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Heat penetration and quality attributes of superheated steam sterilization (SHS) home meal replacement (HMR) meat products stew

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A R T I C L E I N F O

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A B S T R A C T

Retort sterilization (RTS) is essential for the production of shelf-stable home meal replacement (HMR)-type Korean foods. However, the thermal abuse caused by excessive retort processing can result in quality degradation. Short processing times can minimize quality degradation and nutritional loss during sterilization. The potential of superheated steam sterilization (SHS) for producing shelf-stable HMR was investigated. The effect of SHS at 140 °C on HMR meat products stew was compared with that of RTS. SHS allowed a rapid temperature increase in the sausages and spam. In the sterilization equivalence of sausage, SHS at 140 °C and 1 s showed the F_0 value of 34.7 ± 5.9 which could sufficiently satisfy the microbial safety standard of F_0 values at 7–10 min. Thermal doses of SHS treated sausage was 97 ± 9 k°C·s which has lesser values (119 ± 9 k°C·s) than that of RTS. The sausage hardness after SHS was 107.7 ± 13.3 N, which has lower thermal degradation than the 78.9 ± 7.1 N observed after RTS. This study demonstrates the potential of SHS treatment for maintaining the quality of sterilized HMR products.

1. Introduction

Home meal replacement (HMR) is a convenient food prepared outside the home for in-home consumption (Bumbudsanpharoke & Ko, 2022). Its consumption has been continuously increasing over the past few decades owing to several social circumstances such as an increase in the number of single-person and dual-income households (Choi & Kim, 2020; Yu, Ahn, & Park, 2023). The Korean HMR market has recently focused on soup- and stew-type products, that include meat or meat products based stews *such as Budaejjigae*, *Kimchijjigae*, *Doenjang*, *Seollengtang*, and Galbitang (Jun 2020). Among these soup- and stew-type products, HMR meat products are one of the most popular dishes with a distinctive flavor and texture resulting from their meat-derived ingredients (sausage, spam). Meat products are prepared using ham, sausages, kimchi, pork, and bean curd, which are combined and cooked in a broth (Choi & Kim, 2020). Meat stew is rich in nutrients and water, and is easily contaminated by bacteria, leading to poor taste and even the production of microbial toxins, such as the deadly botulism (Li, Wu, & Xu, 2021; Pelug, 2010; Yang et al., 2023). Therefore, meat products stew should be shelf-stable through commercial sterilization. Currently, shelf-stable HMR products are produced by retort sterilization (RTS). In this process, the food is hermetically sealed into containers, where the holding phase is initiated to ensure that the product reaches the desired cooking and sterilization point through the application of temperatures ranging between 116 and 121 °C for a designated time period (Alexandersson & Ristinmaa., 2021; Giraldo Gil, Ochoa González, Cardona; Sepúlveda, & Alvarado Torres, 2020; Singh, Singh, & Ramaswamy, 2015). As a result, there are significant quality and nutritional losses in HMR products during retort processing owing to intense heating over a long period and subsequent thermal abuse (Park, Balasubramaniam, & Sastry, 2014; Yu et al., 2023). In case of meat products, RTS treatments results in the softening of texture and modification of its own flavor since conductive heating penetration into meat products could be substantially accelerated with current RTS technology (Durance, 1997). Once RTS is aimed to ensure the sterilization of all cold points (worst case processing scenario) in the food product, it essentially induce the

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biochemical changes of major components of meat products such as meat protein, lipid and minerals (Barbosa-Cánovas, Medina-Meza, Candoğan, & Bermúdez-Aguirre, 2014).

Further research is required to determine the optimal sterilization conditions for specific commercial retorted product and new alternative sterilization technology (Choi, Cheigh, & Chung, 2013). Superheated steam would be one of potential alternatives for conventional retort processing. Superheated steam refers to steam supplied with additional sensible heat to raise its temperature above the saturation point at a given pressure, which provides advantages with increased heat transfer and energy efficiency (Cenkowski, Pronyk, Zmidzinska, & Muir, 2007). Superheated steam (generally 125–300 °C) treatment reportedly inactivates vegetative bacteria and spores on dry surfaces rapidly (Ban, Yoon, & Kang, 2014; Jo et al., 2019; Kim, Kim, & Kang, 2020; Park, Balasubramaniam, Snyder, & Sekhar, 2022; Park, Xu, Balasubramaniam, & Snyder, 2021). It has advantages of rapid heat transfer to reduce the sterilization time. Additionally, recent climate change also requires a research need for advanced sterilization technique over conventional retort sterilization. An increase in the global temperature essentially results in the proliferation of microorganisms and subsequent produce food-borne diseases, as the average global temperature reaches the optimal temperatures for these germs (Duchenne-Moutien & Neetoo, 2021; Mirón, Linares, & DÍaz, 2023).

In this study, superheated steam sterilization (SHS) was used to produce HMR meat products stew as an improved retort sterilization (RTS) technique. In this study, we compared the heat penetration and quality attributes of SHS and RTS meat products stew. The objective of this study would be established as followed: 1) Investigate the potential of SHS treatment for alternative sterilization technique of conventional RTS treatment; 2) Provide the equivalent sterilization effect of SHS treatment conditions (temperature, time) to RTS; 3) Analyze the beneficial effect of quality attributes for SHS treatment as compared to those of RTS. The results of this study demonstrate the potential of SHS to produce shelf-stable HMR meat products stew to minimize thermal abuse.

2. Materials and methods

2.1. HMR meat products stew preparation

Precooked HMR meat products stew containing water, red pepper sauce, sausage, spam (canned meat), ginger powder, onion, and squash were provided by SF Innovation Co. (Gangnam-Gu, Seoul, Republic of Korea). HMR products (250 g) were packed in retort pouches (180 mm × 260 mm). A package of tested HMR meat products stew contained water (soup, 160 g), red pepper sauce (6 g), sausage (25.6 g), spam (19.1 g) (canned meat), ginger powder (1.3 g), onion (28 g), and squash (10 g). Sausages and spams used for the heat penetration study were regularly shaped into cylindrical pieces (diameter: 15 mm, length: 40 mm) using a cork borer (Fisher Scientific, Pittsburgh, Pennsylvania, USA). A K-type thermocouple (0.51 mm diameter, TFAL/CY-020, Omega Engineering, Stamford, Connecticut, USA) was used to measure the temperature of the sausage, spam, and soup by insertion at the geometric center of these ingredients.

2.2. SHS system

Fig. 1 shows the custom-designed SHS system used in this study. It was equipped with a steam generator (60 kW), a superheated steam generation unit, SHS chamber, counter pressure air compressor, water-cooling system, pressure transducer, pressure regulator, and data acquisition system (Keysight Technologies, Colorado Springs, CO, USA). Saturated steam was produced from the 60-kW steam generator and then transferred to the superheated steam generation unit. In this unit, the superheater (10 kW) re-heated the saturated steam to produce the superheated steam at 140 °C and 370 kPa, following its transfer to the SHS chamber. During SHS treatment, the temperature and pressure of the superheated steam were automatically controlled using a temperature proportional-integral-differential (PID) controller (ITC-100; Inkbird, Shenzhen, China) and a pressure regulator. Counter-pressure air was supplied to the SHS chamber to prevent breakage of the HMR pouch due to steam generation in the package. After SHS treatment, the HMR meat products stew pouch was rapidly cooled by water spraying.

2.3. Implementation of RTS and SHS

In the present study, RTS was performed for comparison with SHS. A variable temperature retort sterilizer was used for RTS at 121 and 130 °C for 1 s and 1-, 3-, and 5-min. Detailed information on the RTS process has been described by Yu et al. (2023).

In SHS, the superheater continuously re-heated the saturated steam to provide the superheated steam at 140 °C to the HMR meat products stew pouch. In the preliminary experiment, 140 °C was determined as the target temperature because ingredients of HMR meat products stew demonstrated significant quality degradation, such as burnt flavor, textural degradation, and discoloration over 140 °C. Sausage exhibited

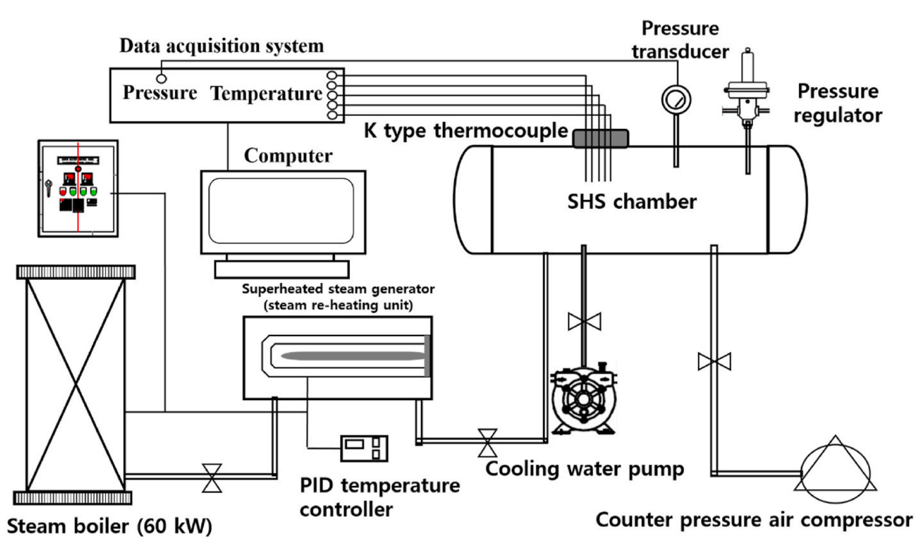

Fig. 1. Schematic diagram of custom fabricated superheated steam sterilization (SHS) equipment for variable target temperatures. (reproduced and modified with permission from Yu et al., 2023: Springer Nature and Copyright Clearance Center: 5660010922718).

the slowest temperature come-up; therefore, it was considered a cold spot. When the temperature of the sausage reached 140 °C, the HMR meat products stew pouch was held for four different holding times (1s, and 1, 3, and 5 min). During the temperature holding time, the PID controller maintained the target superheated steam temperature of 140 °C. Counter pressure is essential to prevent the rupture of the HMR pouch. An air compressor provided pneumatic pressure to maintain the target counter pressure of 370 kPa. The HMR meat products stew pouch was rapidly cooled to below 50 °C by water spraying in the SHS chamber after the holding time. Following SHS treatment, the HMR meat products stew pouch was cooled to room temperature using ice water. Fig. 2 implemented the experimental procedure and processing details.

2.4. Heat penetration evaluation

Heat penetration is essential for evaluating the effect of thermal treatment on the quality attributes of HMR meat product stews. In this study, the heat penetration was assessed based on the temperature come-up time (CUT), heating rate, and thermal dose.

2.5. Temperature come-up time (CUT) and heating rate

CUT was calculated based on the required time (min) for the temperature of sausage and spam to increment from the initial temperature (20 °C) to the target temperatures (121, 130, and 140 °C). The heating rate was used to estimate the temperature increment of the HMR meat products stew ingredients per minute, as shown in Eq. (1).

$$\text{Heating rate } (^\circ\text{C}/\text{min}) = \frac{T_t - T_i}{\text{CUT}} \tag{1}$$

Here, T_i and T_t are the initial and target temperatures (°C). CUT is the temperature come-up time to the target temperature.

2.6. Cumulative lethality (F_0)

In this study, sterilization equivalence between RTS and SHS was estimated through lethality F_0 value as shown in Eq. (2).

$$F_0 = \int_{t_i}^{t_f} 10^{\left(T - T_{ref}\right)/z} dt \tag{2}$$

Here, F_0 is cumulative lethality (min), t_i: initial time of sterilization, t_f: final time of sterilization, T is the cold spot temperature measured at arbitrary time (t), T_{ref} is standard retort temperature (121.1 °C), z is set to 18 °C for *Geobacillus streaothermophilus which is thermophile* (Bouveresse, Cerf, Guilbert, & Cheftel, 1982; Fraiha, Ferraz, & Biagi, 2010). In general, shelf stable HMR products require the F_0 value of 7–10 min (Lee & Lee, 2009). In this study, F_0 value was numerically calculated using the trapezoidal integration function of the MATLAB software (Version 7.9.0.529, Mathworks Inc., MA, USA).

2.7. Thermal dosage (T_d)

In a previous study (Yu et al., 2023), the thermal dose (T_d, °C·s) was successfully used to estimate the extent of HMR food thermal exposure during the sterilization process as shown in Eq. (2), and was calculated using Eq. (2). T_d was calculated by integrating the cold spot temperature (T) as a function of the RTS and SHS times (t).

$$T_d = \int_{t_i}^{t_f} T dt = \frac{(T_0 + T_1)\cdot\Delta t}{2} + \frac{(T_1 + T_2)\cdot\Delta t}{2} + \frac{(T_2 + T_3)\cdot\Delta t}{2} + \ldots + \frac{(T_{n-1} + T_n)\cdot\Delta t}{2} \tag{3}$$

Here, T_d is thermal dose (°C·s), t_i: initial time of sterilization, t_f: final time of sterilization, T_n is arbitary tempeature at sterilziation time (t). The above equation was numerically calculated using the trapezoidal integration function of the MATLAB software (Version 7.9.0.529, Mathworks Inc., MA, USA).

2.8. Evaluation of the quality attributes

2.8.1. Analysis of hardness

In this study, the textural qualities of the sausages and spam were examined through analysis of hardness. Texture analyzer (TA-XT2i, Stable Micro System, Surrey, UK) was used to estimate the changes in hardness of sausage and spam after RTS and SHS treatment. The Warner–Bratzler shear force was selected to produce a deformation curve that demonstrated either the force exerted over time or the force exerted versus the distance traveled by the cutting blade (Girard, Bruce, Basarab, Larsen, & Aalhus, 2012). The Warner Bratzler v-slot blade (HDP/WBV) cut the treated sausage and spam with a pretest speed of 5.0 mm/s, a cross-head speed of 3.0 mm/s, and post-test speed of 5.0 mm/s as described in a previous study (Purohit, Reed, & Mohan, 2016).

2.8.2. Electronic nose aroma analysis of HMR meat products stew sauce

Changes in the aroma of RTS- and SHS-treated HMR stew sauce were investigated using a flash gas chromatography electric nose (Heracles II; Alpha-MOS, Toulouse, France) followed by previous study (Wojtasik-Kalinowska et al., 2016). For this analysis, 1 mL of sauce was transferred into a 20 mL headspace vial with sealing. These samples were incubated at 40 °C for 5 min under agitation (300 rpm) and then headspace was injected into the gas chromatography column within 13 s under pressure of 10 kPa. The results of electronic nose aroma analysis were quantitatively represented through principal component analysis

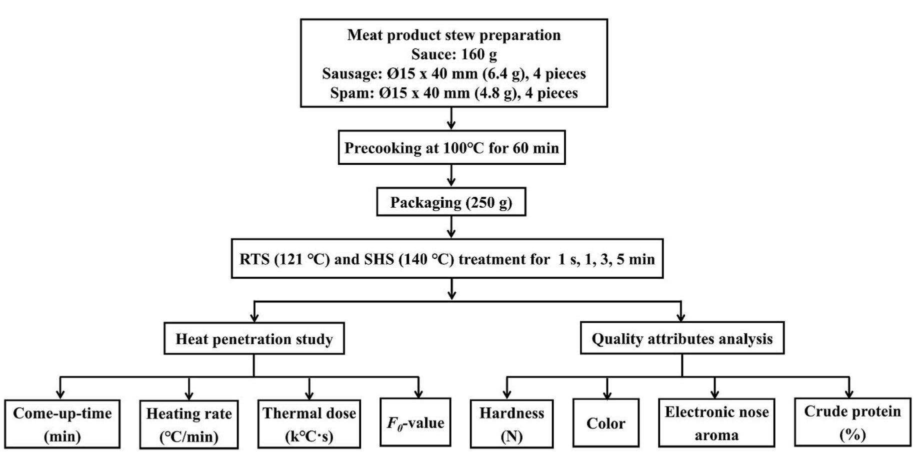

Fig. 2. Flow chart of experimental procedure for retort sterilization (RTS) and superheated steam sterilization (SHS).

(PCA) followed by previous study (Kang et al., 2021). In the PCA of the electric nose aroma, the X and Y axes were adopted for first and second principal aroma analyses, respectively and then coordinate distance were calculated from control sample. Longer coordinate distance from control sample implies more aromatic changes of SHS and RTS treated meat products sauce.

The numerical estimation of coordinate distance was conducted using an image analysis program (CellProfiler, https://cellprofiler.org/about). It is expressed as a non-dimensional number.

2.8.3. Color analysis

Discoloration of the sausages and spam was measured using a portable colorimeter (CR-10; Konica Minolta Sensing Inc., Sakai, Osaka, Japan). In this study, eight different RTS conditions and four different SHS conditions were evaluated. Therefore, the color measurement focused only on sausage and spam redness (a^* value) for clarity of data interpretation. a^* value (redness) is the most substantial value for meat product consumers. Most of consumers prefer redder pork chops and processed meats when they purchase the products in the market (Altmann et al., 2022; Guerra et al., 2023; Kong et al., 2023).

2.8.4. Crude protein analysis of meat products stew soup

The crude protein content of HMR meat products stew was analyzed for soup since protein of meat products will be released with cooking and sterilization. A nitrogen factor of 6.25 was selected for the Kjeldahl method (AOAC, 1990).

2.8.5. Statistical analysis

All experimental measurements and analyses were performed in triplicates. Multiple comparisons of the experimental data were conducted using analysis of variance and Fisher's least significant difference test at a 95% confidence interval (CI). SAS statistical software (version 9.1.3; SAS Institute, Cary, NC, USA) was used.

3. Results and discussion

3.1. Heat penetration studies

3.1.1. Temperature profiles, temperature come-up time, and heating rate

Fig. 3 shows the representative temperature history of a 5 min holding time for RTS (Fig. 3a and b) and SHS (Fig. 3c). Under all tested conditions of RTS and SHS, sauce showed the fastest temperature come-up, followed by spam and sausage. Spams showed a faster temperature increase than sausages. For example, in the case of SHS at 140 °C, sausage showed a CUT of 16.47 ± 1.0 min, whereas that of spam was 14.74 ± 0.8 min (Table 1). Accordingly, the heating rate of spam was significantly higher than that of sausages under all tested sterilization conditions ($P < 0.05$). This implied that the sausage casing functioned as a thermal insulator, resulting in reduced heat transfer. For both sausage and spam, SHS (140 °C) showed a significantly enhanced heating rate compared to RTS (121 and 130 °C) ($P < 0.05$). For example, in sausage, the rapidest heating rate of 7.30 ± 0.4 °C/min was found for SHS at 140 °C compared to those of RTS (5.73 ± 0.2 °C/min at 121 °C and 6.85 ± 0.3 °C/min at 130 °C). SHS resulted in a higher thermal gradient between the product and ambient steam than the retort treatment; therefore, an increased heat-transfer coefficient was possible for convective heat transfer in the chamber. Superheated steam provides advantages, such as increased heat transfer and improved energy efficiency (Ban et al., 2018).

3.1.2. F_0 value

Table 2 compares the F_0 values of different RTS and SHS treatments at different target temperatures and holding times. F_0 values increased as a function of increased sterilization temperature and holding times for both sausage and spam. RTS at 121 °C and 5 min satisfied with the sterilization criterial for shelf stable sausage and spam where F_0 ranges

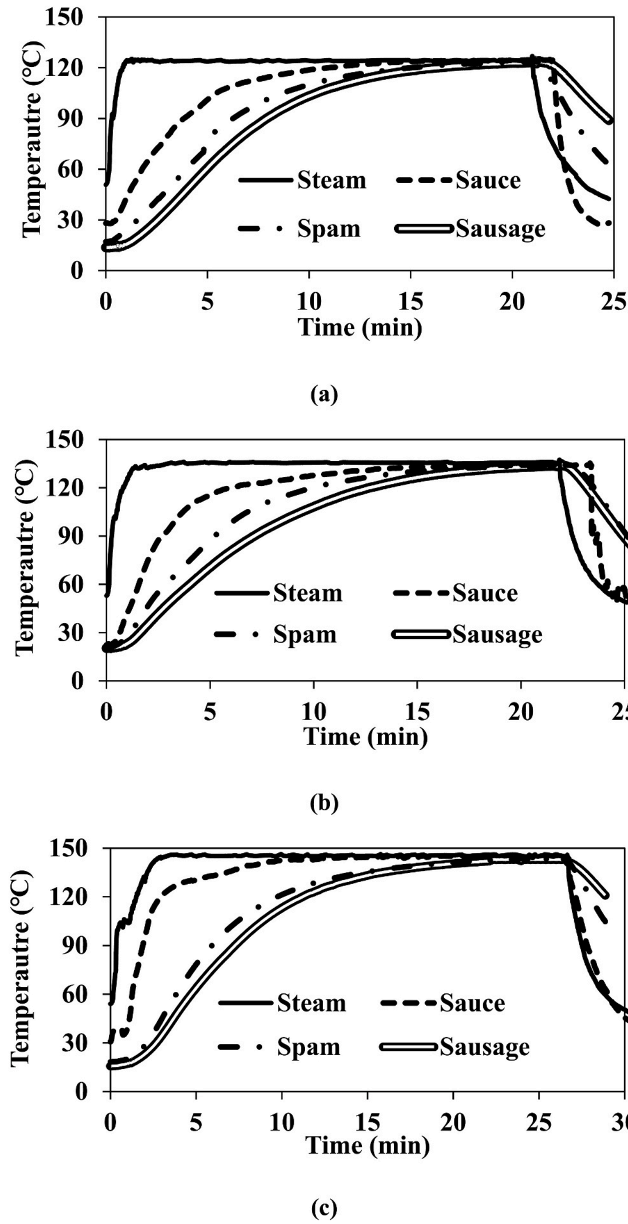

Fig. 3. Temperature histories of steam and HMR *meat products stew* ingredients (sauce, spam, sausage) during different target retort temperatures: (a) 121 °C; (b) 130 °C; (c) 140 °C.

at 7–10 min (Lee & Lee, 2009). SHS could significantly reduce the sterilization time for shelf stable product ($P < 0.05$). For example, SHS at 140 °C and 1 s showed the F_0 values of 34.7 ± 5.9 and 39.4 ± 7.8 for sausage and spam, respectively. In the sterilization equivalence, SHS at 140 °C and 1 s could sufficiently exceed the criteria of F_0 values (7–10 min) for shelf-stable products. This meant the SHS treatment at 140 °C and 1 s could be sufficient sterilization equivalence to conventional retort processing (121 °C and 5 min). In this study, F_0 value of SHS treatment could be considered for excessive sterilization treatment since its magnitude is significantly higher than F_0 magnitude of conventional retort processing ($P < 0.05$). However, in consideration of recent climate change, more severe thermal treatment could be required to adequately assure the storage stability of shelf stable product. Two highly influential climatic variables that affect the occurrence of foodborne diseases are temperature and precipitation (Duchenne-Moutien & Neetoo, 2021; Semenza et al., 2012). Climatic temperature increment of 2–3 °C increases the food spoilage and poisoning unless appropriate preservation

Table 1
Temperature come-up time (min) and heating rate (°C/min) of sausage and spam in the HMR *meat products stew* at different target RTS and SHS.

	Treatment	Target temperature (°C)	Sample	
			Sausage	Spam
Temperature come-up time (CUT, min)	RTS	121	17.47 ± 0.6^{a}	15.11 ± 0.5^{cd}
		130	16.05 ± 0.6^{bc}	13.99 ± 0.4^{d}
	SHS	140	16.47 ± 1.0^{ab}	14.74 ± 0.8^{d}
Heating rate (°C/min)	RTS	121	5.73 ± 0.2^{E}	6.74 ± 0.2^{D}
		130	6.85 ± 0.3^{CD}	7.85 ± 0.2^{AB}
	SHS	140	7.30 ± 0.4^{BC}	8.15 ± 0.4^{A}

$^{a\text{-}d}$Means (±Standard deviation) with a different letter within the sausage and spam are significantly different for come-up time ($P < 0.05$).
$^{A\text{-}E}$Means (±Standard deviation) with a different letter within the sausage and spam are significantly different for heating rate ($P < 0.05$).

Table 2
F_0-value of sausage and spam in the HMR *meat products stew* after different target retort temperatures.

Sample	Treatment	Target temperature (°C)	Holding time			
			1 s	1 min	3 min	5 min
Sausage	RTS	121	3.0 ± 0.3^{i}	3.8 ± 0.3^{hi}	5.8 ± 0.2^{hi}	8.2 ± 0.4^{ghi}
		130	9.3 ± 0.5^{gh}	12.5 ± 0.5^{g}	20.3 ± 0.3^{f}	29.7 ± 0.6^{e}
	SHS	140	34.7 ± 5.9^{de}	46.1 ± 5.7^{c}	72.7 ± 5.6^{b}	104.4 ± 5.5^{a}
Spam	RTS	121	3.4 ± 0.5^{hi}	4.2 ± 0.6^{hi}	6.2 ± 0.5^{hi}	8.3 ± 0.3^{ghi}
		130	9.2 ± 0.7^{gh}	12.5 ± 0.8^{g}	20.1 ± 0.6^{f}	29.2 ± 0.4^{e}
	SHS	140	39.4 ± 7.8^{d}	50.8 ± 7.5^{c}	77.6 ± 6.5^{b}	108.3 ± 5.1^{a}

$^{a\text{-}i}$Means (±Standard deviation) with a different letter within the sausage and spam are significantly different for F_0-value ($P < 0.05$).

technique is improved (Duchenne-Moutien & Neetoo, 2021; James & James, 2010). This study would provide the potential of SHS treatment for more strengthened sterilization process as well as better quality retention of HMR foods as compared to those of conventional RTS treatment.

3.1.3. *Thermal dose (°C·s)*

Table 3 shows the thermal dose of HMR meat products stew ingredients (sausage and spam) during RTS (121 and 130 °C) and SHS (140 °C) treatments. Spam has a higher heating rate than sausage; consequently, spam reaches its target temperature earlier than sausage. As a result, sausages were selected as the cold-spot products of the HMR meat products stew. During the sterilization process, heat transfer can occur by convection or conduction, and there is a region of slowest heating called a cold spot (Augusto, Tribst, & Cristianini, 2014). All the RTS-treated sausages exhibited significantly higher thermal doses than those treated with SHS for the same holding time ($P < 0.05$). RTS treatment requires a temperature holding time longer than 4 min at the central food temperature of 121 °C (Jeong et al., 2011). The microbial inactivation test was not done in this study, but RTS at 121 °C for 5 min is considered to ensure sufficient sterilization of shelf-stable HMR food. This RTS treatment demonstrated a thermal dose of 119 ± 9 k°C·s for sausage. In the microbial safety consideration of F_0 values, SHS

Table 3
Thermal dose (k°C·s) of sausage and spam in the HMR *meat products stew* after different target retort temperatures.

Sample	Treatment	Target temperature (°C)	Holding time			
			1 s	1 min	3 min	5 min
Sausage	RTS	121	74±2^{k}	87 ±5^{ijk}	105 ±9^{defgh}	119 ±9^{cd}
		130	83 ±6^{jk}	99 ±6^{ghi}	112 ±1^{defg}	127 ±1^{c}
	SHS	140	97 ±9^{ghij}	115 ± 12^{cdef}	129 ±2^{bc}	142 ±2^{b}
Spam	RTS	121	83 ±5^{jk}	97 ± 10^{ghij}	104 ±2^{efgh}	118 ±5^{cde}
		130	96 ±3^{hij}	103 ±5^{fgh}	118 ±5^{cde}	128 ±2^{bc}
	SHS	140	103 ±3^{fgh}	119 ±5^{cde}	129 ±1^{bc}	160 ±2^{a}

$^{a\text{-}k}$Means (±Standard deviation) with a different letter within the sausage and spam are significantly different for thermal dose ($P < 0.05$).

treatment at 140 °C and 1s would assure the sterilization equivalence to RTS treatment 121 °C and 5 min. Thermal doses of sausage were 119 ± 9 and 97 ± 9 k°C·s which corresponded to RTS (121 °C for 5 min) and SHS (140 °C for 1 s). In the sterilization equivalence, SHS showed significantly lesser thermal dose than RTS treatment ($P < 0.05$) and its efficacy is also evaluated in the quality attributes.

The thermal dose of spam showed a trend similar to that of the sausages. Our previous study (Yu et al., 2023) reported that the thermal dose could explain the effect of thermal treatment on the quality of various vegetable ingredients in shelf-stable HMR. Spam also showed significantly lesser thermal dose of 103 ± 3 k°C·s with SHS treatment (140 °C for 1 s) as compared to those of RTS treatment as 118 ± 5 k°C·s (121 °C for 5 min) ($P < 0.05$).

3.2. *Quality attributes*

3.2.1. *Hardness*

Table 4 presents the changes in the hardness of HMR meat products stew ingredients (sausage and spam) after RTS and SHS treatments. The untreated sausages (control) had a hardness of 234.1 ± 37.8 N. The hardness of the sausage significantly decreased with prolonged RTS holding time ($P < 0.05$); subsequently, it decreased to 78.9 ± 7.1 N following RTS at 121 °C for 5 min.

Cooking time considerably affects the textural properties of hardness, gumminess, chewiness, and springiness, but not adhesiveness, cohesiveness, or elasticity (Chen, Marcotte, & Taherian, 2009). Among those parameters, hardness of meat products represents the structure of protein matrix and emulsion stability (Estévez, Ventanas, & Cava, 2005; Zhang, Xu, Xue, Jiang, & Liu, 2019). Thermal treatment strongly influences the texture, protein content, and other important quality factors (color, flavor, and juiciness) (Abdulhameed, Yang, & Abdulkarim, 2016; Ayadi, Makni, & Attia, 2009; Wattanachant, Benjakul, & Ledward, 2005). Prolonged cooking reduces the textural parameters of sausages by denaturing myosin and collagen (Ayadi et al., 2009; García-Segovia, Andrés-Bello, & Martínez-Monzó, 2008; Khan et al., 2014). In the sterilization equivalence of F_0 value, SHS at 140 °C for 1s could adequately assure the microbial safety and shelf stable products for RTS at 121 °C for 5 min. As a result, it would be meaningful to compare the textural quality of sausage between RTS at 121 °C for 5 min and SHS at 140 °C for 1 s. The hardness of the sausage was 78.9 ± 7.1 and 107.7 ± 13.3 N after RTS at 121 °C for 5 min and SHS at 140 °C for 1 s, respectively. SHS showed a higher hardness of sausage as compared to that of RTS, implying that SHS minimized the textural degradation of sausage during the sterilization process. SHS has higher thermal energy than an equivalent amount of water at a given temperature for rapid heat transfer (James et al., 1998; Rana, Chen, Balasubramaniam, & Snyer,

Table 4
Hardness (N) of sausage and spam in the HMR *meat products stew* after different target retort temperature sterilization.

Sample	Treatment	Target temperature (°C)	Holding time			
			1 s	1 min	3 min	5 min
Sausage	Control		234.1 ± 37.8^{a}			
	RTS	121	163.9 ± 21.2^{b}	125.3 ± 3.3^{cd}	84.2 ± 18.4^{ef}	78.9 ± 7.1^{f}
		130	133.8 ± 2.8^{c}	109.4 ± 8.7^{cde}	101.5 ± 15.1^{def}	88.0 ± 8.5^{ef}
	SHS	140	107.7 ± 13.3^{de}	95.6 ± 6.5^{ef}	79.2 ± 11.0^{f}	45.4 ± 4.8^{g}
Spam	Control		13.98 ± 1.0^{A}			
	RTS	121	14.2 ± 0.5^{A}	13.1 ± 1.6^{ABC}	12.2 ± 1.4^{ABCD}	11.5 ± 0.4^{BCDE}
		130	13.5 ± 1.8^{AB}	11.1 ± 1.5^{CDE}	10.9 ± 1.0^{DE}	10.0 ± 1.2^{E}
	SHS	140	11.9 ± 1.8^{BCDE}	12.4 ± 0.2^{ABCD}	12.6 ± 1.1^{ABCD}	14.0 ± 0.3^{A}

$^{a\text{-}e}$Means (±Standard deviation) with a different letter within the sausage are significantly different for hardness ($P < 0.05$).
$^{A-E}$Means (±Standard deviation) with a different letter within the spam are significantly different for hardness ($P < 0.05$).

2022). For the textural qualities of spam, there was no significant difference between RTS treatment at 121 °C and SHS treatment at 140 °C. The tested spam ingredient was a commercial product that had been retort-sterilized before SHS treatment. This could be attributed to the lack of significant differences in textural qualities between the RTS and SHS treatments. This study demonstrates the potential of SHS treatment to minimize textural changes in sausage ingredients in sterilized shelf-stable HMR meat products.

3.2.2. Color

Table 5 presents the changes in the representative color value (a^* value) of sausages and spam after RTS and SHS treatments. The control sausage showed an a^* value of 27.4 ± 0.9. Neither RTS nor SHS treatments induced no significant changes in sausage color (P > 0.05). This might be due to the sausage casing, which insulated the structure; therefore, the soup from the HMR meat products stew could not be infused into the sausage. In this study, there was no bursting of the sausage casing in the HMR meat products stew because care was taken to control the counter pressure to prevent breakage of the HMR pouch using an air compressor and water pump during temperature come-up, target temperature holding, and cooling. Accurate pressure drop control is critical for delicate foods, including sausages, because of the increased risk of the casing bursting at rapid pressure drop rates (Feng, Drummond, Zhang, & Sun, 2014).

Spam showed discoloration following both the RTS and SHS treatments. For example, the control spam showed an a^* value of 20.4 ± 0.1, and then it increased to 24.4 ± 3.1 after RTS at 121 °C for 5 min. In case of equivalent SHS treatment (140 °C for 1 s) of spam to RTS (121 °C for 5 min), it showed the a^* value of 22.5 ± 0.8 which is lesser discoloration. Sodium nitrite ingredients of meat products contribute the development of red color with high temperature cooking (Hwang et al., 2018). Terns, Milkowski, Rankin, and Sindelar (2011) reported that higher a^* redness values associated with more rapid formation of cured pigment. In the SHS treatment, minimized thermal dose would contribute lesser changes in a^* values of spam as compared to that of RTS. No detrimental effects of SHS treatment were observed on the color attributes of spam during the production of shelf-stable HMR meat products stew.

Table 5
Color (a^*) of sausage and spam in the HMR *meat products stew* after different target retort temperature sterilization.

Sample	Treatment	Target temperature (°C)	Holding time			
			1 s	1 min	3 min	5 min
Sausage	Control		27.43 ± 0.9^{ab}			
	RTS	121	27.2 ± 1.2^{ab}	26.8 ± 0.5^{ab}	26.1 ± 1.2^{b}	26.8 ± 1.0^{ab}
		130	27.0 ± 1.1^{ab}	27.0 ± 1.3^{ab}	26.7 ± 0.2^{ab}	26.3 ± 1.2^{ab}
	SHS	140	27.8 ± 0.5^{a}	27.0 ± 0.4^{ab}	26.4 ± 1.6^{ab}	27.4 ± 0.3^{ab}
Spam	Control		20.37 ± 0.1^{E}			
	RTS	121	21.1 ± 0.4^{DE}	22.2 ± 1.2^{CDE}	23.8 ± 1.1^{BC}	24.4 ± 3.1^{AB}
		130	21.5 ± 0.5^{DE}	23.8 ± 3.6^{BC}	23.5 ± 0.4^{BC}	24.9 ± 0.4^{AB}
	SHS	140	22.5 ± 0.8^{CD}	24.8 ± 0.5^{AB}	25.7 ± 1.5^{A}	24.9 ± 2.3^{AB}

$^{a\text{-}f}$Means (±Standard deviation) with a different letter within the sausage are significantly different for each color value of a^*values ($P < 0.05$).
$^{A-F}$Means (±Standard deviation) with a different letter within the spam are significantly different for each color value of a^* values ($P < 0.05$).

3.2.3. Electronic nose aroma analysis of HMR meat products stew sauce

Table 6 presents the aromatic changes in the HMR meat products stew soup after different RTS and SHS treatments through the isolation distance of the electric nose analysis. Aroma is a key sensory characteristic of meat-based soups and is important for consumer appeal (Wang et al., 2022). RTS treatment for 1 s resulted in an isolation distance of 511 ± 102, which increased to 643 ± 46. The isolation distance significantly increased with elevated sterilization temperatures and prolonged holding times (P < 0.05). In the SHS sterilization (140 °C for 1 s) equivalence to RTS (121 °C for 5 min), the isolation distance increased up to 1336 ± 48, indicating the significant aromatic changes of HMR meat products stew soup. Both volatile and nonvolatile compounds determine the aromatic characteristics and contribute to most flavor characteristics of meat-based products (Qi, Liu, Zhou, & Xu, 2017; Wang et al., 2022; Zhang et al., 2018). Retort flavor occurs in meat products heated at temperatures above 100 °C and is associated with the

Table 6
Numerical estimation of PC1 electronic nose analysis results through isolation distance of HMR *meat products stew* sauce after different target retort temperature sterilization.

Treatment	Target temperature (°C)	Holding time			
		1 s	1 min	3 min	5 min
RTS	121	511 ± 102^{hi}	544 ± 103^{h}	466 ± 51^{i}	643 ± 46^{g}
	130	539 ± 17^{h}	784 ± 59^{f}	870 ± 20^{e}	989 ± 35^{d}
SHS	140	1336 ± 48^{c}	1386 ± 39^{c}	1521 ± 83^{b}	1607 ± 44^{a}

$^{a\text{-}i}$Means (±Standard deviation) with a different letter within the sauce are significantly different for aromatic distance ($P < 0.05$).

presence of sulfides, disulfides, and thiophenes (Li, Belloch, & Flores, 2023; Migita et al., 2017). In general, higher heating temperatures provide a stronger meat aroma during retort processing (Migita et al., 2017; Simmons, Carr, & McKeith, 1985). Flavor changes of thermal treated meat products attributes to lipid oxidation and lipid hydrolysis as well as Maillard–lipid interactions (Barbosa-Cánovas et al., 2014; Bindu, Ravishankar, & Srinivasa, 2007; Brunton, Cronin, & Monahan, 2002) In this study, no perceptible off-flavors were found in the SHS stew meat products. Further studies should investigate the sensory evaluation and consumer preferences for SHS-treated HMR products.

3.2.4. Crude protein analysis of meat products stew soup

Fig. 4 shows the changes in crude protein content of RTS and SHS treated HMR meat products stew soup. Control sample showed in the crude protein content of 6.31 ± 0.47 g/L Prolonged holding time increased the crude protein contents of both RTS and SHS treated soups. For example, crude protein contents of RTS samples at 121 °C were 9.22 ± 0.48 g/L, 9.66 ± 0.37 g/L, 10.31 ± 0.33 g/L and 11.33 ± 0.36 g/L at 1 s, 1 min, 3 min and 5 min holding times, respectively. Qi et al. (2022) reported that crude protein content increased in the braised soup of chicken meat. All the SHS treated soup of HMR meat products stew contained significantly higher crude protein content as compared to same holding time of RTS soup ($P < 0.05$). In the holding time of 1 s, SHS treated soup at 140 °C for 1 s contained significantly higher crude protein content of 11.80 ± 0.37 g/L than that (9.22 ± 0.48 g/L) of RTS soup at 121 °C for 1 s. When meat based soup is braised, proteins in meat were continuously migrated and it led to the enrichment of protein in the soup (Qi et al., 2022). Temperature is more important parameter than cooking time to release the protein based compounds to soup from meat products which are responsible for nutrition and flavor formation (Cambero, Ordoñez, García de Fernando, & Pereira-Lima, 2000; Jayasena, Dong, Nam, & Jo, 2013; Meng et al., 2022; Suleman, Wang, Aadil, Hui, & Zhang, 2020).

4. Conclusions

The custom SHS system enabled rapid heat penetration into HMR stews during the sterilization process. SHS enhanced the heating rates of meat products (sausages and spam) compared to RTS. In the sterilization equivalence, SHS at 140 °C for 1 s satisfied the F_0 value of conventional RTS at 121 °C for 5 min. Therefore, rapid SHS treatment could be potential sterilization technique to minimize the thermal abuse of conventional RTS treatment. SHS resulted in reduced thermal dose than that of RTS and it contributed better texture retention of meat products in stew. In the electric nose aroma analysis, no significant off-flavors were found in the SHS stew meat products. SHS treatment increased the crude protein contents in soup as compared to RTS treated soup. It would provide better nutrition and flavor formation for consumers.

This study demonstrates the potential of SHS treatment in the production of shelf-stable meat products with minimal thermal abuse and good quality retention.

CRediT authorship contribution statement

Han Soo Ahn: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Seung Su Yu:** Methodology, Visualization, Writing – review & editing. **Cho Yeon Kim:** Methodology, Visualization, Writing – review & editing. **Ye Won Kim:** Methodology, Visualization, Writing – review & editing. **Yohan Yoon:** Methodology, Visualization, Writing – review & editing. **Hanla Lee:** Methodology, Visualization, Writing – review & editing. **Sung Hee Park:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

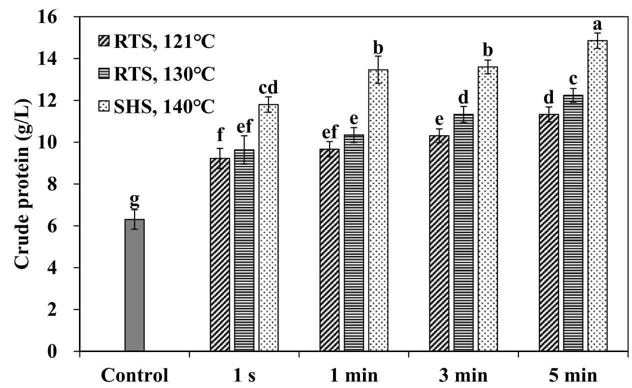

Fig. 4. Crude protein contents in soup of HMR *meat products stew* during different temperature and treatment time (121 °C, 130 °C, 140 °C treatment for 1 s, 1, 3, 5 min).

[a-g]Means (±Standard deviation) with a different letter within the sauce are significantly different for crude protein ($P < 0.05$).

Declaration of competing interest

All the authors declared that there were not financial/commercial conflicts of interest.

Data availability

Data will be made available on request.

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