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Microwave pasteurization for ready-to-eat meals

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The food industry and the research community have shown interest in microwave pasteurization of packaged food products since the 1970s. Microwave heating offers possibilities of shorter processing time and better heating uniformity compared to conventional thermal processing using steam or hot water. It, thus, holds potential to deliver safe and higher quality foods. Factors that have hindered commercial applications of microwave pasteurization include engineering challenges in system design, relatively high costs for new equipment installation and operation, and un-familiarity with microwave heating systems. Consumer desire for convenience, food safety risks associated with e-commerce and home delivery of prepared meals, and regulatory requirements imposed by the Food Safety Modernization Act (FSMA) in the USA have generated great commercial interest in in-package pasteurization technologies. In this paper, we will review pathogens of concern in designing thermal pasteurization processes, regulatory guidelines for pasteurization, and advancements in microwave pasteurization system designs. We offer opinions as to how microwave assisted pasteurization will help the food deliver safe and high quality ready-to-eat meals to consumers through various distribution methods.

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Introduction

Chilled meals are gaining popularity in retail markets and in home-delivery businesses. But without proper thermal processing and chemical preservatives, chilled meals have very limited shelf-life and present great concern for food safety. Commercial production of not ready-to-eat (NRTE) meals does not have a final kill step for food-borne pathogens after the meals are packaged and before shipment. The food industry relies on consumers to closely follow cooking instructions printed on food packages to ensure safety of those products. Failure to follow cooking instructions creates a great safety risk to the consumer, economic losses to the companies, and potentially shatters consumer confidence in the industry as a whole. Food companies are particularly sensitive to negative news about their products which can be spread rapidly through social media. Effective pasteurization technologies are needed for commercial production of ready-to-eat (RTE) meals, frozen or chilled, that are free from bacterial and viral pathogens while satisfying consumers' desire for taste, nutrition and convenience. Microwave pasteurization offers opportunities for the food industry to produce high quality frozen and chilled RTE meals. This article aims to discuss current status regarding important bacterial and viral pathogens considered in design of thermal processes and related regulatory guidelines. We will also introduce advancements in microwave pasteurization system design and new tools for process development for RTE meals. Finally we will share our opinions about future applications of in-package microwave pasteurization technologies in addressing food safety concerns.

Processing conditions for pasteurization

Selection of target pathogens

Industrial pasteurization processing conditions are selected to control the bacterial and viral pathogens that likely contaminate the products. Considerations are also given to post-processing storage conditions and expected shelf-life. For instance, nonproteolytic *Clostridium botulinum* can grow at low temperatures (above 3.3 °C) and in a low oxygen environment. It is commonly selected as the target bacterium for vacuum or modified packaged products, in particular for seafood, with a reasonably long shelf-life. For high-quality and minimally processed meals, *Listeria monocytogenes* may be selected as the target bacterium. But the shelf-life of those meals are relatively short. Table 1 summarizes the thermal resistances (D and z values) of pathogenic bacteria of general safety concern and related process conditions required for 6 log reductions of those pathogens. The shelf-life of pasteurized food depends on both process and storage conditions. The minimum growth temperature for each bacterium serves as a good guideline for selecting appropriate storage conditions for the processed products. Detailed discussion about microbial safety concerns associated with chilled meals, criteria for selecting pasteurization process conditions, and expected shelf-life those products can be found in Daelman *et al.* [1], Silva and Gibbs [2], and Peng *et al.* [3••].

Table 1

Reported minimum growth temperature and thermal resistances of pathogenic microorganisms and viruses relevant to pasteurization

Organisms	Minimum growth temperature (°C)	Materials	Container	Reference temperature (°C)	D-value (min)	z-value (°C)	General process temperature (°C)	Time for 6D process (min)^a	Note	References
Microorganisms										
Bacillus cereus	4	Distilled water	Capillary tube (0.1g, D7 × H75 mm)	90	4.0	8.0	90	24.2	Spore (type AVTZ415)	[7,30]
				95	9.8	8.4		231.5	Spore (type INRAAVZ421)	
		Pork luncheon roll	Vacuum polyethylene bag (10 g, W70 × H130 mm)	95	2.0	8.6		45.8	Spore	[7,31]
				60	1.0	6.6	70	0.2	Vegetative cell	
Non-proteolytic *Clostridium botulinum*	3.3	Phosphate buffer	Pyrex tube (9 × 150 mm)	82.2	4.2	16.5	90	8.4	Spore (type ATCC 17844)	[7,32]
					1.5	8.3		1.0	Spore (type B CBW25)	
					16.7	6.5		6.3	Spore (type 17B)	
		Blue crab^b	TDT tube (1 g, 10 × 75 mm)		0.7	9.0		0.6	Spore (type E)	[5,7,33]
		Sardines in tomato sauce	–		2.9	6.3		0.18	Spore (type E Saratoga)	[7,34]
		Whitefish chubs			2.2	7.6		0.6	Spore (type E Alaska)	
		Rainbow trout	Glass tube (5 g)	93	0.4	10.4		4.7	Type E	[7,35]
		Whitefish		90	1.0	10.1		6.0		
Escherichia coli O157:H7	6.5	Chicken (3-11% fat)	TDT tubes (2 g)	60	0.4–0.6	4.4–4.5	70	0.01–0.02	Strain 204P	[7,36]
		Turkey and beef			0.5–0.6	4.4–4.8		0.02–0.03		
		Pork sausage (7-30%)			0.4–0.6	4.6–4.7		0.02		
		Ground beef	Whirl-pak bag (3 g, 150 × 229 mm)	65	0.4	6.0		0.3	EDL-931, 45753-35, CI-9218 and 933	[7,37]
Listeria monocytogenes	–0.4	Minced beef	Vacuumed plastic bag (10 g, W70 × H75 × T3 mm)	56	2.3–3.0	5.3–5.9	70	0.05	Serotype 4b (NCTC 11994)	[7,38]
		Beef	Vacuumed plastic bag (50 g, W50 × H50 × T20 mm)	56	3.1–3.3	5.5–5.6		0.1		
		Lobster meat	Flexible pouch (25 g, W80 × H110 mm)	62.7	1.1	5		0.2	HPB16 (Ser.3); HPB43 (Ser.l); HPB59 (Ser.3a); HPB395 (Ser. l/2b); HPB397 (Ser.4b); and HPB563 (Ser.l/2b)	[7,39]
		Chicken gravy	Glass vial (4 g)	65	0.5	6.1		0.5	Strain Scott A	[7,40]
		Ground beef	TDT tube (10 × 60 mm)	62.8	0.6–1.2	5.1–6.3		0.1–0.5		[7,41]
Salmonella spp.	6	Ground beef	TDT tube (10 × 60 mm)		0.5–0.7	5.6		0.2	–	[7,41]
		Chicken breast & thigh	Whirl-pak bag (3 g. 150 × 229 mm)	62.5	0.7–0.8	6.9–8.1		0.4–0.5	*S. Mbandaka, S. Heidelberg, S. Typhimurium, and S. Montevideo*	[7,42]
Staphylococcus aureus	10	Medium	–	60	4.8–6.5	7.7–8.0	70	2.0	Five strains	[7,43]

Table 1 (*Continued*)

Organisms	Minimum growth temperature (°C)	Materials	Container	Reference temperature (°C)	D-value (min)	z-value (°C)	General process temperature (°C)	Time for 6D process (min)[a]	Note	References
Viruses										
Hepatitis A virus	–	Blue mussel homogenate			1.07	13		9.1	Strain HM175	[44]
		Fetal monkey kidney (FRhK4) cells	Vial (2 mL)	72	0.9	12.5	70	7.8		[45]
		Mussel	PET pouch (10 g)	75	7.0	12	90	2.4		[46]
		Turkey deli meat	Plastic vacuum bag (6g, 130 × 190 mm)	72	1.0	12.8	70	8.6		[47]
		Spinach			0.9	13.9		7.6		[48]
Murine Norovirus[c]	–	RAW264.7 cell	Vial (2 mL)	72	0.3	9.3	70	3.0	MNV-1	[45]
		Turkey deli meat			0.2	11.0		1.8		[47]
Feline Calicivirus[c]	–	Blue mussel	Vial (2 mL)		0.1	11.4		0.9	FCV-F9	[50]
		Spinach			0.2	9.9		1.9		[49]
		Turkey deli meat	Plastic vacuum bag (6g, 130 × 190 mm)	72	0.1	11.9	70	0.9		[47]

[a] Values are extrapolated.

[b] National Blue Crab Industry Pasteurization and Alternative Thermal Processing Standards requires a $F_{85^{\circ}C}$ =31 min due to the recovering of the pathogen [5].

[c] Surrogate of Human Norovirus.

Regulatory guidelines

Pasteurization is generally defined as 'the process to reduce the most resistant microorganisms of public health significance to a level that is not likely to present a public health risk under normal conditions of distribution and storage' by the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) [4]. In the USA, specific pasteurization guidelines have been provided by the Food and Drug Administration (FDA) or the U.S. Department of Agriculture Food Safety and Inspection Service (USDA-FSIS) for only a limited number of products [3••]. For example, the FDA requires 6-log reduction of *C. botulinum* (nonproteolytic types B, E, and F) in seafood products [5]. The USDA-FSIS recommends at least 5-log reduction of *Salmonella* Enteritis in shell eggs [6]. There is no clearly defined process conditions recommended for vegetables and other products.

The European Chilled Food Federation (ECFF) provides guidelines for chilled food production [7]: 6-log reduction of *L. monocytogenes* (cold-spot heated to 70 °C and held for 2 min); or non-proteolytic *C. botulinum* (cold-spot heated to 90 °C and held for 10 min). The shelf-life of the pasteurized meals depends on characteristics of foods such as microbial cleanliness of the ingredients, pasteurization process and post-process storage conditions. In general, the recommended shelf life for products after a 70 °C–2 min process is $\leq$10 days when stored below 5 °C [3••], and after a 90 °C–10 min process is $\leq$6 weeks at 5 °C [3••].

No guidelines have yet been established for control of viruses. But frequent occurrences of foodborne viral infections have forced the industry to consider the inactivation of virus such as Hepatitis A virus (HAV) or human norovirus (HuNoV). Although viruses including HAV, HuNoV, and murine norovirus (MNV) cannot replicate in foods before transferring to the host, they can survive for 2 weeks at 4 °C [8•]. Table 1 summarizes recent data on thermal resistance of pathogenic viruses or viral surrogates. HAV is the most heat resistant among the listed viruses. The 90 °C–10 min processes should result in complete control of those viral pathogens. But the process condition for *L. monocytogenes* (70 °C for 2 min) is not sufficient to inactivate HAV. According to Peng *et al.* [3••], 72 °C–10 min should result in 6-log reduction of HAV and more than 6-log reduction of Hepatitis E virus. With a z value of 15 °C for HAV [3••], this process is also equivalent to an 80 °C–3 min process.

The optimum storage temperature for pasteurized RTEs is considered as below 5 °C. Strains of proteolytic *C. botulinum* are not inactivated in pasteurization, yet they do not grow under 10 °C [10•]. But short exposures to higher temperatures may not allow *C. botulinum* to produce toxins. For example, Golden *et al.* [11] reported no toxin production in nine different inoculated meals after 90 °C 10 min processing and stored at 25 °C for 48 h.

Process development

In an industrial in-package pasteurization process, product temperature changes with process time, the rate of temperature change depends on package dimension, physical and thermal properties of the product, and the heating method. Temperatures measured at the cold spot of the food packages are used to assess the accumulative thermal effect of the process on a target food pathogen. Numerous research has been reported on pasteurization of a wide range of products in different package sizes using conventional thermal processes [5]. Table 2 summarizes the processing conditions that targeted different bacterial pathogens and corresponding shelf-life. As illustrated in Table 2, product shelf-life increased with increasing processing time and reduced storage temperature.

In-package microwave pasteurization

Microwave systems

Microwave heating reduces processing time [12]. Thus, it is particularly suitable for pasteurization of pre-packaged heat-sensitive, high-viscous, semisolid, solid, multi-component meals [12]. Commercial systems used in European countries are summarized in Table 3. OMAC was the leader in the design of commercial microwave pasteurization systems in the late 1980s [12]. An OMAC system consisted of a horizontal cylindrical pressure vessel that had internal devices for five functions: compression, heating, equilibrating, holding, cooling, and decompression. It used multiple magnetrons at 2450 MHz for the heating section, and relied on compressed hot air to eliminate energy losses in the microwave heating sections and the holding section. After microwave heating, the temperature of product was equilibrated in a holding section before moving to the cooling section. The products were then moved into the decompression section before leaving the system [12]. Their design was later modified by TOPS Food in Belgium and Otsuka Chemical Co. in Japan in production of shelf-stable and chilled RTE meals [13••]. TOPS Food, for example, produced Italian spaghettis, Chicken Satay, and Kikka Madras in multiple compartment trays, with a shelf-life of 35 days when stored at or below 7 °C.

More recently, Micvac of Sweden (Micvac; URL: https://www.micvac.com) combined a unique package design with in-package microwave heating for production of ready-to-eat chilled meals with 30 days shelf-life at 8 °C. The process starts with filling food ingredients in polymer trays on a moving belt. The trays are sealed with a thin-layer film, and a hole is punched in the lid film on each tray. A patch with a valve is then attached to cover the hole before the trays are heated in a tunnel by 2450 MHz microwaves. Microwave heating generates steam inside the trays, causing expansion of the headspace in each tray. The internal pressure increases with microwave heating until it opens the valve and vents the steam and air. After exiting the heating zone, the product cools, the valve closes, and the remaining steam condenses, thereby creating vacuum in the package (Micvac–packaging options; URL: https://www.micvac.com/retail-solutions/packaging).

Early research in the USA was focused on development and regulatory filing of microwave assisted thermal sterilization (MATS) systems and processes [13••]. Starting in 2011, the USDA's National Institute of Food and Agriculture (NIFA) supported the development of in-package microwave pasteurization technology at Washington State University (WSU). Unlike other pasteurization systems used in Europe, the Microwave Assisted Pasteurization System (MAPS) developed by WSU consists of 915 MHz single-mode cavities along with water immersion (Figure 1). The new design overcomes major drawbacks in traditional 2450 MHz multi-mode microwave heating cavity designs, in particular the unpredictable heating patterns and severe edge heating in food packages. The single-mode microwave cavity provides stable and predictable heating patterns. Longer wavelength of 915 MHz microwaves allows the single-mode cavities to accommodate a wide range of food packages, from 300 g single meals to 2500 g institutional meals, which are difficult for much smaller sized 2450 MHz single-mode cavities. In addition, 915 MHz microwaves have deeper penetration in foods than 2450 MHz, enabling better temperature uniformity [14]. In MAPS, food packages are transported inside a shallow bed of water at high temperatures during microwave heating. The water immersion helps reduce severe edge heating commonly observed in domestic microwave ovens or previously reported industrial microwave systems [13••].

A MAPS system consists of four sections: preheating, microwave heating, holding, and cooling, each having a water circulation system with temperature control [15]. The microwave heating section has four inter-connected 915 MHz single-mode cavities. Food trays or pouches are moved through the four sections in stainless steel carriers. In contrast to the MATS technology developed by WSU [13••], MAPS doesn't require overpressure, and it is much easier to design continuous commercial systems, and is less expensive for uses in small and medium sized companies.

Tools for process developments

Significant advancements have been made in developing new tools to support the development of microwave heating processes. These include chemical marker-based model foods for heating pattern determination, mobile temperature sensors for accurate real-time temperature measurement in high power microwave heating systems, and computer simulation models for continuous microwave heating processes. Specifically, in order to develop an in-package microwave pasteurization to achieve the

Table 2

Process conditions of pasteurized products and their expected shelf-lives

Product	Process condition[a]			Targeted bacteria	Storage temperature (°C)	Expected shelf-life[b]	References
	Temperature (°C)	Time (min)	Package size				
Seafood products							
Blue crabmeat	85	31	*n.d.*[c]	C. botulinum type B, E, and F	5	<6 wks[d]	[5]
Broiler fillets, marinade	82.2	83.9[e]	200×500 mm, 1500g pouch		8	21 days	[51]
Fish bandong	70	2	300 g pouch	*L. monocytogenes*	3/8	3–4/1–2 wks	[52]
Meat Products							
Beef cube	82.2	496.7[e]	200×500 mm, 1500g pouch	*C. botulinum* type B, E, and F	8	21 days	[51]
		186.7[e]				14 days	
Pork cube		153.5[e]				30 days	
Beef tournados	68-69	2	*n.d.*	*L. monocytogenes*	3/8	3–4/1–2 wks	[52]
Leg of lamb							
Sirloin roast, steak							
Poultry products							
Chicken product	75	–[f]	300g pouch	*Spoilage microflora*	4	12–13 days	[53]
Chicken and turkey breast	70	2	*n.d.*	*L. monocytogenes*	3/8	3–4/1–2 wks	[52]
Vegetable products							
Baby potatoes	90	5	*n.d.*	*L. monocytogenes*	3/8	3–4/1–2 wks	[52]
Julienne carrots							
Broccoli puree	80	30	400 g or 180 g polypropylene trays	*Spore forming bacteria*	4	21 days	[54]
Courgette puree					10	<12 days	

[a] Process conditions indicates cumulative total lethality at cold spot.

[b] Mainly considered microbial aspects, not qualities of foods.

[c] Not described specifically.

[d] Chilled food regulation in Europe for 6-log reduction process. There are no references for shelf-life of specific food.

[e] Time includes come-up time.

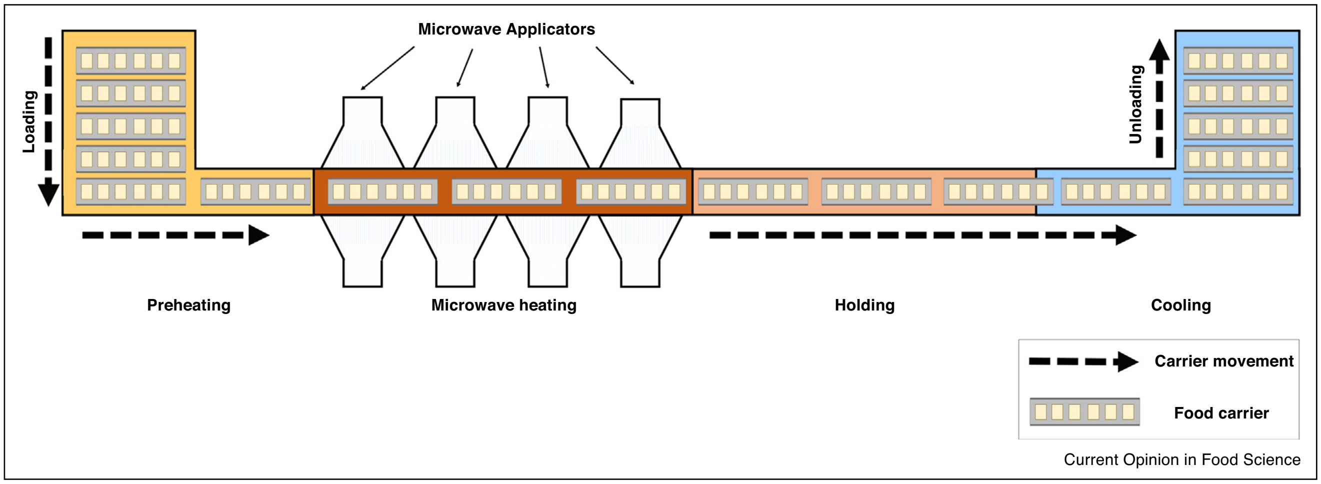
[f] Not specified, but pasteurized sample until the temperature of cold spot reached at least 75 °C.

Table 3

Commercial systems of microwave pasteurization for RTE meals

Company/University	Microwave Conditions		Zones of system	Specific Comment	References
	Type of cavity	Frequency			
OMAC	Multi-mode	2450 MHz	Compression ▶ heating ▶ equilibrating ▶ holding ▶ cooling ▶ decompression	Hot air is provided in the heating and holding sections to assist in convection heating.	[12]
Berstorff	Multi-mode	2450 MHz	Preheating (air) ▶ heating ▶ holding ▶ cooling	The product is hot filled at 55 ºC.	[55]
Top's Food	Multi-mode	2450 MHz	Heating ▶ holding ▶ cooling	Before microwave heating section, products are precooked.	[13••]
Micvac	Multi-mode	2450 MHz	Heating ▶ holding ▶ cooling	The special design of package valve on the film) allows natural vacuum upon cooling.	(micvac.com/retail-solutions/packaging)
WSU	Single-mode	915 MHz	Preheating (water immersion) ▶ heating ▶ holding ▶ cooling	All zones are in water bath to reduce the adverse effect of edge heating.	[13••]

Figure 1



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Schematic diagram on microwave assisted pasteurization system (MAPS) at Washington State University.

desired level of inactivation of a selected target bacterium, cold spots in food packages need to be determined first. Compared to conventional thermal processing, heating patterns in a microwave process are more complicated [13••]. Several model food systems have been developed at Washington State University for heating pattern determination in microwave pasteurization systems for processing temperatures between 70 and 100 °C [16•,17•,18,19]. When combined with a computer-based vision system [20], these model foods allow rapid detection of the cold and hot spots. The developed model foods include egg white, mashed potato, and gellan gel with M-2 chemical marker precursors [15]. These model foods can be used for heating pattern determination under different process conditions, depending on target bacteria such as *C. botulinum* spores or *L. monocytogenes* [21], or as a tool to evaluate quality changes in different thermal pasteurization processes, including microwave pasteurization [16•,17•,19].

Sharply increased computation power and memory capacities have made it possible to develop computer simulation models on desktop computers for microwave heating of moving food packages in a continuous system. Recently, food models were used to validate computer simulation based on a finite-difference time domain method for microwave assisted thermal processing systems [22]. The validated computer models were then used to study heating pattern stability as influenced by a possible shift of microwave generators [23,24] or insertion of metallic mobile temperature sensors [25]. In the near future, computer simulation models will likely be integrated with kinetic data for quality changes in thermal processing to allow food companies to select optimum process parameters based on food formulations and desired thermal lethality and shelf-life.

Quality of microwave pasteurized products

When using MAPS, it typically takes about 2–3 min for product temperature to increase from a preheating temperature of, for example, 50 °C to a final temperature of, for example 90 °C. Thus, it is expected that microwave pasteurized products have better quality than conventional thermally processed products [18]. Evidence for higher quality microwave pasteurized foods, compared to hot water pasteurization, has been documented in several published papers. For example, microwave processed carrots showed less color changes than hot water processed carrots with same $F_{90\,^{\circ}C}$ value [9]. Bottled acidified asparagus spears processed by microwave pasteurization had less texture degradation compared to those treated by hot water heating [26]. RTE pasta processed by MAPS had similar sensory quality compared to heat-and-eat pasta dishes [27] (Figure 2). These results indicate the potential of microwave pasteurization for pre-packaged food with improved quality and safety.

Potentials for microwave pasteurization of RTE meals

The food market is changing rapidly in response to increasing consumer demands for convenient and healthy foods with clean labels [28,29,56]. The mild thermal treatments provided by microwave pasteurization technology will allow food companies to produce a wide range of chilled or frozen RTE meals for different consumers. In particular, microwave pasteurization can be a viable processing option for companies to stay in compliance with new FSMA rules. Yet large food companies are typically slow in adopting new food processing technologies that could potentially disrupt their existing food production and distribution systems. It is very likely that small and medium sized companies or new start-ups will use flexible microwave pasteurization systems to produce chef inspired or specially formulated (for health benefits) high quality chilled RTE meals free from bacterial and viral pathogens. These meals can be served by airlines, schools, nursing home and hospitals, delivered to consumers at home via e-commerce, and marked in retail stores or through refrigerated vending machines.

Figure 2

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Seafood pasta processed by MAPS at 90 °C for 10 min.

In the USA, an alarming 31% of the food supply is wasted at either the retail or consumer level (USDA OCE—U.S. Food Waste Challenge FAQs; URL: https://www.usda.gov/oce/foodwaste/faqs.htm). With advancement of effective wireless sensors to monitor temperature changes through distribution and storage, it is possible that new software applications on smart phones will allow meal providers, retailers, and consumers to obtain accurate information on the shelf-lives of RTE meals to avoid waste.

Conflict of interest statement

Nothing declared.

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