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Domestic refrigerator temperatures in Spain: assessment of its impact on the safety and shelf-life of cooked meat products

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Abstract

Temperature is one of the main factors governing the growth of microorganisms. The aim of the present study was to provide temperature conditions representative of the food products stored in domestic refrigerators and to assess the impact of the temperature (fluctuation) on the shelf-life of refrigerated cooked meat products, from the safety and the spoilage point of view. The analysis of the time-temperature profiles recorded from 160 domestic refrigerators of households from small (28%) and large (72%) municipalities in Catalonia (Spain) showed that the 24h-registers mean temperature could be described by a normal distribution (mean = 5.4 °C, standard deviation = 2.3 °C) with a mean value within the upper limit of the appropriate storage temperature of refrigerated products (i.e. ≤ 6 °C). The impact of door openings or day and night was not significant. Temperature distribution showed differences depending on the season, being higher in the cold season than in the warm one. Noteworthy, refrigerators of elderly (≥ 65 years old) household showed a higher percentage of time at temperatures > 8°C in comparison with those of the general population. Overall, the 75th percentile of the distribution of the 24h-mean temperature values was 6.7 °C. This study can be used as a scientific evidence of the consumer storage stage when food business operators or laboratories conduct shelf-life studies. According to the simulation of the growth of *Listeria monocytogenes* and lactic acid bacteria in cooked meat products, risk scenarios were identified in which the critical level of the pathogen could be reached before lactic acid bacteria achieved the spoilage level. The fluctuation of the refrigerator temperature ranged from 0.5 up to 12.2 °C within the 24h-profile. The assessment of the safety of cooked meat products stored at constant temperature or under different time-temperature profiles showed that both the mean and the fluctuation of the profile had an impact

on the shelf-life, which was higher at low temperatures. The improvement of the household refrigerated storage would be an effective way to increase food safety of refrigerated ready-to-eat food.

1. Introduction

The control of the time and temperature along the food cold chain (from producer to consumer) is of paramount importance for maintaining the safety and quality of perishable food products because temperature is one of the main factors governing the growth of microorganisms. Within the cold chain maintenance, the first steps (i.e. processing and distribution) are under the responsibility of the food business operator (FBO) and are in most cases reasonably well controlled (EFSA, 2008). During the subsequent household storage, in which products may spend a considerable part of their shelf-life, the temperature control depends on the diligence of the consumers. Home storage is probably one of the most critical parts of the cold chain and tends to be the weakest link. Data of foodborne diseases indicate that up to 87 % of reported foodborne disease outbreaks occur at household level and improper handling, storage and preparation have a major role in this figure (Food Standards Agency, 2018; Redmond & Griffith, 2003).

The current EU regulations establish that the responsibility of the safety of commercialized products relies on the FBO, who have to demonstrate to the competent authority that the food products they put on the market are safe throughout its shelf-life taking into account the reasonably foreseeable conditions of distribution, storage and use, thus including the normal storage and use by the consumers (European Commission, 2002, 2005). Reliable data on consumer storage conditions and up-to-date information on consumers' refrigerator temperatures is key for setting up shelf-life of perishable refrigerated products. This type of data was one of the identified data gaps that need to be fulfilled to reduce uncertainty of quantitative microbial risk assessments and to conclude on the quantitative impact of the factors contributing to food safety (EFSA BIOHAZ Panel, 2018; EURL Lm, 2014; Pérez-Rodríguez, Carrasco, Bover-Cid, Jofré, & Valero, 2017). Moreover, data representativeness in relation to the temperature of the food products is in some cases limited as these characteristics depend on the type of measurement (discrete or continuous), its duration, the location of the probe (e.g. inside the refrigerator or on the surface or the inner parts of a product) and the sensitivity or thermal inertia of the probe.

Psychrotrophic bacteria that can grow during refrigerated storage are particularly of concern. This is the case of lactic acid bacteria (LAB) and *Listeria monocytogenes* in ready-to-eat (RTE) cooked meat products that have the potential to be contaminated with these microorganisms and support their growth to high numbers due to their physicochemical properties (EFSA BIOHAZ Panel, 2018). The contamination of cooked meat products commercialised in convenient formats (e.g. sliced and packaged under modified atmosphere or vacuum) with *L.*

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monocytogenes often occurs at the processing level as the pathogen may be present on equipment, facilities and at the point of sale, for example during slicing (EFSA, 2013). Though the initial levels due to exposure after post-lethality contamination are usually below the quantification limit (Jofré et al., 2016), the growth of the pathogen during storage of the product limits its shelf-life, known as the period during which the products keeps pathogen at levels below the maximun allowed level (i.e. 100 cfu/g in EU; European Comission, 2015). An extensive literature search reported prevalence of *L. monocytogenes* ranging between various studies from 0 to 50% (mean 7%) in cooked meats (Jofré et al., 2016). Additionally, cooked meat products are often highly perishable due to their pH and high water activity and when exposed to post-lethality contamination become high-risk foods regarding *L. monocytogenes*, particularly for elderly population and pregnant woman (EFSA-ECDC, 2018; Pérez-Rodríguez et al., 2017).

The aim of the present study was: *(i)* to provide new data on general population (including the elderly) domestic refrigerators' time-temperature profiles representative of the temperature of refrigerated food, in particular RTE cooked meat products and *(ii)* to evaluate the effect of the storage temperature on the safety and the shelf-life of cooked meat products by simulating the growth of *L. monocytogenes* and LAB as the main pathogen and spoilage organisms, respectively.

2. Material and Methods

2.1. Evaluation of thermal inertia of data loggers and cooked ham

Temperature records of a 175-T1 data logger (Testo) were compared with the records of a 177-T4 data logger (Testo) connected to T type thermocouple inserted in the centre of a 1-cm thick slice of cooked ham. The assembly was stabilized at 24 °C in an incubator (Memmert IPP500, Schwabach, Germany) and subsequently put in a laboratory refrigerator (Heraeus Labor 140, Hanau, Germany) set at 5 °C. After 16 h, the assembly was put back to 24 °C. The study of the effect of door openings was performed by stabilizing at 5 °C an assembly consisting of a 175-T1 data logger, a thermocouple inserted in the centre of a 1-cm thick slice of cooked ham and a thermocouple measuring air temperature placed close to the same slice of cooked ham. The door of the refrigerator was opened four times (for 30, 30, 30 and 60 s) every 5 min. Each data logger recorded the temperature every 10 s. Temperature values recorded by the data loggers were downloaded using Testo Comfort Basic software (Testo, Lenzkirch, Germany) and analysed with Microsoft Excel 2013 (Microsoft, Redmond, USA).

2.2. Temperature data collection of domestic refrigerators

The temperature of 160 domestic refrigerators of households was surveyed in Catalonia (Spain). Participants were selected to include small (<10,000 habitants; 28% of households) and large population municipalities (>10,000 habitants; 72% of households). Temperatures were monitored for a minimum period of 24 h with Testo 175-T1 data loggers (Testo, Alton, UK) programmed to record the temperature at 10 min intervals. Data loggers were calibrated within the range of temperatures recorded with a maximum permited error of ± 1 °C. Participants were asked to place data loggers in the position where they usually store cooked meat products and to fill in a brief questionnaire requesting information about: (i) Participant household basic information (age, gender and place of residence); (ii) Date and time of the beginning/end of the temperature recording; (iii) Brand of the refrigerator; (iv) Position of the data logger inside the refrigerator and (v) Refrigerator load level (i.e. nearly empty-half, full-completely, full). For a set of 20 refrigerators, the temperature was recorded twice, in the cold and the warm season. Recorded values were downloaded from the data loggers as described in section 2.1.

2.3. Data analysis

For each refrigerator, all temperatures recorded when the temperature of the data logger was stabilized were used to calculate the minimum, maximum, fluctuation amplitude, mean refrigerator temperature ($\overline{X}_{24h}$), mean night temperature ($\overline{X}_{Night}$, temperatures recorded from 21:00 to 08:59) and mean day temperature ($\overline{X}_{Day}$, temperatures recorded from 9:00 to 20:59). The mean temperature of each refrigerator ($\overline{X}_{24h}$) was used to calculate the distribution of the $\overline{X}_{24h}$ in terms of mean, standard deviation, minimum, maximum, range, percentiles and percentage of domestic refrigerators showing $\overline{X}_{24h}$ temperatures above -2, -1, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 °C. Cold and warm seasons were established based on the Catalonia monthly average air temperature (available at the *Servei Meteorològic de Catalunya*, www.meteo.cat) considering cold and warm season those months in which mean temperature was below 10 °C or exceeded 20 °C, respectively. Elderly population households were considered those inhabited by people aged over 64 (n=27). Statistical analysis was conducted with T-test (for day-night and cold-warm season comparisons) and one-way ANOVA with the post-hoc Tukey test (for position and load level comparisons) using Statistica 8.0 software (Statsoft, Tulsa, UK).

2.4. Simulation of growth of L. monocytogenes *and lactic acid bacteria in cooked meat products at different temperatures*

The growth behaviour of *L. monocytogenes* and LAB were estimated using the predictive model "*Listeria monocytogenes* in seafood and chilled meat products" and "*Listeria monocytogenes* and lactic acid bacteria" available at the *Food Spoilage and Safety Predictor* (FSSP v4.0, specific equations are shown in the help function of the application (http://fssp.food.dtu.dk/),

which were satisfactorily validated for cooked meat products (Mejlholm & Dalgaard, 2009), demonstrating their reliability for predictive purposes. The following model inputs were used: (i) constant temperature and dynamic time-temperature profiles from surveyed domestic refrigerators were used as inputs of the predictive model; (ii) physico-chemical characteristics representative of cooked meat products currently available on the market: pH=6.0, a_w=0.974, NaCl=2.9%, residual nitrite below 5 mg/kg, lactate=0.75% and moisture=73.63% (Bover-Cid, Jofré, Belletti, & Garriga, 2015); (iii) no lag time was included in the simulation as a conservative (worst-case) scenario; (iv) *L. monocytogenes* initial contamination level was set at 1 cfu/g, a conservative but reasonably foreseeable scenario (Ross, 2010) and several scenarios for LAB contamination, from 10 to 10^5 cfu/g were assessed.

From the food safety perspective, the shelf-life of cooked meat products was established as the time required for *L. monocytogenes* to reach 100 cfu/g, the maximum allowed level in several regulations (e.g. Regulation (EC) 2073/2005 (Europe), Policy on *Listeria monocytogenes* in Ready-to-Eat Foods (Canada), Food standards code 1.6.1 (Australia & New Zealand)), i.e. time to 2-log increase (Hereu, Dalgaard, Garriga, Aymerich, & Bover-Cid, 2014). Time to spoilage was estimated through the simulation of the growth of LAB, which are known to be the main cause of spoilage of vacuum packaged cooked meat products when they reach 10^7 cfu/g (EFSA BIOHAZ Panel, 2016). The effect of temperature and initial LAB counts to time to spoilage was investigated using the same physico-chemical characteristics described above as inputs of the predictive model.

3. Results and discussion

3.1. Thermal inertia of the data loggers

Figure 1A compares the temperature profiles registered by a Testo 175-T1 data logger and a highly responsive T type thermocouple inserted in the centre of a 1-cm thick slice of cooked ham. The profiles showed that both temperature decrease and increase was faster in the Testo 175-T1 data logger than in cooked ham when they were placed from room temperature to a refrigerator and *vice versa*. For example, it took 2.8 and 5.0 h to the data logger and the cooked ham, respectively, to decrease from 24 °C to 5.5 °C. However, in the presence of frequent door openings once the assembly was stabilised in a laboratory refrigerator set at 5 °C, the temperature profile of both the data logger and the cooked ham kept constant at 5.1-5.2 °C, while the profile obtained with a thermocouple measuring air temperature fluctuated widely, with minimum and maximum temperatures of 3.3 and 8.7 °C, respectively (Figure 1B). In agreement, previous studies showed significantly lower temperature variations in foods or water than in the surrounding environment (Garrido, García-Jalón, & Vitas, 2010; Raab et al., 2008). Conversely, in surveys using highly responsive probes, door openings were related to increased refrigerator temperature and mean and maximum temperature fluctuation ranges of 0.2-3.6 °C

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and 1.1-7.6 °C, respectively, were recorded (Brennan, Kuznesof, Kendall, Olivier, & Ladha, 2013). Accordingly, a temperature profile provided by the type of data logger used in the present study would be more representative from the temperature of food products stored in the refrigerator than a thermocouple measuring air temperature. Taking into account inertia studies, it would be expected that usual door openings in a household refrigerator would not produce wide fluctuations in the refrigerated products temperature nor have negative effects from the food safety point of view, despite it would increase the energy consumption of the refrigerator (Laguerre, Duret, Hoang, & Flick, 2014; Saidur, Masjuki, Hasanuzzaman, & Kai, 2008).

3.2. Domestic refrigerators temperature analysis

The analysis of the time-temperature profiles recorded from 160 domestic refrigerators belonging to 27 different brands showed, in general, a cyclical fluctuation of the temperature during the recorded period. The amplitude of the temperature fluctuation was highly variable, ranging from 0.5 °C for the less fluctuating profile to 12.2 °C for the most fluctuating profile, depending mainly on the refrigerator brand design and the on-off cycles of the compressor. No statistically significant differences between day and night were observed. Accordingly, differences in ambient temperature of the room (lower at night) or the frequency of door opening (higher during the day) did not cause relevant changes in the temperature profile recorded with the data logger and, according to the thermal inertia results, to the temperature of the food products stored in the refrigerators.

The mean 24 h-temperature profiles ($\overline{X}_{24h}$) of the surveyed refrigerators followed a normal distribution N(mean=5.4, SD=2.3) with minimum and maximum $\overline{X}_{24h}$ values of -0.03 and 12.7 °C, respectively (Figure 2A). A temperature of 5.4 °C is within the range of temperatures appropriate for the preservation of perishable RTE meat products (≤ 6 °C), for which a strict control of the temperature and optimal values of 2-4 °C are recommended (CAC, 2007). However, 41% of the refrigerators showed $\overline{X}_{24h}$ temperatures above the recommended value of 6 °C (Figure 6B), the percentile 75th being at 6.7 °C. These results are in agreement with the outputs of a recent review (James, Onarinde, & James, 2017) showing that the use and temperature performance of household refrigerators has not remarkably changed over the last decades, showing mean air temperatures ranging from 3.5 to 9.3 °C in different countries. Despite the recommendations included in numerous food safety campaigns addressed to consumers, the storage of chilled foods is frequently performed at temperatures >6 °C, higher than those recommended by the Codex Alimentarius, Regulation (EC) 853/2004 and USA Food Code (CAC, 2007; European Commission, 2004; FDA, 2013).

3.2.1. Effect of position and load level on refrigerator temperature

Most of the interviewed consumers claimed to store cooked meat products in the refrigerator core (94%), especially in the upper shelves. Only 4% stored them in the refrigerator door and 2% in specific extra-cold compartment (Table 1). The analysis of the temperatures registered in each position showed statistically different $\overline{X}_{24h}$ between the extra-cold compartment (0.9 ℃, Standard Deviation (SD)=0.6), the core of the refrigerator (5.4 ℃, SD=2.1) and the door (8.0 ℃, SD=3.3)(p<0.05). The position also affected the maximum and the minimum registered $\overline{X}_{24h}$ as well as the proportion of time at temperature ≥ 4 ℃, ≥ 6 ℃ and ≥ 8 ℃ (p<0.05), but not the range of the $\overline{X}_{24h}$ (Table 1). Previous research showed no consistent results regarding the warmest and coldest temperature positions in a refrigerator and differences of more than 5 ℃ have been reported between different places in the same refrigerator being the door temperature always the warmest (Evans & Redmond, 2016; Janjić et al., 2016; James et al., 2017; Marklinder & Erikkson, 2015; Koutsoumanis, Pavlis, Nychas, & Xanthiakos, 2010). However, when considering only those studies reporting simultaneous recordings of temperature in different positions of the refrigerator using a data logger (temperature measurement every 1 to 10 min), the bottom shelves showed lower mean temperature values than top shelves (0.7 ℃ lower in Marklinder & Erikkson, 2015, 0.88 ℃ lower in Koutsoumanis et al. (2010) and 0.34 ℃ lower in Janjić et al. (2016). In the present study, no significant differences were observed in the refrigerators mean 24h-temperature ($\overline{X}_{24h}$) or range in relation with the refrigerator load level, which is in agreement with the findings showed by Evans and Redmond (Evans & Redmond, 2016).

3.2.2. Effect of season on refrigerators' temperature

The analysis of the 24-h mean temperature values ($\overline{X}_{24h}$) from warm and cold seasons did not show statistically significant differences (p>0.05) regarding the descriptors of the distribution of the $\overline{X}_{24h}$ values, i.e. mean, minimum, maximum, range or percentage of time during which $\overline{X}_{24h}$ refrigerator temperature was ≥ 4 ℃ and ≥ 8 ℃, though the values for warm season were slightly higher than those of the cold season (Figure 2C and 2D). To further assess the possible effect of ambient temperature on the storage temperature, 20 domestic refrigerators included in the survey were monitored both in cold and warm season. In this case, paired data comparison showed statistically significant (p<0.05) differences in the refrigerator temperature distribution depending on the season, with means of 4.7 ℃ (SD=2.0) in cold and 3.8 ℃ (SD=2.0) in warm season. Remarkably, $\overline{X}_{24h}$ mean and minimum temperatures were significantly lower (p<0.05) in warm season, with differences between seasons and for specific refrigerators, of up to 3.2 ℃ in the mean and 5.2 ℃ in the minimum temperature. These results could be explained, at least partially, by the fact that some of the consumers participating in the survey (i.e., 21.4%) stated having set the thermostat to a lower temperature in the warm season. However, lower temperatures were also observed in refrigerators where no temperature modification was

applied. In those cases, lower temperature levels should be explained by other reasons such as higher compressor on-off cycling in response to the higher ambient temperature. On the other side, the amplitude of the temperature fluctuations was lower in the cold season ($p<0.05$), probably due to the lower difference between ambient and refrigerator temperatures.

Previous surveys have evaluated domestic refrigerator temperatures. Two extensive reviews were published in 2008 and 2017 (James et al., 2017; James, Evans, & James, 2008). The latter concluded that worldwide, the domestic storage of chilled food is highly variable and frequently performed at temperatures higher than those recommended for refrigerated storage and without improvement in the temperature performance in the last 30 years. The mean temperature determined in the present study, 5.4 °C, is in the range of those reported by previous studies, for instance 4.8 °C (SD=3.1) (Marklinder & Erikkson, 2015); 5.2 °C (SD=2.5) (Gilbert, Whyte, Bayne, Lake, & van der Logt, 2007); 5.9 °C (SD=3.1) (Derens-Bertheau, Osswald, Laguerre, & Alvarez, 2015) and slightly lower than 6.1 °C, the overall weighed arithmetic mean calculated by James et al. (2017) based on the results of 35 surveys worldwide. Taking into account the relevance of factors such as the type of measurement (discrete or continuous), the inertia of the device (data logger with a built-in sensor or connected to a highly sensitive probe), the matrix (air versus food product or water), the duration and frequency of the recording, the output data format (point estimate, mean or distribution), etc. on the reported mean temperature, the comparison of the results from different surveys, with temperature-measurement procedures not always well described, should be performed carefully. Additionally, when applying storage temperature data in microbial risk assessment and shelf-life studies, rather than data from sporadic point measurements, reliable temperature profile distributions such as those recorded in the present study are essential to draw consistent conclusions.

Refrigerator temperatures have a potential impact on the human listeriosis risk, an illness that has shown an increasing trend in the European Union and Economic Area during the last 9 years (EFSA-ECDC, 2018). Listeriosis cases are most frequently reported in the elderly population, a group more susceptible to this illness and for which unsafe practices such as storage time and temperature are quite common (> 10% of persons studied) (EFSA BIOHAZ Panel, 2018). The findings of the present study confirm this fact as the percentage of time the 24h-mean temperature of the refrigerators is ≥ 8 °C was higher for the elderly (22%, 75th percentile=7.3 °C) than for the general population (8%, 75th percentile=6.6 °C) ($p<0.05$).

3.3. Refrigerator temperature impact on the shelf-life of RTE cooked meat products
In shelf-life studies, the selection of the consumer storage temperature is critical because if the temperature is lower than the usually encountered there may be an underestimation of bacterial

growth, and in case of *L. monocytogenes* an overestimation of the length of the shelf-life (EURL Lm, 2014). For this reason, the use of conditions of abuse of temperature such as the 75th percentile of the observations made for the country have been recommended by several European guidelines (e.g. EURL Lm, 2014; Food Safety Authority of Ireland, 2017) or 12 °C if consumer storage temperature information is not available (EURL Lm, 2014). Roccato, Uyttendaele, & Membré (2017), after the analysis of temperature distributions of European domestic refrigerators from literature, determined that the overall temperature variability for the southern and northern Europe countries was described by the normal distributions N(7.0, 2.7) °C and N (6.1, 2.8) °C, respectively. Based on these distributions, they recommend 8.0 and 8.5 °C as 75th percentile temperatures for northern and southern EU countries, respectively. More specifically, a temperature of 8 °C is recommended for the consumer storage phase of shelf-life studies performed in Ireland (Food Safety Authority of Ireland, 2017), while slightly lower temperature, i.e. 7 °C, is recommended by other guidelines to account for expected consumer storage temperature (Betts, 2010; NACMCF, 2010). The results of the present study provide the scientific documentation that the FBO can use to justify conducting shelf-life studies at 6.7 °C, as the 75th percentile temperature of the Spanish consumer storage stage.

The use of predictive microbiology has become an important and recognized tool for assessing and managing food safety, particularly regarding shelf-life studies for RTE products (EURL Lm, 2014; European Commission, 2005, 2013; Messens, Hempen, & Koutsoumanis, 2018). In the present study predictive models have been used to evaluate the impact of the refrigerator temperatures on the growth of *L. monocytogenes* (indicating shelf-life limit as time to 2-log increase) and LAB causing spoilage (when reaching 10^7 cfu/g) in a standard cooked meat product (see section 2.4). Table 2 shows the results of the simulations carried out. Regarding the *L. monocytogenes* growth, at the mean temperature recorded for domestic refrigerators, 5.4 °C, the shelf-life for a typical cooked meat product would be around 12 days. At a reference refrigeration temperature of 4 °C the predicted shelf-life for the same cooked meat product would be of at least 3 weeks, while at 10 °C it would be reduced to 4.2 days, corresponding to a shelf-life 5 and 20-fold lower than the estimated at 4 and 2 °C, respectively.

Regarding the growth of LAB, the simulations indicate that the time to reach the spoilage level is generally shorter than the time taken by *L. monocytogenes* to increase 2 log units, particularly when the storage temperature is below 5 °C and/or the initial LAB contamination is relatively high. In these scenarios, the ratio between the time to 2-log increase of the pathogen (i.e. safe time) and the time to spoilage is higher than 1, thus the product would be spoiled before the pathogen reaches the safety level permitted by the current EU legislation. It is worth to highlight that for products with low initial contamination by LAB (e.g. sliced under aseptic conditions in a clean room) stored at temperatures equal or higher than 5 °C (e.g. which correspond to *ca.*

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50% of the mean temperature recorded for domestic refrigerators in the present study), the ratio between the safe and spoilage time is lower than 1. These scenarios constitute risk areas as defined by Devlieghere et al. (2001) in which food pathogens can develop before spoilage has occurred.

As shown in the present study, the fluctuation of the temperature observed in refrigerators can be, in some cases, remarkable and refrigerator temperature profiles with the same mean temperature can have very different amplitude, a fact that can be relevant from the food safety point of view. Figure 3 shows some examples of profiles showing the same mean temperature but different fluctuation pattern. At 6.8 °C, the highest mean temperature depicted in Fig 3 (A), the time to 2-log increase of *L. monocytogenes* in cooked ham was the shortest (7.5 days) and no remarkable differences were observed between the two different patterns of fluctuation and the constant temperature. At a mean temperature of 3.9 °C (Fig 3B) a slight decrease in the time to 2-log increase was observed when temperature fluctuated more (profile B1), with a relative shelf-life when compared with storage at constant temperature of 87%. The highest reduction of the shelf-life was observed at the lower mean temperature evaluated (2.1 °C, Fig 3C). When compared to a 2.1 °C constant temperature, profile C1 (6.2 °C of amplitude) and profile C2 (2.2 °C of amplitude) showed relative shelf-life of 62 and 93%, respectively. Taken together, figures show that the effect of temperature fluctuation is higher at low temperatures and, in general, the higher the amplitude of the fluctuation the higher the shelf-life reduction as the growth rate of *L. monocytogenes* increases exponentially with temperature (Hereu et al., 2014; Mejlholm & Dalgaard, 2009). Consequently, to evaluate the effect of temperature on the shelf-life of RTE food under reasonably foreseeable conditions of storage, not only the mean of the temperature distribution but also the magnitude of the fluctuation (variability) should be considered.

In contrast, amplitude of the temperature fluctuation had a lower impact on the time taken by LAB to reach the spoilage level (Table 3) in comparison with the effect on the time to 2-log increase of the pathogen. These results can be explained by the different effect of storage temperature changes on each parameter. As shown in Table 2, the rise of temperature from 2 °C to 4 °C reduced the time to 2-log increase of *L. monocytogenes* by 75%, while the same temperature increase caused a 39% reduction of the time to reach the spoilage level by LAB. The impact of the amplitude of temperature fluctuation on the ratio between the shelf-life determined by the growth of the pathogen and that limited by the growth of spoilage LAB was very limited. In agreement with the results of the simulation at constant temperature, the scenarios at risk were detected for the temperature profiles with mean values of 6.8 °C (A1, A2 and A3) when the initial LAB were low (Table 3).

Considering that a remarkable proportion of domestic refrigerators operate at mean temperatures outside the range recommended for perishable products and the high impact that temperature has on the growth of *L. monocytogenes* in cooked meat products in particular and the food safety of RTE food in general, the increase of consumers' awareness in relation to refrigeration practices would be an effective measure to promote food safety and reduce food waste.

Declaration of Competing Interest

Authors have no conflict of interests.

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Figure 1. Temperature profiles from an assembly consisting of a 175-T1 Testo data logger and a T type thermocouple measuring the core temperature of a 1-cm thick slice of cooked ham. A: Assembly was stabilized at 24 ℃, transferred to a 5 ℃-refrigerator for 16 h and transferred back to 24 ℃ for 5 h. B: Assembly was stabilized at a 5 ℃-refrigerator and submitted to door openings (arrows) every 5 min.

Figure 2. Distribution of the mean 24h-temperature profile ($\overline{X}_{24h}$) of the 160 surveyed domestic refrigerators (A) and refrigerators surveyed in cold (C) and warm (D) season. Percentage of refrigerators (B) with mean temperatures at optimum (< 4 ℃), acceptable (4-6 ℃) and abuse temperatures (> 6 ℃). Mean, minimum (Min), maximum (Max) and range of $\overline{X}_{24h}$ are indicated for each plot.

Figure 3. Temperature profiles of domestic refrigerators with mean temperature of 6.8 ℃ (A), 3.9 ℃ (B) and 2.1 ℃ (C). For each mean temperature, profiles of two different refrigerators are shown (1 and 2) in comparison with the constant temperature (3) at the mean value. Relative shelf-life percentage (RSL) was calculated in relation to the maximum shelf-life at the selected constant temperature profile. Shelf-life indicated as the time to 2-log increase of *L. monocytogenes* levels.

Table 1. Reported positions of storage of cooked meat products in domestic refrigerators. Statistical descriptive parameters calculated from the mean 24h-temperature profiles ($\overline{X}_{24h}$) registered for each refrigerator at the monitored position.

Position	Frequency (%) of refrigerators	Temperature (ºC)				Percentage of time at:			
		Mean	Min	Max	Range	< 4 ºC	≥ 4 ºC	≥ 6 ºC	≥ 8 ºC

Core	94	5.4[a]	3.9[a]	7.4[a]	3.5[a]	25.5[a]	74.5[a]	41.7[a]	12.3[a]
Upper shelves	59	5.8[A]	4.1[A]	6.8[A]	3.8[A]	18.6[A]	81.4[A]	48.7[A]	14.8[A]
Lower shelves	41	5.0[B]	3.6[A]	7.9[B]	3.2[A]	34.6[B]	65.4[B]	33.0[B]	10.4[A]
Door	4	8.0[b]	5.8[a]	10.4[b]	4.6[a]	11.6[a]	88.4[a]	72.8[b]	48.1[b]
Extra cold compartment	2	0.9[c]	-0.1[b]	2.2[c]	2.4[a]	100[b]	0[b]	0[c]	0[c]
Overall values[a]	**100**	**5.4**	**0.0**	**12.2**	**3.7**	**28.7**	**71.3**	**41.3**	**10.6**

Values with different superscript small letters indicate statistically significant differences between different positions and different superscript capital letters indicate statistically significant differences between upper and lower shelves ($p < 0.05$).
[a]The same as shown in Figure 2A

Table 2. Results of the estimated shelf-life (time to 2-log increase of *L. monocytogenes* and time to spoilage) of RTE cooked ham stored at different temperatures according to the simulation[1] of the growth of *L. monocytogenes* and LAB, respectively. The ratio between both times is shown in parenthesis.

Temperature	Time (days) to 2-log increase of *L. monocytogenes*	Time (days) to reach spoilage level from different initial concentrations (N_0) of LAB				
		$N_0=10$ cfu/g	$N_0=10^2$ cfu/g	$N_0=10^3$ cfu/g	$N_0=10^4$ cfu/g	$N_0=10^5$ cfu/g
2 ℃	90.0	27.1 (3.3)	22.6 (4.0)	18.1 (5.0)	13.6 (6.6)	9.1 (9.9)
4 ℃	22.6	16.6 (1.4)	13.9 (1.6)	11.1 (2.0)	8.3 (2.7)	5.6 (4.1)
5 ℃	14.1	**13.5** (**1.0**)[2]	11.3 (1.2)	9.0 (1.6)	6.8 (2.1)	4.5 (3.1)
6 ℃	9.7	**11.2** (**0.9**)	9.4 (**1.0**)	7.5 (1.3)	5.6 (1.7)	3.8 (2.6)
10 ℃	4.2	**6.1** (**0.7**)	**5.1** (**0.8**)	**4.1** (**1.0**)	3.1 (1.4)	2.1 (2.1)

[1]Simulations were carried out with the predictive models available on the FSSP v4.0 using input values representative of RTE cooked meat products as described in section 2.4.

[2]Scenarios at risk, i.e. the ratio between the time to 2-log increase of the pathogen and the time to spoilage is equal or lower than 1, are highlighted in bold.

Table 3. Results of the estimated shelf-life (time to 2-log increase of *L. monocytogenes* and time to spoilage) of RTE cooked ham stored at different temperature profiles[a] showing the same mean temperature according to the simulation[b] of the growth of *L. monocytogenes* and LAB, respectively. The ratio between both times is shown in parenthesis.

Mean temperature	Profile	Time (days) to 2-log increase of *L. monocytogenes*	Time (days) to reach spoilage level from different initial concentrations (N_0) of LAB								
			$N_0=10$ cfu/g		$N_0=10^2$ cfu/g		$N_0=10^3$ cfu/g		$N_0=10^4$ cfu/g		$N_0=10^5$ cfu/g	
2.1 °C	C1	51.6	24.7	(2.1)	20.6	(2.5)	16.4	(3.1)	12.3	(4.2)	8.3	(6.2)
	C2	78.1	25.7	(2.9)	21.5	(3.5)	17.2	(4.4)	12.9	(5.9)	8.7	(8.8)
	C3	84.3	26.3	(3.2)	22.0	(3.8)	17.6	(4.8)	13.2	(6.4)	8.8	(9.5)
3.9 °C	B1	19.9	16.4	(1.2)	13.7	(1.5)	11.0	(1.8)	8.2	(2.4)	5.5	(3.6)
	B2	22.9	16.9	(1.4)	14.1	(1.6)	11.3	(2.0)	8.4	(2.7)	5.7	(4.0)
	B3	23.3	17.0	(1.4)	14.1	(1.7)	11.4	(2.0)	8.5	(2.7)	5.8	(4.0)
6.8 °C	A1	7.7	**9.8**	*(0.8)*[c]	**8.2**	*(0.9)*	6.6	(1.2)	4.9	(1.6)	3.3	(2.4)
	A2	7.5	**9.8**	*(0.8)*	**8.1**	*(0.9)*	6.5	(1.1)	4.9	(1.5)	3.3	(2.3)
	A3	7.5	**9.8**	*(0.8)*	**8.2**	*(0.9)*	6.5	(1.1)	4.9	(1.5)	3.3	(2.3)

[a]Temperature profiles shown in Table 3.

[b]Simulations were carried out with the predictive models available on the FSSP v4.0 using input values representative of RTE cooked meat products as described in section 2.4.

[c]Scenarios at risk, i.e. the ratio between the time to 2-log increase of the pathogen and the time to spoilage ratio is equal or lower than 1, are highlighted in bold.

Graphical abstract

Highlights

- The mean 24h-temperature of 160 surveyed domestic refrigerators was 5.4 °C

- The study indicates 6.7 °C as the 75th percentile for consumer storage stage

- Risk scenarios where *L. monocytogenes* develops before LAB spoilage were identified

- Temperature fluctuation negatively affects the safety of RTE products
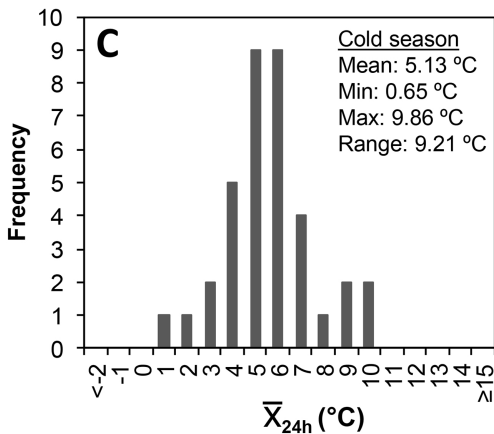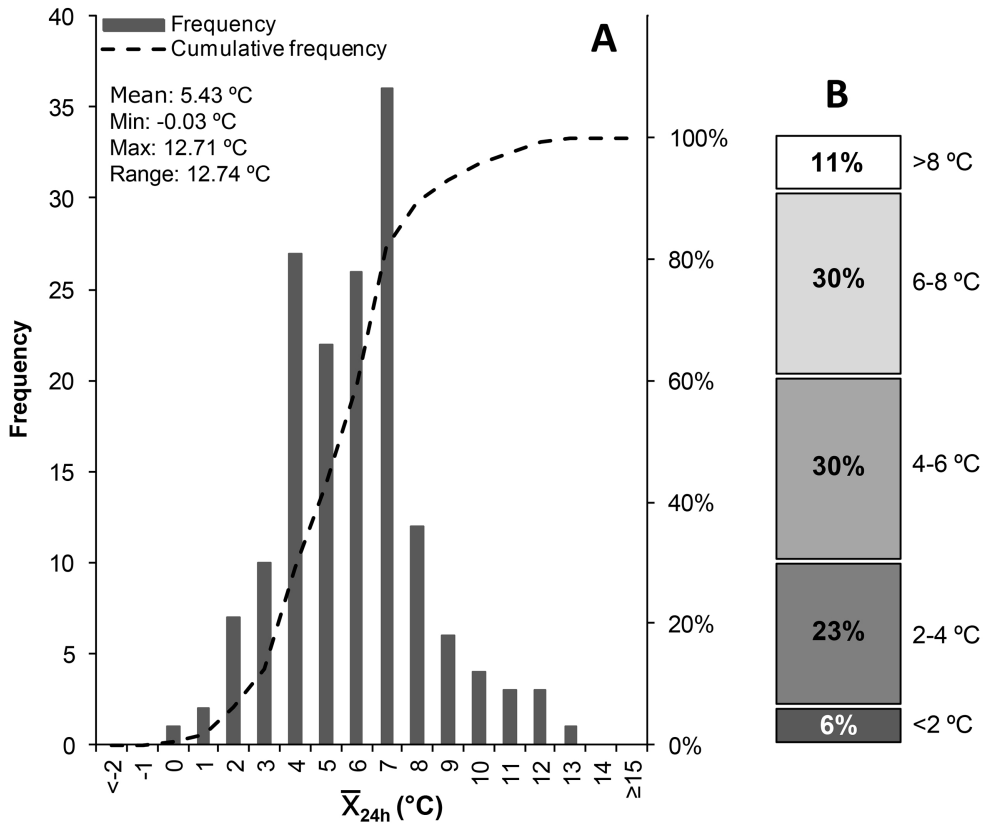
Figure 1

Figure 2
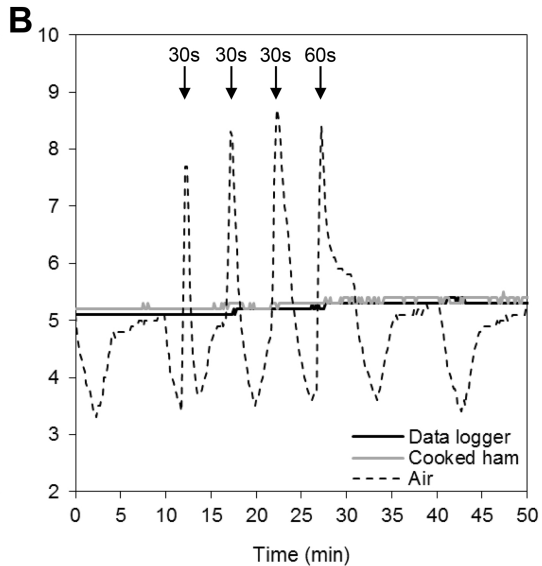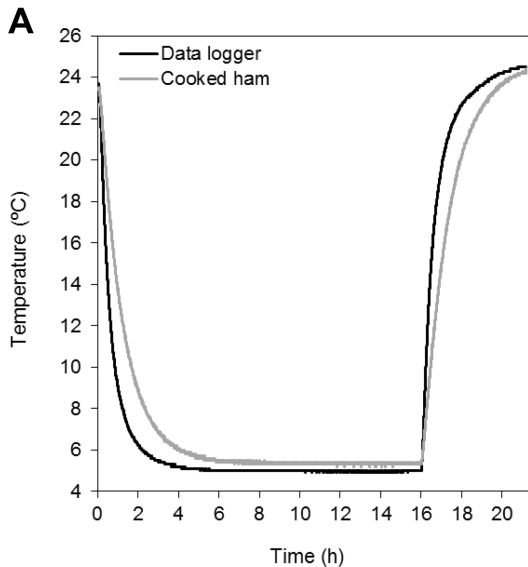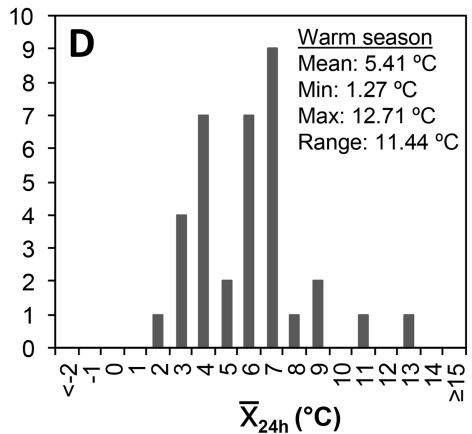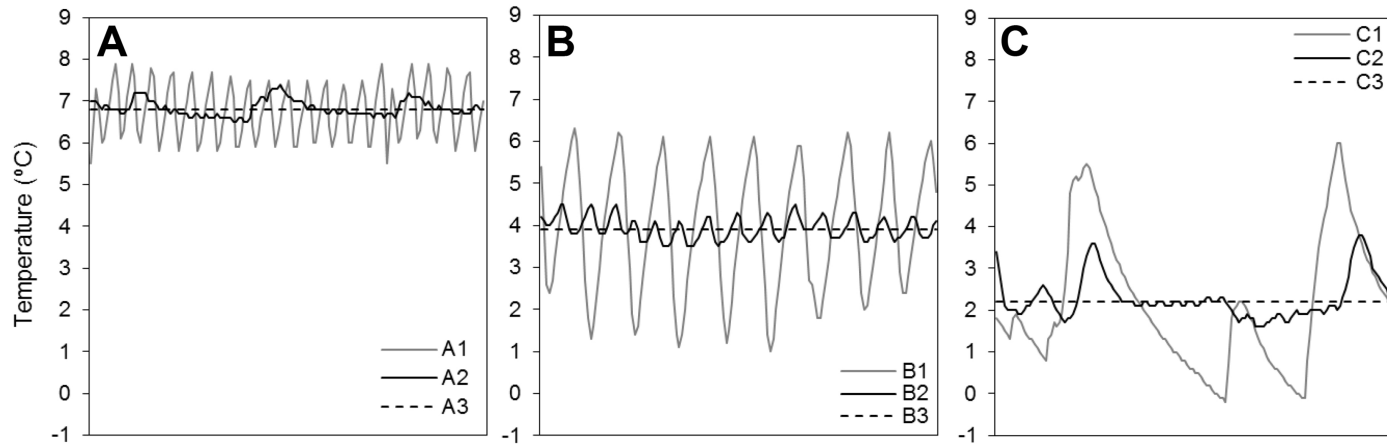
Profile	A1	A2	A3		B1	B2	B3		C1	C2	C3
Mean (ºC)	6.8	6.8	6.8		3.9	3.9	3.9		2.1	2.1	2.1
Min (ºC)	5.5	6.5	6.8		1.0	3.3	3.9		-0.2	1.6	3.9
Max (ºC)	7.9	7.4	6.8		6.3	4.6	3.9		6.0	3.8	3.9
Amplitude (ºC)	2.4	0.9	-		5.3	1.3	-		6.2	2.2	-
Shelf-life (d)	8	8	8		20	23	23		52	78	84
RSL (%)	**100**	**100**	**100**		**87**	**100**	**100**		**62**	**93**	**100**

Figure 3