.5$ °C/13.5 °F for a million to one reduction in *Listeria monocytogenes* and applies to all foods (FDA, 2011). For less conservative pasteurization times, see Baldwin (2008) and Fig. 5. This calculation uses a thermal diffusivity of 1.11×10^{-7} m^2/s, a surface heat transfer coefficient of 95 W/m^2-K, and $\beta = 0$ up to 30 mm and $\beta = 0.28$ above 30 mm in (*).

Thickness (mm)	55 °C 131 °F	56 °C 132.8 °F	57 °C 134.6 °F	58 °C 136.4 °F	59 °C 138.2 °F	60 °C 140 °F
5	3:33	2:41	2:00	1:30	1:08	0:51
10	3:35	2:43	2:04	1:36	1:15	1:00
15	3:46	2:55	2:16	1:48	1:28	1:13
20	4:03	3:11	2:32	2:04	1:44	1:28
25	4:17	3:25	2:46	2:18	1:57	1:41
30	4:29	3:38	3:00	2:32	2:11	1:55
35	4:45	3:53	3:15	2:46	2:25	2:09
40	4:59	4:07	3:29	3:00	2:39	2:22
45	5:21	4:29	3:50	3:22	3:00	2:42
50	5:45	4:53	4:14	3:44	3:21	3:03
55	6:10	5:18	4:39	4:08	3:45	3:26
60	6:38	5:45	5:06	4:35	4:10	3:50
65	7:07	6:15	5:34	5:02	4:36	4:15
70	7:40	6:45	6:03	5:30	5:04	4:42

Thickness (mm)	61 °C 141.8 °F	62 °C 143.6 °F	63 °C 145.4 °F	64 °C 147.2 °F	65 °C 149 °F	66 °C 150.8 °F
5	0:40	0:31	0:25	0:20	0:17	0:14
10	0:49	0:41	0:35	0:30	0:27	0:24
15	1:02	0:53	0:47	0:42	0:38	0:35
20	1:17	1:08	1:01	0:56	0:52	0:48
25	1:30	1:21	1:13	1:08	1:03	0:59
30	1:43	1:33	1:26	1:19	1:14	1:10
35	1:56	1:46	1:38	1:31	1:26	1:21
40	2:09	1:59	1:50	1:43	1:37	1:32
45	2:29	2:17	2:08	2:00	1:53	1:48
50	2:49	2:37	2:27	2:19	2:11	2:05
55	3:11	2:58	2:47	2:38	2:30	2:23
60	3:34	3:20	3:09	2:58	2:50	2:42
65	3:58	3:43	3:31	3:20	3:11	3:02
70	4:23	4:08	3:54	3:43	3:32	3:23

the convection steam ovens they tested heated sous vide pouches uniformly when fully loaded; it took the slowest heating (standardized) pouch 70–200% longer than the fastest heating pouch to go from 20 °C/68 °F to 75 °C/167 °F when set to an operating temperature of 80 °C/176 °F. They believe this variation is a result of the relatively poor distribution of steam at temperatures below 100 °C/212 °F and the ovens dependence on condensing steam as the heat transfer medium. In contrast, circulating water baths heat very uniformly and typically have temperature swings of less than 0.1 °C/0.2 °F. To prevent undercooking, it is very important that the pouches are completely submerged and are not tightly arranged or overlapping (Rybka-Rodgers, 1999). At higher cooking temperatures, the pouches often balloon (with water vapor) and must be held under water with a wire rack or some other constraint.

Before the mid-2000s, the water bath or steam oven's temperature was usually 5–10 °C/10–20 °F higher than the desired final core temperature of the food; see, for example, Roca and Brugués (2005). In the late-2000s and early-2010s, setting the water bath or steam oven's temperature to be at or just above the desired final core temperature of the food became standard; see, for example, Baldwin (2008), Keller et al. (2008), and Myhrvold et al. (2011).

When cooking in a water bath with a temperature significantly (5–10 °C/10–20 °F) higher than the desired final core temperature of the food, the food must be removed from the bath once it has come up to temperature to keep it from overcooking. This precludes pasteurizing in the same water bath that the food is cooked in. Since there is significant variation in the rate at which foods heat (see Appendix A), a needle temperature probe is typically used to determine when the food has come up to temperature. To prevent air or water from entering the punctured bag, the temperature probe is usually inserted through closed cell foam tape or a thermocouple feed-through connector.

Cooking at or just above the desired final core temperature of the food has several benefits: since the slow changes

(discussed in Section 2) take much longer than the fast changes, it is easy to compute tables of heating times based on the slowest expected heating for a given food, shape, and thickness (see Table 1). Moreover, since it is easy to hold the food at its desired final core temperature and slowest expected heating times can be computed, pasteurization tables based on thickness and water bath temperature can be computed (see Table 2). While cooking times are longer than traditional cooking methods, the meat comes up to temperature surprisingly quickly because the thermal conductivity of water is 23 times greater than that of air.

When cooking tender meats, it is the fast changes that are the most important because the slow changes are mainly used to increase tenderness. Thus, for tender meat you just need to get the center up to temperature and, if pasteurizing, hold it there until any pathogens have been reduced to a safe level. In general, the tenderness of meat increases from 50 °C/122 °F to 65 °C/150 °F but then decreases up to 80 °C/175 °F (Powell et al., 2000; Tornberg, 2005).

When cooking tough meats, the dissolving of collagen into gelatin and the reduction of inter-fiber adhesion is important and this takes either a long time or high temperatures. Prolonged cooking (e.g., braising) has been used to make tough cuts of meat more palatable since ancient times. Indeed, prolonged cooking can more than double the tenderness of the meat by dissolving all the collagen into gelatin and reducing inter-fiber adhesion to essentially nothing (Davey et al., 1976). At 80 °C/176 °F, Davey et al. (1976) found that these effects occur within about 12–24 h with tenderness increasing only slightly when cooked for 50–100 h.

At lower temperatures (50 °C/120 °F to 65 °C/150 °F), Bouton and Harris (1981) found that tough cuts of beef (from animals 0–4 years old) were the most tender when cooked to between 55 °C/131 °F and 60 °C/140 °F. Cooking the beef for 24 h at these temperatures significantly increased its tenderness (with shear forces decreasing 26–72% compared to 1 h of cooking). This tenderizing is caused by weakening of connective tissue and proteolytic enzymes decreasing myofibrillar tensile strength. Indeed, collagen begins to dissolve into gelatin above about 55 °F/131 °F (This, 2006). Moreover, the sarcoplasmic protein enzyme collagenase remains active below 60 °C/140 °F and can significantly tenderize the meat if held for more than 6 h (Tornberg, 2005).

For example, tough cuts of meat, like beef chuck and pork shoulder, take 10–12 h at 80 °C/175 °F or 1–2 days at 55–60 °C/130–140 °F to become fork-tender. Intermediate cuts of meat, like beef sirloin, only need 6–8 h at 55–60 °C/130–140 °F to become fork-tender because the tenderization from the enzyme collagenase is sufficient.

Chilling for later use

For cook-chill and cook-freeze sous vide cooking, the food is rapidly chilled in its vacuum sealed pouch and refrigerated or frozen after pasteurizing. Before finishing for service, the food is then reheated in a water bath at or below the temperature it was cooked in. Typically, meat is reheated or rethermalized in a 53–55 °C/127–131 °F water bath for the times listed in Table 1 since the optimal serving temperature for meat is between 50–55 °C/120–130 °F (Charley and Weaver, 1998).

The danger with cook-chill is that pasteurizing does not reduce pathogenic spores to a safe level. If the food is not chilled rapidly enough or is refrigerated for too long, then pathogenic spores can outgrow and multiply to dangerous levels. For a detailed discussion, see Section 4.

Finishing for service

Since sous vide is essentially a very controlled and precise poach, most food cooked sous vide has the appearance of being poached. So foods like fish, shellfish, eggs, and skinless poultry can be served as it is. However, steaks and pork chops are not traditionally poached and usually require searing or saucing. Searing the meat is particularly popular because the Maillard reaction (the browning) adds considerable flavor.

The Maillard or browning reaction is a very complex reaction between amino acids and reducing sugars. After the initial reaction, an unstable intermediate structure is formed that undergoes further changes and produces hundreds of reaction by-products. See McGee (2004) for a non-technical description or (Belitz et al., 2004) for a technical description.

The flavor of cooked meat comes from the Maillard reaction and the thermal (and oxidative) degradation of lipids (fats); the species characteristics are mainly due to the fatty tissues, while the Maillard reaction in the lean tissues provides the savory, roast, and boiled flavors (Mottram, 1998). The Maillard reaction can be increased by adding a reducing sugar (glucose, fructose or lactose), increasing the pH (e.g., adding a pinch of baking soda), or increasing the temperature. Even a small increase in pH greatly increases the Maillard reaction and results in sweeter, nuttier, and more roasted-meat-like aromas (Meynier and Mottram, 1995). The addition of a little glucose (e.g., a 4% glucose wash) has been shown to increase the Maillard reaction and improve the flavor profile (Meinert et al., 2009). The Maillard reaction occurs noticeably around 130 °C/265 °F, but produces a boiled rather than a roasted aroma; good browning and a roasted flavor can be achieved at temperatures around 150 °C/300 °F with the addition of glucose (Skog, 1993). Although higher temperatures significantly increase the rate of the Maillard reaction, prolonged heating at over 175 °C/350 °F can significantly increase the production of mutagens.

Mutagens formed in the Maillard reaction (heterocyclic amines) have been shown to be carcinogenic in mice, rats, and non-human primates; however, while some epidemiological studies have shown a relation with cancer development, others have shown no significant relation in humans (Arvidsson et al., 1997). These mutagens depend strongly on

both temperature and time: they increase almost linearly in time before leveling off (after 5–10 min); an increase in temperature of 25 °C/45 °F (from 150 °C/300 °F to 175 °C/350 °F or 175 °C/350 °F to 200 °C/390 °F) roughly doubles the quantity of mutagens (Jägerstad et al., 1998). While adding glucose increases browning, it can decrease the production of mutagens (Skog, 1993; Skog et al., 1992). The type of fat used to sear the meat in a pan has only minor effects on the formation of mutagens, but the pan residue using butter was significantly higher in mutagens than when using vegetable oil (Johansson et al., 1995).

In order to limit overcooking of the meat's interior, very high temperatures are often used to brown meat cooked sous vide. Typically, this means either using a blowtorch or a heavy skillet with just smoking vegetable oil. Butane and propane blowtorches can burn at over 1900 °C/3500 °F in air, and produce a particularly nice crust on beef; Baldwin (2008) and Norén and Arnold (2009) recommend using a butane blowtorch since propane can leave an off-flavor. Some chefs prefer the lower temperature of a skillet with just smoking vegetable or nut oil (200 °C/400 °F to 250 °C/500 °F) when searing fish, poultry and pork. Since the searing time at these high temperatures is very short (5–30 s), mutagens formation is unlikely to be significant (Skog, 2009).

Poultry

Today's poultry, like today's meat, is leaner and younger than ever before. This is why traditional cooking methods often produce dry and tasteless poultry.

Cooking poultry is very similar to cooking meat. Both lean poultry and lean meat are only plump and juicy if they do not exceed 60–65 °C/140–150 °F—see Section 2.2. Tougher (and fattier) cuts of meat and poultry can be cooked to higher temperatures and remain juicy, because the melted fat lubricates the lean meat (McGee, 2004).

Traditional cooking methods make poultry safe by cooking the coldest part to 74 °C/165 °F or above. Poultry can also be made safe at lower temperatures, it just takes longer. Indeed, cooking chicken and turkey breasts at 60 °C/140 °F for the times listed in Table 2 is just as safe as cooking them to 74 °C/165 °F.

For example, chicken and turkey breasts are moist, plump, and juicy when pasteurized between 58 °C/136 °F and 63 °C/145 °F for the times in Table 2 and duck breasts are usually pasteurized at 57 °C/135 °F for the times in Table 2. Dark poultry meat, such as legs and thighs, is usually cooked well done at 70–80 °C/160–175 °F until it is fall-apart tender, about 4–6 h at 80 °C/175 °F or 8–12 h at 70 °C/160 °F.

Fish and shellfish

Fish is cooked to change its texture, develop flavor, and destroy food pathogens. Traditionally, fish is considered to be cooked when it flakes. Fish flakes when the collagen separating the flakes is converted into gelatin at around 46–49 °C/115–120 °F (Belitz et al., 2004). This temperature is too low, however, to destroy any food pathogens. Many chefs cook salmon and arctic char to rare at 42 °C/108 °F and most other fin and shellfish to medium-rare at 49 °C/120 °F for 15–20 min (cf. Norén and Arnold, 2009). While FDA (2011) generally recommends pasteurizing fish as in Table 2, which will reduce all non-spore forming pathogens and parasites to a safe level, it will not reduce the risk of hepatitis A virus (HAV) or norovirus infection from shellfish. Since a 4-$\log_{10}$ reduction of HAV in molluscan shellfish requires holding at an internal temperature of 90 °C/194 °F for 90 s, the risk of viral contamination is best controlled through proper sanitation and hygiene (National Advisory Committee on Microbiological Criteria for Food, 2008). Since the spores of non-proteolytic *Clostridium botulinum* are not inactivated by pasteurization, the fish should be stored at below 3.3 °C/38 °F for less than 4 weeks; see Section 4 for more details. Note that Ghazala et al. (1996) found that fish cooked sous vide retains more healthful omega-3 fatty acids and nutrients than traditionally cooked fish.

Plants

While vegetables are a rich source of vitamins and minerals, boiled or steamed vegetables lose nutrients to their cooking water (Charley and Weaver, 1998). Sous vide cooked vegetables, in comparison, retain nearly all their nutritive value (Creed, 1995; Schellekens, 1996; Stea et al., 2006). This superior retention of nutrients also intensifies the flavor inherent in the vegetable and can cause some vegetables, such as turnips and rutabaga, to have a flavor that is too pronounced for some people (Baldwin, 2010).

Vegetables that are boiled, steamed, or microwaved lose their nutrients because the cell walls are damaged by heat and allow the water and nutrients in the cells to leach out (Charley and Weaver, 1998). Sous vide vegetables leave the cell walls mostly intact and make the vegetables tender by dissolving some of the cementing material that holds the cells together (cf. Plat et al., 1988; Greve et al., 1994; Georget et al., 1998; Kunzek et al., 1999; Sila et al., 2006). In vegetables, this cementing material starts to dissolve around 82–85 °C/180–185 °F. This cementing material can be strengthened by pre-cooking, say at 50 °C/122 °F for 30 min (Ng and Waldron, 1997; Waldron et al., 1997). Starchy vegetables can be cooked at the slightly lower temperature of 80 °C/175 °F because their texture is also changed by the gelatinization of the starch granules in their cells (García-Segovia et al., 2008; Baldwin, 2010).

While fruits are often eaten raw, chefs sometimes cook apples and pears until they are tender. Tart (high acid) apples, such as Granny Smith, soften faster than sweet (low acid) apples, such as Gala or Fuji, because the acid lowers the temperature at which the cementing material dissolves (cf. Charley and Weaver, 1998).

Legumes (beans, peas, lentils) are cooked to gelatinize their starches, make their proteins more digestible, and to

weaken the cementing material that holds their cells together so you can chew them; see, for instance, Charley and Weaver (1998). Legumes cooked sous vide do not need to be pre-soaked, because they can absorb the same amount of water in 50 min at 90 °C/195 °F as they would in 16 h at room temperature (Charley and Weaver, 1998). Moreover, since the legumes are cooked in their soaking water, their water-soluble vitamins and minerals are retained.

Since vegetables, fruits, and legumes are cooked at 80–90 °C/175–195 °F, their pouches may balloon and need to be held under the surface of the water (say, with a metal rack). The pouches balloon because the residual air left in the pouch after vacuum-sealing expands and because some of the moisture in the food is converted into water vapor.

For example, Baldwin (2010) suggests that non-starchy vegetables be cooked sous vide at 82–85 °C/180–185 °F for about three times as long as they would be boiled, starchy vegetables at 80 °C/175 °F for about twice as long as they would be boiled, and legumes at 90 °C/195 °F for 3–6 h, depending on the species and when it was harvested.

Food safety

Non-technical background

The goal is maximizing taste and minimizing the risk from foodborne pathogens. While pathogenic microorganisms can be controlled with acids, (ionizing) radiation, salts, and some spices, sous vide cooking relies heavily on temperature control (Snyder, 1995; Rybka-Rodgers, 2001).

You were probably taught that there is a "danger zone" between 4.4 °C/40 °F and 60 °C/140 °F. These temperatures are not quite right: it is well known that food pathogens can only multiply between −1.3 °C/29.7 °F and 52.3 °C/126.1 °F, while spoilage bacteria begin multiplying at −5 °C/23 °F (Snyder, 2006; Juneja et al., 1999; FDA, 2011). Johnson et al. (1983) reported that *Bacillus cereus* could multiply at 55 °C/131 °F, but no one else has demonstrated growth at this temperature and so *Clostridium perfringens* is used instead. Moreover, contrary to popular belief, food pathogens and toxins cannot be seen, smelt or tasted.

So why were you taught that food pathogens do not multiply below 4.4 °C/40 °F and grow all the way up to 60 °C/140 °F? Because it takes days for food pathogens to grow to a dangerous level at 4.4 °C/40 °F (FDA, 2011) and it takes many hours for food to be made safe at just above 52.3 °C/126.1 °F—compared with only about 12 min (for meat) (FDA, 2009, 3-401.11.B.2) and 35 min (for poultry) (FSIS, 2005) to be made safe (for immuno-compromised people) when the coldest part is at 60 °C/140 °F. Indeed, the food pathogens that can multiply down to −1.3 °C/29.7°F – *Yersinia enterocolitica* and *Listeria monocytogenes* – can only multiply about once per day at 4.4 °C/40 °F and so you can hold food below 4.4 °C/40 °F for 5–7 days (FDA, 2011). At 52.3 °C/126.1 °F, when the common food pathogen *C. perfringens* stops multiplying, it takes a very long time to reduce the food pathogens we are worried about – namely the *Salmonella* species, *L. monocytogenes*, and the pathogenic strains of *Escherichia coli* – to a safe level; in a 54.4 °C/130 °F water bath (the lowest temperature usually recommend for cooking sous vide) it will take you about $2\frac{1}{2}$ h to reduce *E. coli* to a safe level in a 25 mm/1 in. thick hamburger patty and holding a hamburger patty at 54.4 °C/130 °F for $2\frac{1}{2}$ h is inconceivable with traditional cooking methods—which is why the "danger zone" conceived for traditional cooking methods does not start at 54.4 °C/130 °F but at 60 °C/140 °F.

Sous vide cooking can be divided into three broad categories: (i) raw or unpasteurized, (ii) pasteurized, and (iii) sterilized. See Fig. 4 for a brief flow diagram of sous vide cooking. Most people cook food to make it more palatable and to kill most the pathogenic microorganisms on or in it. Killing enough active, multiplying food pathogens to make your food safe is called pasteurization. Some bacteria are also able to form spores that are very resistant to heat and chemicals; heating the food to kill both the active microorganisms and the spores is called sterilization.

Sterilization typically requires a pressure cooker or autoclave for low-acid foods: the raw food is vacuum-sealed in retort pouches and heated in an pressure cooker or autoclave until the coldest part is heated to the equivalent of 121 °C/250 °F for 3 min to achieve a 12-$\log_{10}$ reduction (10^{12}:1) in *C. botulinum* spores. This very severe thermal processing produces a room-temperature-stable product and is sometimes used for confit-style preparations. Very few restaurants or home cooks are currently interested in this type of sous vide cooking but there are a few sous vide recipes that use an autoclave or pressure cooker in Myhrvold et al. (2011).

Pasteurization is a combination of both temperature and time. Consider the *Salmonella* species: at 60 °C/140 °F, all the *Salmonella* in a piece of ground beef does not instantly die—it is reduced by a factor 10 every 5.48 min (Juneja et al., 2001). This is often referred as a 1-$\log_{10}$ or one decimal reduction and is written $D_{60}^{6.0} = 5.48$ min, where the subscript specifies the temperature (in °C) that the *D*-value refers to and the superscript is the *z*-value (in °C). The *z*-value specifies how the *D*-value changes with temperature; increasing the temperature by the *z*-value decreases the time needed for an one decimal reduction by a factor 10. So, $D_{66}^{6.0} = 0.55$ min and $D_{54}^{6.0} = 54.8$ min. How many decimal reductions are necessary depends on how contaminated the beef is and how susceptible you are to *Salmonella* species. For healthy, immuno-competent people, a 3-$\log_{10}$ reduction of the *Salmonella* species is the minimum recommended for restaurants and home cooks; this is because raw meat, fish, and poultry typically has 10 pathogens/g of food of the *Salmonella* species (as well as for the pathogenic strains of *E. coli* and *L. monocytogenes*) and the estimated illness dose for a healthy person is more than a thousand pathogens per gram (Snyder, 1995). For immuno-compromised people,

a few infective vegetative (active) pathogens of the *Salmonella* species or the pathogenic strains of *E. coli* in the serving could cause them to become ill. Thus, FSIS (2005) recommends a 6.5-$\log_{10}$ reduction of *Salmonella* species in beef and a 7-$\log_{10}$ reduction in poultry. So, for our example, the coldest part should be at least 60 °C/140 °F for at least $6.5 \times D_{60}^{6.0} = 35.6$ min.

The rate at which the bacteria die depends on many factors, including temperature, meat species, muscle type, fat content, acidity, salt content, certain spices, and water content. The addition of acids, salts, or spices can all decrease the number of active pathogens. Chemical additives like sodium lactate and calcium lactate are often used in the food industry to reduce the risk of spore forming pathogens like the *Clostridium* species and *B. cereus* (Aran, 2001; Rybka-Rodgers, 2001).

Some sous vide recipes, especially for fish, do little more than warm the food and any pathogenic bacteria or parasites are likely to survive. This raw or undercooked food should only be served to informed healthy adults who understand and accept the risks and never to immuno-compromised people. Even for healthy people, it is important that raw and unpasteurized foods are consumed before food pathogens have had time to multiply to dangerous levels; most foods should not be above 21 °C/70 °F for more than 2 h and fish should not be above 27 °C/80 °F for more than 1 h (FDA, 2011).

Pathogens of interest

Sous vide processing is used in the food industry to extend the shelf-life of food products; when pasteurized sous vide pouches are held at below 3.3 °C/38 °F, they remain safe and palatable for 3–4 weeks (Armstrong and McIlveen, 2000; Betts and Gaze, 1995; Church, 1998; Creed, 1995; González-Fandos et al., 2004, 2005; Hansen et al., 1995; Mossel and Struijk, 1991; Nyati, 2000a; Peck, 1997; Peck and Stringer, 2005; Rybka-Rodgers, 2001; Simpson et al., 1994; Vaudagna et al., 2002).

The simplest and safest method of sous vide cooking is cook-hold or cook-serve: the raw (or partially cooked) ingredients are vacuum sealed, pasteurized, and then held at 54.4 °C/130 °F or above until served. While hot holding the food will prevent any food pathogens from growing, meat and vegetables will continue to soften and may become mushy if held for too long. How long is too long depends on both the holding temperature and what is being cooked. Most foods have an optimal holding time at a given temperature; adding or subtracting 10% to this time would not change the taste or texture noticeably; holding for up to twice this time is usually acceptable (Baldwin, 2010; Myhrvold et al., 2011).

For cook-hold sous vide, the main pathogens of interest are the *Salmonella* species and the pathogenic strains of *E. coli*. There are, of course, many other food pathogens but these two species are relatively heat resistant and require very few vegetative bacteria per gram to make an immuno-compromised person sick. For a healthy person, a 3-$\log_{10}$ reduction in the *Salmonella* species should be sufficient (Snyder, 1995); indeed, many of the time and temperature combinations in FDA (2009) correspond to less than a 3-$\log_{10}$ reduction in the *Salmonella* species—for example, FDA (2009, 3-401.11.A.1) recommends 15 s at 63 °C/145 °F for raw eggs, fish, and meat raised for food while a 3-$\log_{10}$ reduction in the *Salmonella* species takes 1.6 min using the *D*- and *z*-values in FDA (2009, 3-401.11.B.2). For immuno-compromised people, most experts recommend a 6.5–7-$\log_{10}$ reduction of the *Salmonella* species and a 5-$\log_{10}$ reduction of pathogenic strains of *E. coli*; Fig. 5 shows a plot of experimentally determined times and temperatures for a 7-$\log_{10}$ reduction in the *Salmonella* species, a 6-$\log_{10}$ reduction in *L. monocytogenes*, and a 5-$\log_{10}$ reduction in the pathogenic strains of *E. coli*.

The most popular methods of sous vide cooking are cook-chill and cook-freeze: raw (or partially cooked) ingredients are vacuum sealed, pasteurized, rapidly chilled (to avoid sporulation of *C. perfringens*, Andersson et al., 1995), and either refrigerated or frozen until reheating for service. Typically, the pasteurized food pouches are rapidly chilled by placing them in an ice water bath for at least the time listed in Table 3.

For cook-chill sous vide, *L. monocytogenes* and the spore forming pathogenic bacteria are the pathogens of interest. That is because *Listeria* is the most heat resistant non-spore forming pathogen and can grow at refrigerator temperatures (Nyati, 2000b; Rybka-Rodgers, 2001). For extended shelf-life, a 6-$\log_{10}$ reduction in *Listeria* is generally recommended; then it is the (germination,) growth, and toxin formation of spore forming pathogens that limit the shelf-life. If the food was pasteurized for the *Salmonella* species instead of *Listeria* then the growth of

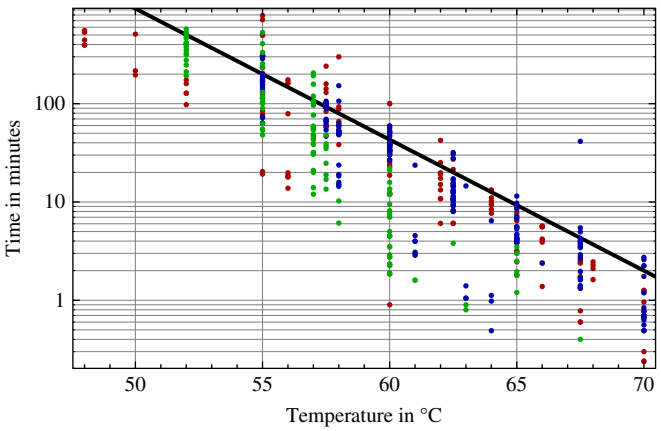

Fig. 5. The dots show experimentally determined times and temperatures to achieve a 5-$\log_{10}$ reduction in pathogenic *E. coli* in green, a 6-$\log_{10}$ reduction in *Listeria monocytogenes* in red, and a 7-$\log_{10}$ reduction in the *Salmonella* species in blue; the experimental data is for meat, fish, and poultry and came from O'Bryan et al. (2006), Bolton et al. (2000), Hansen and Knøchel (1996), and Embarek and Huss (1993). The black line shows the 2-min-at-70 °C/158 °F-equivalents used in Table 2; notice how almost all the experimentally determined times and temperatures are below this line and is why it is considered generally conservative.

Table 3
Approximate cooling time from 55–80 °C/130–175 °F to 5 °C/41 °F in an ice water bath that is at least half ice. These calculations assume that the food's thermal diffusivity is 1.1×10^{-7} m^2/s and the ice water bath has a surface heat transfer coefficient of 100 W/m^2-K.

Thickness (mm)	Slab-like	Cylinder-like	Sphere-like
5	5 min	3 min	3 min
10	14 min	8 min	6 min
15	25 min	14 min	10 min
20	35 min	20 min	15 min
25	50 min	30 min	20 min
30	1¼ h	40 min	30 min
35	1½ h	50 min	35 min
40	1¾ h	1 h	45 min
45	2¼ h	1¼ h	55 min
50	2¾ h	1½ h	1 h
55	3¼ h	1¾ h	1¼ h
60	3¾ h	2 h	1½ h
65	4¼ h	2¼ h	1¾ h
70	4¾ h	2¾ h	2 h
75	5½ h	3 h	2¼ h
80	–	3½ h	2½ h
85	–	3¾ h	2¾ h
90	–	4¼ h	3 h
95	–	4¾ h	3½ h
100	–	5 h	3¾ h
105	–	5½ h	4 h
110	–	6 h	4½ h
115	–	–	4¾ h

Listeria limits shelf-life to less than 7 days at −0.4–5 °C/31.3–41 °F (FDA, 2011; Snyder, 1995).

While keeping the food sealed in its plastic pouches prevents recontamination after cooking, spores of *C. botulinum*, *C. perfringens*, and *B. cereus* can all survive the mild heat treatment of pasteurization. Therefore, after rapid chilling, the food must either be frozen or held at

- below 2.5 °C/36.5 °F for up to 90 days,
- below 3.3 °C/38 °F for less than 31 days,
- below 5 °C/41 °F for less than 10 days, or
- below 7 °C/44.5 °F for less than 5 days

to prevent spores of non-proteolytic *C. botulinum* from outgrowing and producing deadly neurotoxin (Gould, 1999; Peck, 1997).

A few sous vide recipes – mainly confit-style recipes – use temperature and time combinations that can reduce *C. botulinum*, type E and non-proteolytic types B and F, to a safe level; specifically, a 6-$\log_{10}$ reduction in non-proteolytic *C. botulinum* type B takes 520 min (8 h 40 min) at 75 °C/167 °F, 75 min at 80 °C/176 °F, or 25 min at 85 °C/185 °F (Fernández and Peck, 1999; Peck, 1997), FDA (2011) gives a more conservative time of 10 min at 90 °C/194 °F with $z = 7.0$ °C/12.6 °F for temperatures less than 90 °C/194 °F. The food may then be stored at below 4 °C/39 °F indefinitely, the minimum temperature at which *B. cereus* can grow (Andersson et al., 1995). While O'Mahony et al. (2004) found that the majority of pouches after vacuum packaging had high levels of residual oxygen, this does not imply that the *Clostridium* species – which require the absence of oxygen to grow – are not a problem since the interior of the food often has an absence of oxygen. Most other food pathogens are able to grow with or without oxygen.

HACCP

Science-based food safety criteria are usually based on the Hazard Analysis and Critical Control Point (HACCP) system; for a detailed and nuanced discussion on science-based food safety criteria and regulations, see Committee on the Review of the Use of Scientific Criteria and Performance Standards for Safe Food (2003). Snyder (1995) gives a comprehensive and detailed application of the HACCP-system to refrigerated sous vide products. Because of limited space, only some of the biological hazards for sous vide cooking and their controls are discussed below:

1. You buy your raw food and it usually has millions of microorganisms on and in it—most of which are spoilage bacteria. To reduce the risk of the harmful pathogens from multiplying rapidly, you store your meat, fish, or poultry in a refrigerator (or in a freezer) and use it before its "best by" date.
2. You vacuum-seal your raw food. Vacuum packaging does not reduce the microorganisms, so you must either return it to the refrigerator or freezer or (in most cases) begin cooking immediately in a temperature controlled water bath.
3. You heat your vacuumized raw food in a temperature controlled water bath or steam oven. Recall that it is important that the pouches are completely submerged and not overlapping in order to heat evenly.
   (a) As the food heats, microorganisms begin to multiply rapidly with most of them growing fastest between 30 °C/85 °F and 50 °C/120 °F. If you are not heating to pasteurize, then minimizing the growth of these pathogens is a critical step. For example, fish cooked rare or medium-rare should not spend more than about 1 h above 27 °C/80 °F (FDA, 2011). While the interior of intact steaks, chops, and roasts is generally considered to be sterile, and is the reason that most traditional cooking methods do not pasteurize steaks or roasts, many processors are now mechanically tenderizing the meat before it reaches local markets and this can push food pathogens from the surface of the meat into the interior. This mechanically tenderized meat should be pasteurized in order to make it safe to eat.
   (b) Once the temperature of the food exceeds about 52.3 °C/126.1 °F, then all the known food pathogens stop growing and begin to die. Many recommend

that the core of the food reach 54.4 °C/130 °F within 6 h to keep *C. perfringens* to less then 10 generations (or less than 2 h 10 min between 35 °C and 52 °C as per Willardsen et al., 1977), but this is not a critical control point: while *C. perfringens* does produce toxins, it only produces them while sporulating (and so is not a concern when heating) and the toxin is easily destroyed by heating (since it is destroyed in only 10 min at 60 °C/140 °F); see, for instance, Jay (2000, Chapter 24). So, it is only the vegetative form of *C. perfringens* that is a hazard when heating and they are easily reduced to safe level when pasteurizing for *Salmonella*, *Listeria* or *E. coli*. Therefore, heating to 54.4 °C/130 °F within 6 h is only a critical control point if the food is not then being pasteurized and the growth of other pathogens is usually a greater concern. However, FDA (2011) recommends a maximum time of 2 h above 21 °C/70 °F to control the germination, growth, and toxin formation by *C. botulinum* type A and proteolytic types B and F; since these species of *C. botulinum* have a maximum temperature of 48 °C/118.4 °F, this gives the same recommendation that the core of the food reach 54.4 °C/130 °F within 6 h—this is a critical control point since these toxins are not destroyed when pasteurizing for active or vegetative pathogens.

(c) If pasteurizing, then you hold the food at 52.3 °C/126.1 °F or above until any active or vegetative pathogens have been reduced to a safe level. Lund and O'Brien (2011) estimate that 15–20% of the US and UK population is more susceptible to food-borne disease. For healthy people, a 3-$\log_{10}$ reduction of the *Salmonella* species is generally recommended while a 7-$\log_{10}$ reduction of the *Salmonella* species is generally recommended for immuno-compromised people. If extended refrigerator shelf-life is desired, then a 6-$\log_{10}$ reduction in *L. monocytogenes* is generally recommended. See Table 2 for times that are sufficient to achieve both a 6-$\log_{10}$ reduction in *L. monocytogenes* and a 7-$\log_{10}$ reduction of the *Salmonella* species.

4. If the cooked food is served immediately, then you do not have to worry about any additional pathogens growing.
5. If you plan to chill or freeze the food for later use, then it is important to follow a few simple steps:
   (a) You have to chill the food rapidly to limit sporulation of *C. perfringens* (since it creates its toxins while sporulating); cooling to 4.4 °C/40 °F within 11 h is generally recommended (Snyder, 1995). This is usually done in an ice-water bath; see Table 3 for cooling times.
   (b) You must leave it in its vacuumized pouch to prevent recontamination.
   (c) You need to properly store the food either in a refrigerator (see above for times at different temperatures) or in a freezer: proper storage is critical in preventing spores of *C. botulinum* and *B. cereus* from outgrowing and producing toxins, which are not destroyed when reheating or rethermalizing (neither *S. aureus* nor *B. cereus* toxins are destroyed by heating and *C. botulinum* toxins need either a high temperature or a very long time to be destroyed).
6. When you reheat or rethermalize your chilled food, it is important to prevent toxin formation by *C. botulinum* and *B. cereus* and the growth of *C. perfringens*, since you should have already reduced the non-spore forming pathogens in the pasteurization step. Reheating to a core temperature of 54.4 °C/130 °F within 6 h is generally recommended.

Conclusion

Sous vide cooking is a powerful tool in the modern kitchen: precise temperature control gives superior reproducibility, better control of doneness, reduction of pathogens to a safe level at lower temperatures, and more choice of texture than traditional cooking methods; vacuumized packaging improves heat flow, extends the shelf-life of the food by eliminating the risk of recontamination, reduces off-flavors from oxidation, and reduces the loss of nutrients to the cooking medium.

Precise temperature control lets you take advantage of both the fast and the slow changes when cooking: the fast changes, such as doneness, are mostly determined by the highest temperature that the food reaches; the slow changes typically take hours to days and let you make tough cuts of meat, which would usually be braised, tender while maintaining a medium-rare doneness. Precise temperature control also gives you the ability to pasteurize meat and poultry at lower temperatures than traditional cooking methods and so they no longer need to be cooked well-done to be safe.

Vacuumized packaging is important when extended shelf-life is required: the vacuumized pouch prevents recontamination of food during storage and allows for the efficient transfer of heat. Vacuumized packaging is not necessary when doing cook-hold sous vide cooking and many restaurants do not vacuum package the food and cook directly in a convection steam oven or in a temperature controlled bath of fat (e.g., oil or butter) or flavored broth (e.g., stock) if it will be served immediately.

Appendix A. The mathematics of sous vide cooking

This section is primarily interested in modeling how long it takes the food to come up to temperature and how long it takes to pasteurize the food. These are non-trivial tasks. Many simplifications and assumptions are necessary.

The transfer of heat (by conduction) is described by the partial differential equation,

$$T_t = \nabla \cdot (\alpha \nabla T),$$

where $\alpha \equiv k/(\rho C_p)$ is thermal diffusivity (m^2/s), k is thermal conductivity (W/m-K), ρ is density (kg/m^3), and C_p is specific heat (kJ/kg-K). If we know the temperature at some initial time and can describe how the temperature

at the surface changes, then we can uniquely determine T. Although k, ρ and C_p depend on position, time, and temperature, we will assume the dependence on position and time is negligible.

Since we are only interested in the temperature at the slowest heating point of the food (typically the geometric center of the food), we can approximate the three dimensional heat equation by the one dimensional heat equation

$$\begin{cases} \rho C_p(T)T_t = k(T)\{T_{rr} + \beta T_r/r\}, \\ T(r,0) = T_0, \quad T_r(0,t) = 0, \\ k(T)T_r(R,t) = h\{T_{\text{Water}} - T(R,t)\}, \end{cases}$$

where $0 \le r \le R$, $t \ge 0$, $0 \le \beta \le 2$ is a geometric factor, T_0 is the initial temperature of the food, T_{Water} is the temperature of the fluid (air, water, steam) that the food is placed in, and h is the surface heat transfer coefficient (W/m^2-K).

The geometric factor allows us to approximate any shape from a large slab ($\beta = 0$) to a long cylinder ($\beta = 1$) to a sphere ($\beta = 2$). Indeed, a cube is well approximated by taking $\beta = 1.25$, a square cylinder by $\beta = 0.70$, and a 2:3:5 brick by $\beta = 0.28$. See Fig. A1 to see an example of a block of agar–agar heated in a SousVide Supreme® water bath.

For thawed foods, k, ρ and C_p are essentially constant. Sanz et al. (1987) reported that beef with above average fatness had: a thermal conductivity of 0.48 W/m-K at 32 °F (0 °C) and 0.49 W/m-K at 86 °F (30 °C); a specific heat of 3.81 kJ/kg-K at both 32 °F (0 °C) and 86 °F (30 °C); and a density of 1077 kg/m^3 at 41 °F (5 °C) and 1067 kg/m^3 at 86 °F (30 °C). This is much less than the difference between beef sirloin ($\alpha = 1.24 \times 10^{-7}$ m^2/s) and beef round ($\alpha = 1.11 \times 10^{-7}$ m^2/s) (Sanz et al., 1987). Therefore, we can model the temperature of thawed foods by

$$\begin{cases} T_t = \alpha\{T_{rr} + \beta T_r/r\}, \\ T(r,0) = T_0, \quad T_r(0,t) = 0, \\ T_r(R,t) = (h/k)\{T_{\text{Water}} - T(R,t)\} \end{cases} \qquad (*)$$

for $0 \le r \le R$ and $t \ge 0$. Since h is large (95–155 W/m^2-K for most consumer and restaurant water baths), even large deviations in h/k cause only minor deviations in the core temperature of the food (Nicolaï and Baerdemaeker, 1996); in comparison, home and (low convection) commercial ovens have surface heat transfer coefficients of only 14–30 W/m^2-K and even small deviations in h can result in large deviations of the core temperature of the food.

Most foods have a thermal diffusivity between 1.2 and 1.6×10^{-7} m^2/s (Baerdemaeker and Nicolaï, 1995). Thermal diffusivity depends on many things, including meat species, muscle type, temperature, and water content. Despite these variations in thermal diffusivity, we can always choose a (minimum) thermal diffusivity which will underestimate the temperature of the meat as it cooks (and overestimate the temperature as it cools); see Table A1. Thus, so long as the pouches do not float to the surface or are packed too tightly in the water bath, we can generate heating (Table 1), cooling (Table 3), and pasteurization (Table 2) tables.

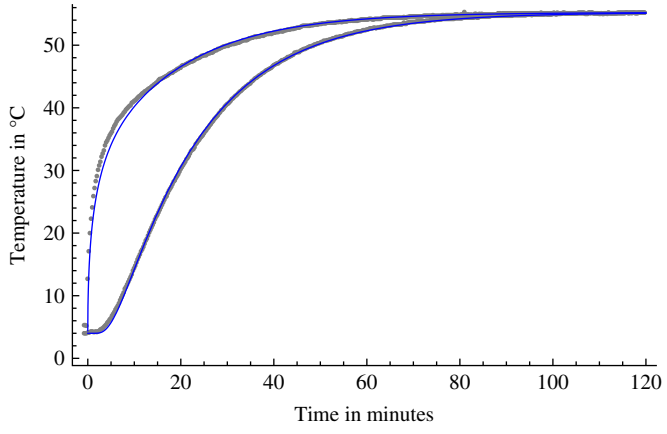

Fig. A1. A comparison of experimentally measured temperature with temperature predicted by (*) of an agar–agar gel block in a SousVide Supreme water bath. The model used the thermal diffusivity of water (1.4×10^{-7} m^2/s) and a surface heat transfer coefficient of 95 W/m-K. The data-logging thermometer used T-type thermocouple with one placed in the center and one at the surface. The top line is the temperature at the surface of the block and the lower line is the temperature at the center of the block.

Table A1
The thermal diffusivity (at 0 °C to 65 °C) of various types of food reported in the literature.

Food	Thermal diffusivity (10^{-7} m^2/s)	Reference
Beef	1.35–1.52	Markowski et al. (2004)
	1.22–1.82	Sheridan and Shilton (2002)
	1.11–1.30	Sanz et al. (1987)
	1.18–1.33	Singh (1982)
	1.19–1.21	Donald et al. (2002)
	1.25–1.32	Tsai et al. (1998)
Pork	1.12–1.83	Sosa-Morales et al. (2006)
	1.17–1.25	Sanz et al. (1987)
	1.28–1.66	Kent et al. (1984)
	1.18–1.38	Singh (1982)
Chicken	1.36–1.42 (White) and 1.28–1.33 (Dark)	Siripon et al. (2007)
	1.46–1.48 (White)	Vélez-Ruiz et al. (2002)
	1.08–1.39	Sanz et al. (1987)
Fish	1.09–1.60	Sanz et al. (1987)
	0.996–1.73	Kent et al. (1984)
	1.22–1.47	Singh (1982)
Fruits	1.12–1.40 (Apple), 1.42 (Banana), 1.07 (Lemon), 1.39 (Peach), 1.27 (Strawberry)	Singh (1982)
Vegetables	1.68 (Beans), 1.82 (Peas), 1.23–1.70 (Potato), 1.71 (Squash), 1.06–1.91 (Sweet Potato), 1.48 (Tomato)	Singh (1982)

Using the above models for the temperature at the slowest heating point of the meat, the classical model for the log reduction in pathogens is

$$\mathrm{LR} = \frac{1}{D_{\mathrm{Ref}}} \int_0^t 10^{(T(t')-T_{\mathrm{Ref}})/z}\, dt',$$

where D_{Ref} is the time required for an one decimal reduction in the pathogen at the reference temperature T_{Ref} and the z-value is the temperature increment needed for a 10-fold decrease in D. Despite concerns in Geeraerd et al. (2000) that the classical model is inappropriate for the mild heat treatment of sous vide cooking, Huang (2007) found that the classical model was (1–2D) more conservative than experimental observations for *Listeria*.

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