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## Temperatures and storage conditions in domestic refrigerators - Slovenian scenario

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### ABSTRACT

Cold chain maintaining is least stable at its end, where domestic storage often represents one of the most critical links because of storage time and inappropriate temperatures, increasing the risk of food-borne outbreaks in domestic households. Considering the time-temperature profile of refrigerators as a food safety indicator, the purpose of this study is to gain insight into refrigeration temperatures in parallel with refrigerator and household characteristics that could potentially influence the refrigeration temperatures. During a 24 h period in 15-min intervals, internal temperature of the test product, refrigerator air and ambient air temperatures were measured with one penetration and two air probes coupled with a data logger. The internal temperature of the test product was measured with pre-prepared "Karlsruhe Test Material", which had thermal properties similar to those of lean beef. Refrigerator and household characteristics were collected with a pre-defined observational sheet and short, structured questionnaire. In total, 50 households and their refrigerators were included. Gaps related to the cold storage and cross-contamination were observed. Temperature displays were present in 16% while control thermometers were not observed at all; 20% of the refrigerators enabled 24 h average internal temperature lower than 4 °C, 30% between 4 and 6 °C and 50% over 6 °C. Refrigerator age, type and load were observed but had no significant impact, which suggests thermostat setting as a key factor influencing refrigerator temperatures. Food distribution inside refrigerators was related to the refrigerator load with significant risk for cross-contamination in overpacked refrigerators. High temperatures combined with a non-systematic distribution of food in the refrigerator, expired dates of durability, and non-systematic cleaning strategies allow favourable preconditions for food infections occurring at the end of the food supply chain. Tailored acceleration of existing food safety messages could and should help consumers to minimise food safety risks, improve food quality, and reduce food wastage.

### 1. Introduction

There are more than 1.4 billion domestic refrigerators worldwide (Barthel & Götz, 2012) and refrigerated foods often comprise a sizeable portion of perishable food items in a household (Davenport, Qi, & Roe, 2019). Inadequate food temperature control, including time and temperature of cooking, cooling, processing and storage, is one of the most common causes of food-borne illness, as well as the deterioration of organoleptic quality and food spoilage (WHO & FAO, 2009). Although abuse or misuse of cold-chain maintenance might happen along the entire food chain, the most critical part of cold chain maintaining is at its end (Derens-Bertheau, Osswald, Laguerre, & Alvarez, 2015; James, Onarinde, & James, 2017; Jofré, Latorre-Moratalla, Garriga, & Bover-Cid, 2019). Specifically critical are the last three steps of the cold chain (display cabinet, transport after purchase, and domestic refrigerator) of which the last two include consumer actions and for which domestic storage represents one of the most sensitive parts of the entire cold chain (Derens-Bertheau et al., 2015).

Microbial pathogens may occasionally be present, and their levels

can be dynamic. Although they can be kept low by proper temperature control, they can also substantially increase with incorrect maintaining of cold chain conditions (e.g., improper food storage temperatures) often combined with cross-contamination from other foods (WHO & FAO, 2009). Although *Listeria monocytogenes* and *Yersinia enterocolitica* are pathogens capable of growing below 5 °C (James et al., 2017), *Salmonella* is reported as a predominated causative agent (63.4%) among strong-evidence FBO occurred at home (EFSA & ECDC, 2019). The domestic environment also represents the majority (40.5% and 53.3% among EU and non-EU members, respectively) of FBO with strong-evidence (EFSA & ECDC, 2019). As reported by James et al. (2017), many domestic refrigerators, especially those owned by the elderly (Jevšnik et al., 2013), are operating above the recommended temperatures and support suboptimum but still significant growth of mesophilic organisms, such as *Salmonella* spp.

Food safety and the quality of refrigerated food depend on the good performance of the refrigerator and are closely linked to temperature distribution and airflow inside the refrigerator (Ledesma & Belman-Flores, 2017). Many surveys published since 1987 and

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systematically reviewed by James et al. (2017; 2008) have shown that temperature control in domestic refrigerators is inadequate. Refrigerator temperatures, especially because of ready-to-eat foods, should never exceed 6 °C (preferably they should be between 2 and 4 °C) (WHO & FAO, 2009). Compliance with short shelf lives can additionally ensure that microbial growth to any significant degree does not occur before the consumption. The Slovenian National Institute for Public Health (NIPH), like the European Food Safety Authority (EFSA) and the World Health Organization (WHO), advises consumers that foods should be refrigerated  $\leq 5$  °C (NIPH, 2011; Ricci et al., 2018; WHO, 2006).

As reported by James et al. (2017), consumers around the world are often unaware of what temperature is recommended for refrigerator storage and do not know the temperature at which their refrigerator is running. A previous study has also pointed out that Slovenian consumers do not always respect instructions regarding time and temperature of storage or preparation of refrigerated foods (Jevšnik, Hlebec, & Raspor, 2008a,b). Consumers that are familiar with the concept of the cold chain are, as a rule, also professionally engaged in the field of food safety (Ovca & Jevšnik, 2009a). Slovenian consumers demonstrate a lack of awareness about recommended temperatures and mostly do not know (43.7%) and/or do not check (67.8%) the temperature of their refrigerator (Jevšnik, Hlebec, & Raspor, 2008a,b; Ovca & Jevšnik, 2009a). Also, studies that have focused on practices of vulnerable consumer groups confirm the findings among the general population; 73.3% of Slovenian elderly people confessed that they did not know the temperature in their domestic refrigerator, and 80.2% confirmed that they had never measured their refrigerator's temperature (Jevšnik et al., 2013). A study of Slovenian pregnant women revealed that, when compared to non-pregnant women, they never or rarely (32.7%) pay attention to this area of good housekeeping practice (Jevšnik, Hlebec, & Raspor, 2008a, b). A study of Slovenian children (10–12-years old) additionally revealed a particular lack of knowledge regarding the impact of temperature on microorganisms (Ovca, Jevšnik, & Raspor, 2014), substantiating a risk that deficiencies in food handling among adults may be passed on to children.

Considering the time-temperature profile of refrigerators as a food safety indicator, the purpose of the current study was to obtain insight into 24 h profile of temperatures inside consumers' refrigerators, which was achieved through measurements of refrigerator air temperature in parallel with the internal temperature of a validated test product. Additionally, ambient air temperature outside the refrigerator, refrigerator characteristics, and household characteristics that could potentially influence the temperatures inside the refrigerator were monitored.

## 2. Materials and methods

The research study was conducted mostly during the wintertime (From November 2019 until January 2020). A linear snowball sampling approach with a convenience sample of the initial subject (Hartnoll et al., 1997) was applied to reach the households that participated in the research study. The responsible household member was informed about the aim of the research. When the member agreed to participate, the date and hour were determined via telephone with the researcher who visited the household. During the home visit, the researcher first explained to the responsible household member the planned activities and what information would be provided afterwards as feedback. After an explanation of all activities, the responsible household member was asked once again regarding consent and, if they agreed, the researcher asked for access to the refrigerator. If there was more than one refrigerator, the responsible household member was asked to provide access to the main refrigerator used by household members. After the measurements, the responsible household member was informed about the status of their refrigerator and received oral recommendations from the researcher for the improvements in refrigerator temperature settings and/or storage conditions. However, participants were also informed about the possibility of refusing participation or changing their mind at

any time during the measurements, without any consequences. All the data were collected with consent.

### 2.1. Temperature measurements

The internal temperature of the test product (ITTP) was measured in the pre-prepared "Karlsruhe Test Material" with a weight of 254 g. Karlsruhe Test Material, previously validated by Anderson and Singh (2005) with thermal properties similar to that of lean beef, is homogeneous and can be reused for several repetitions. During the measurements, a Testo waterproof NTC penetration probe (measuring range  $-50$  to  $+150$  °C,  $\pm 0.4$  °C accuracy) was inserted into the test product's interior. The test product with the inserted internal probe was located on the middle shelf, inside the refrigerator. Next to the test product, a second Testo air probe thermocouple type T (measuring range  $-50$  to  $+350$  °C,  $\pm 0.4$  °C accuracy) for refrigerator air temperature (RAT) was located. ITTP and RAT were both measured solely at one location, as close as possible to the centre of the refrigerator (centre of the middle shelf of the refrigerator). The third probe, a Testo air probe thermocouple type T, (measuring range  $-50$  to  $+350$  °C,  $\pm 0.4$  °C accuracy) was located outside the refrigerator measuring the ambient air temperature (AAT). ITTP, RAT, and AAT were measured in 15-min intervals. For the collection of data during temperature measurements, a Testo 177-T4 data logger (measuring range  $-200$  °C to  $+400$  °C, 0.1 °C resolution and  $\pm 0.3$  °C accuracy) was used.

According to our previous test, 30 h of measurements were necessary. The first 6 h were considered to be an adjustment period for the test product. That period was necessary because of the temperature difference between the test product and the refrigerator air after installation. The next 24 h represented the actual measurement included in the further data analysis.

### 2.2. Refrigerator characteristics

During this activity, technical information (refrigerator age, ventilation, freezer unit, built-in display, control thermometer) and refrigerator interior status (refrigerator load, food distribution from prevention of cross-contamination point of view, visible surface cleanliness, shelf material, and durability dates) were gathered. Data referring to the refrigerator characteristics were collected with a predefined observational sheet and a photo of the refrigerator's interior. The latter enabled later detailed analysis of the refrigerator storage conditions by the second researcher, to minimise the potential subjectivity of researcher who visited the household. Both researchers compared their lists after independent assessment and discussed discrepancies in order to reach a consensus (Creswell, 2007).

### 2.3. Household characteristics

The number of household members and demographic data (area of residence, gender, age, education) about the household person who mostly buys food were gathered with the help of a short structured questionnaire developed by the authors for this research. After a prior explanation by the researcher, the members of the household, recorded their activity every time they opened the refrigerator door during the measurement period on the separate pre-prepared record sheet.

### 2.4. Data analysis

The data were evaluated and analysed using the Statistic Program for the Social Sciences (SPSS, Version 24.0, Chicago, IL, 2006). Based on average ITTP, the data were divided into categories. To examine the relationships among and between the categorical variables (nominal and dichotomous types), a chi-square test for independence ( $\chi^2$  test) or Fishers' exact test were applied. For comparing the means of continuous variables, an independent *t*-test; for correlations among interval

variables, Pearson's correlation and Spearman's Rank-Order Correlation were used.

### 3. Results

#### 3.1. Temperature measurements

In total, 50 households and their refrigerators were included in the research study. The overall arithmetic means of ITTP, RAT and AAT mean temperatures were 5.95 °C (SD = 2.24), 5.91 °C (SD = 2.23) and 21.21 °C (SD = 2.34) respectively. 20% of the refrigerators enabled average ITTP lower than 4 °C, 30% between 4 and 6 °C and 50% over 6 °C (Table 1). Detailed analysis of RAT 24-h measurement profiles showed that only 4% of refrigerators were operating below 4.0 °C, while 24% of refrigerators were above 6.0 °C during the entire monitoring period. However, a detailed view on ITTP 24-h measurement profiles revealed that in 10% of refrigerators the test product was kept at a temperature below 4.0 °C during the entire monitoring period, while in 38% of the refrigerators, it was above 6.0 °C.

The three time-temperature profiles of refrigerators presented in Fig. 1 and described in detail in Table 2 demonstrate situations in three single refrigerators with the lowest, median, and highest average ITTP during 24 h measurement. Measurements reveal that ITTP are more

stable compared to RAT (Table 1, Fig. 1). Similarly, ITTP and RAT thermal change with cyclic pattern was typical for 86% of all measurements. Among the rest, an atypical and less pronounced pattern was observed. Although a strong association between average ITTP and RAT ( $r = 0.930$ ,  $p < .001$ ) was observed, a detailed view on 24 h profile revealed that RAT change rate during 24 h was much more intense compared to ITTP (Fig. 1). In the case with the lowest average ITTP, the ON and OFF lapse time rate was much more in favour of ON lapses compared to the other two cases (Table 2). Consequently, the average RAT difference in a single cycle was also the biggest. No significant differences were observed between night and daytime. Of the refrigerators characteristics, the most obvious difference is related to refrigerator age and refrigerator type. Case No. 1 represents a refrigerator with a smaller volume and a built-in freezer compartment. In the case of household characteristics, the most obvious difference is related to the number of household members and door openings. The latter seem to have no significant impact on the 24 h temperature profile (Fig. 1).

#### 3.2. Refrigerator characteristics

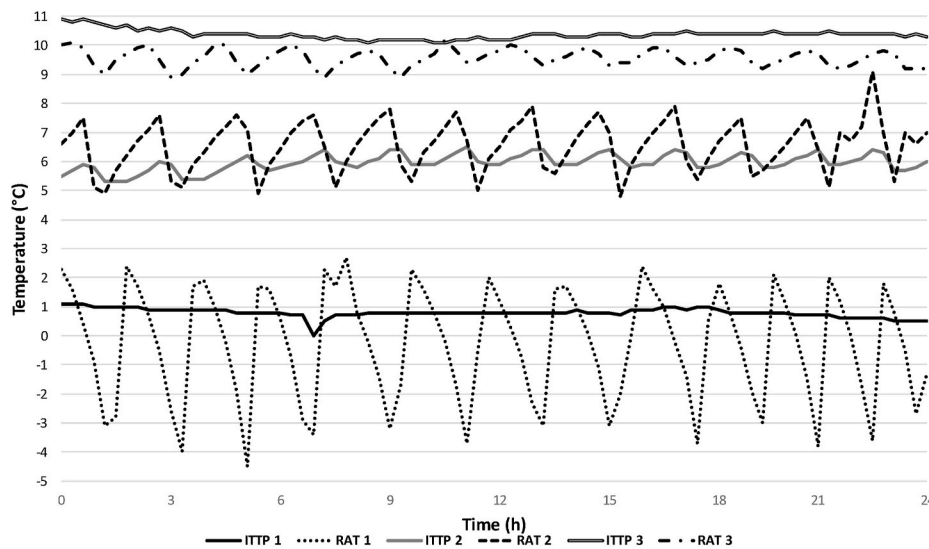
Overall, 34% of refrigerators were less or equal to 4 years old, 22% between 5 and 9 years, 28% between 10 and 14 years, and 16% more

**Table 1**

Average temperatures, refrigerator and household characteristics divided into three categories based on average internal temperature of test product (ITTP).

	Category			Significance <sup>d</sup> <i>p</i> value
	Ideal <sup>a</sup> (n = 10)	Acceptable <sup>b</sup> (n = 15)	Unacceptable <sup>c</sup> (n = 25)	
<b>Temperature measurements</b>				
Average ITTP (°C)	1.0–3.9	4.1–6.0	6.2–10.5	.000
Average RAT (°C)	–0.3–5.7	3.3–6.9	5.1–10.7	.000
Average AAT (°C)	16.6–24.7	16.8–25.2	16.8–26.2	.585
<b>Refrigerator characteristics</b>				
Age of the refrigerator (years)				
≥ 9	7 (70.0%)	8 (53.3%)	13 (52.0%)	.569
10 ≤	3 (30.0%)	7 (46.7%)	12 (48.0%)	
Built-in display				
Yes	2 (20.0%)	2 (13.3%)	3 (12.0%)	.702
No	8 (80.0%)	13 (86.7%)	22 (88.0%)	
Equipped with a fan				
Yes	4 (40.0%)	3 (20.0%)	4 (16.0%)	.306
No	6 (60.0%)	12 (80.0%)	21 (84.0%)	
Freezer compartment				
With	4 (40.0%)	9 (60.0%)	14 (66.0%)	.777
Without	6 (60.0%)	6 (40.0%)	11 (44.0%)	
Refrigerator load				
Almost empty to half full	4 (40.0%)	10 (66.7%)	14 (56.0%)	.774
Full to very full	6 (60.0%)	5 (33.3%)	9 (44.0%)	
Food arrangement <sup>f</sup>				
Appropriate	6 (60.0%)	7 (46.7%)	9 (36.0%)	.254
Inappropriate	4 (40.0%)	8 (53.3%)	16 (64.0%)	
<b>Household characteristics</b>				
Average nr. of household members (SD)	2.7 (1.3)	2.7 (0.8)	3.0 (1.4)	.354
Average door openings in 24 h (SD)	14.9 (12.2)	15.8 (12.3)	13.8 (10.3)	.615
Area of residence				
Urban	5 (50.0%)	11 (73.3%)	9 (36.0%)	.048
Rural	5 (50.0%)	4 (26.7%)	16 (64.0%)	
Responsible person's gender				
Male	1 (10.0%)	2 (13.3%)	10 (40.0%)	.051
Female	9 (90.0%)	13 (86.7%)	15 (60.0%)	
Responsible person's age (years)				
≥ 49	4 (40.0%)	8 (53.3%)	14 (56.0%)	.571
50 ≤	6 (60.0%)	7 (46.7%)	11 (44.0%)	
Responsible person's education				
Elementary or high school	7 (70.0%)	7 (46.7%)	15 (60.0%)	.774
College or university	3 (30.0%)	8 (53.3%)	10 (40.0%)	

ITTP – internal temperature of test product; RAT – refrigerator air temperature; AAT – ambient air temperature <sup>a</sup>Average ITTP: ≤ 4.0 °C; <sup>b</sup>Average ITTP: 4.1–6.0 °C; <sup>c</sup>Average ITTP: 6.1 °C ≤; <sup>d</sup>Combined results of 1st (Ideal) and 2nd (Acceptable) cat. against 3rd (Unacceptable) cat.; <sup>f</sup>from the point of view of cross-contamination prevention.



**Fig. 1.** 24 h profile of test product internal temperature (ITTP) in the refrigerator and refrigerator air temperature (RAT) for three cases considering lowest (1), median (2) and highest (3) average ITTP.

than 15 years old. Although the ratio between newer and older refrigerators was in favour of the first related to average ITTP (Table 1), there was no significant difference ( $p = .213$ ) between average ITTP in newer (less or equal to 9 years) refrigerators (5.6 °C, SD = 2.1) compared to refrigerators older than 10 years (6.4 °C, SD = 2.4). A similar situation was observed for RAT. 90% of all refrigerators had solid glass shelves. 22% were equipped with a fan, more often newer refrigerators ( $p = .014$ ). Although average ITTP was lower inside the refrigerators with a fan (5.4 °C, SD = 2.0) compared to those without

(6.1 °C, SD = 2.3) the difference was not significant ( $p = .379$ ). Only a few (16.0%) of the refrigerators were equipped with temperature displays, while none was equipped with a control thermometer inside the refrigerator.

The most common type of refrigerator observed in our study was one without a freezer compartment (46%) followed by a double-door refrigerator combined with a freezer compartment at the top or bottom (34%) and a single-door refrigerator with a built-in freezer compartment (20%). The highest average ITTP was observed in double-

**Table 2**  
Temperature measurements, refrigerator and household characteristics for three cases presented in Fig. 1

		Case number		
		1	2	3
<b>Temperature measurements</b>				
ITTP	Average (°C)	1.0	5.9	10.5
	SD	0.4	0.3	0.4
RAT	Average (°C)	-0.3	6.9	9.6
	SD	2.0	0.9	0.3
AAT	Average (°C)	20.5	22.0	19.1
	SD	1.0	0.1	0.6
ON lapses	Time (min)	60–75	15–30	30–45
	RAT difference (°C)	5.1	2.6	0.8
	SD	1.0	0.2	0.2
OFF lapses	Time (min)	15–45	60–75	60–75
	RAT difference (°C)	5.2	2.7	0.8
	SD	0.8	0.6	0.2
<b>Refrigerator characteristics</b>				
Age of the refrigerator (years)		5–9	15–19	15–19
Built in display		No	Yes	No
Equipped with a fan		No	No	No
Shelf type		Wire	Glass	Wire
Freezer compartment		Yes (built in)	No	Yes (top)
Refrigerator load		Half full	Empty	Half full
Food arrangement		Appropriate	Appropriate	Appropriate
<b>Household characteristics</b>				
Household members (n)		1	3	4
Door openings in 24 h (n)		2	10	7
Area of residence		Urban	Rural	Urban
Responsible person's gender		Male	Male	Female
Responsible person's age		30–39	50–59	50–59
Responsible person's education		College or university	College or university	College or university

ITTP – internal temperature of test product; RAT – refrigerator air temperature; AAT – ambient air temperature; SD – standard deviation.

door refrigerators with freezer compartments (6.2 °C, SD = 2.3) and the lowest in refrigerators without freezer compartments (5.7 °C, SD = 1.9). However, the statistical test ( $p = .047$ ) confirmed that refrigerators without freezer compartments were the most abundant among those with an age of less or equal to 4 years (70.6%).

The refrigerators' load was estimated based on the occupied volume of the items inside them. The refrigerator was considered empty (22%) when only few items on every shelf were present (average ITTP = 6.8 °C, SD = 2.2), half-full (36%) if around half of the volume was occupied (average ITTP = 5.8 °C, SD = 2.3), full (30%) if the refrigerator capacity was fully met (average ITTP = 5.1 °C, SD = 2.1) and very full (12%) if overpacked, preventing smooth air circulation (average ITTP = 6.8 °C, SD = 1.8).

In 56% of all refrigerators, the food was organised in the way that cross-contamination was prevented. Adequate conditions were more often ( $p = .112$ ) observed in empty and half full refrigerators (65.5%) if compared to full or overpacked refrigerators (42.9%), while a significant risk for cross-contamination was observed in all the overpacked refrigerators. Regarding refrigerator load and food distribution, there was no significant difference according to the gender and educational status of the person who mostly buys food.

Food items with expired dates of durability ("best-before" and "use-by") were observed in 36% of all refrigerators. That was not related to the refrigerator load, gender or educational status of the person who mostly buys food, nor to the average number of household members. Except in one case, expired dates of durability were always related to milk and dairy pre-packed products. High-risk foods were not present among those with expired dates of durability. Based on the conversations with householders, they do not discard foods immediately, but check the smell and colour and, if these conditions are adequate, they still consume them.

Overall, 56% of householders reported that they had cleaned their refrigerator during the last three months, 26% more than three months ago and 18% do not remember when the last time they cleaned their refrigerator was. Reported methods of cleaning were a dish sponge and warm water or water solution of dish detergent. Cleaning of the refrigerators is not done systematically but targeted in the spots of spilt liquids or visible stains. Based on our observations in 68% of refrigerators in rural and 28% in urban areas, no visible dirt and food leftovers on the refrigerator's internal surfaces were observed ( $p = .005$ ). Other demographic characteristics of the household had no significant impact on this parameter. Only in three (6%) refrigerators were materials of wire shelves surfaces not completely intact, but this did not represent a significant health risk.

### 3.3. Household characteristics

The average number of household members was 3.0 (SD = 1.2) in rural and 2.8 (SD = 1.2) in urban ( $p = .487$ ) areas. Among household members who mostly buy the food, 74% were women, 48% were above 50 years old, and 42% had completed higher or tertiary education. Although household members who mostly buy food were on average younger and more highly educated in urban area, there was no significant difference between both sub-samples considering age ( $p = .258$ ) and education status ( $p = .152$ ).

The average ITTP was lower in households with women (5.6 °C, SD = 2.2) than in households where men (6.9, SD = 2.2) were responsible as the person who mostly buys food ( $p = .067$ ). Comparison of ITTP based on other demographic characteristics, such as area of residence ( $p = .209$ ), age ( $p = .465$ ) and education ( $p = .411$ ), showed weaker impact.

The average number of household members weakly correlated with RAT ( $r = 0.245$ ,  $p = .087$ ) and ITTP ( $r = 0.220$ ,  $p = .125$ ). The average frequency of door openings during the 24-h measurements was 14.6 times in 24 h (SD = 11.1) and was associated with number of household members ( $r = 0.373$ ,  $p = .008$ ) but did not correlate with an average ITTP ( $r = -0.032$ ,  $p = .825$ ) nor with average RAT ( $r = -0.028$ ,  $p = .884$ ).

## 4. Discussion

### 4.1. Temperature measurements

Considering average ITTP and RAT, only 36% of all refrigerators maintained temperatures  $\leq 5$  °C, as advised by national and international public health or food safety authorities. However, regarding 24 h profiles, in only 20% was the advised limit not crossed during the entire monitoring period. The overall means of ITTP and RAT in this study are close to the overall arithmetic mean of mean temperatures (6.1 °C) measured in studies throughout the world (James et al., 2017) with similar shares of refrigerators operating above this temperature, which is comparable to the study of Derens-Bertheau et al. (2015) showing that 47% of the products in domestic refrigerators were kept at a temperature above 6 °C.

In the current study, static refrigerators without ventilation were more commonly present. In this type of refrigerator, heat is transferred principally by natural convection, and the airflow is a consequence of variations in air density (Laguerre & Flick, 2004). For comparison, ITTP and RAT were measured close to the centre of the refrigerator on the middle shelf, although the situation in other parts of the refrigerator might be different. Others report that the centre (middle shelf) of the refrigerator was found to be the coldest area (George, Burgess, & Thorn, 2010). However, variations in temperatures in different shelves of the same refrigerator were reported by Marklinder and Eriksson (2015). Additionally, variations in temperatures in different areas can also change with time (Laguerre & Flick, 2004). Variations depend on the refrigerator load, which had a noticeable impact on average temperatures in the current study, and the materials of shelves; refrigerators with solid glass shelves (predominant in the current study) are better in maintaining more consistent air temperature and minimising rises in air temperature, in comparison to wire shelves but can also create layers of different temperatures (George et al., 2010). We can see that in the current study the lowest and the highest average ITTP (Table 2) were measured in the refrigerator with the same shelf type: open wire shelves which enable air to flow freely between the top and bottom of the refrigerator and allow temperatures to equalise more uniformly throughout the refrigerator. The smaller volume of the refrigerated compartment with a built-in freezer compartment in the case of the refrigerator with lowest average ITTP (Table 2) could have an impact as already reported by others (Janjić et al., 2016; Laguerre, Derens, & Palagos, 2002). However, this is possible only with adequate cooling settings while correlations between the size of the refrigerator and measured temperatures were not confirmed on larger numbers of tested refrigerators by others (George et al., 2010).

AAT did not differ significantly among the households and are comparable to previous studies reviewed by James, Evans, and James (2008). Although the AAT did not correlate with ITTP or RAT in the current study, this can have a significant impact in case of power failure, as reported by Ovca and Jevšnik (2009b).

### 4.2. Refrigerator characteristics

Refrigerator age in the current study (with 44% equal or above 10 years) was higher compared to other European countries (Dumitraşcu et al., 2020; Janjić et al., 2016). Similar to other studies (Hassan, Dimassi, & El Amin, 2015; Janjić et al., 2016), we did not prove a significant correlation between refrigerator temperature and age. Also, the fan (with which newer refrigerators were more often equipped) did not make a significant, albeit still noticeable, difference related to average temperatures measured. Door seal conditions, which might become less effective with the higher age of refrigerator, as suggested by others (O'Brien, 1997), were not monitored. Nevertheless, it should not be neglected that older appliances (especially those over 11 years) use more energy than newer appliances do, as demonstrated by Gemmell, Foster, Siyanbola, and Judith (2017).

The rarity of temperature displays is in line with previous studies around the world (James et al., 2017) and also with a recent study among European countries (Dumitraşcu et al., 2020) and could be related to the fact that most refrigerators are still produced without any temperature display. However, the complete absence of control thermometers, despite recommendations by NIPH (2011) to use them, explains the consumer awareness and attitude towards efficiently maintaining the cold chain at its last link. Consequently, consumers cannot know the temperatures in their domestic refrigerators, as also previously noted among Slovenian consumers based on their self-reports (Jevšnik, Hlebec, & Raspor, 2008a,b; Ovca & Jevšnik, 2009a). Although control thermometers also are recommended, some studies (Laguette et al., 2002) found no relationship between the temperature measured with thermometer and data-logger showing that using a control thermometer did not accurately represent the temperature of the refrigerator. As recently reported by Borda et al. (2020), the majority of consumers lack knowledge about how to assess the temperature in the refrigerator, or they simply rely on their judgment, using their hands to evaluate food coldness. Although almost 20% of the consumers were able to detect the exact food and surface temperature kept at 4 °C with this technique, the risk for misvaluation of temperatures remains high. George et al. (2010) also noticed that consumers often incorrectly assume that the refrigerator thermostat-setting button (usually relating to the degree of cooling) corresponds to the refrigerator temperature.

Differences between various types of refrigerators were not always confirmed in previous studies (James et al., 2017). The greatest range of temperature (differences between top, middle, and bottom temperatures) was observed for fridge-freezers (with the freezer on the bottom) (Laguette et al., 2002). Unlike the results reported by Dumitraşcu et al. (2020), in which the combined refrigerator-freezer was the most common type observed, refrigerators without a freezer compartment were most frequently present in our study. Also, the lowest average ITTP was measured among these types of refrigerators, which might be related more to the fact that this type was the most abundant among refrigerators with an age of less or equal to four years.

The impact of different degrees of refrigerator loading on internal temperatures of foodstuffs during the simulation of a power failure was previously reported by Ovca and Jevšnik (2009b). Although the results in the current study were not significant, they indicate that increased load up to the full capacity of the refrigerator contributes to the lower ITTP, for which overpacked refrigerators demonstrate again higher ITTP. Overpacked refrigerators can block air circulation inside the refrigerator, especially in case of static refrigerators (without fan) with heat transfer by natural convection. This fact is particularly relevant during the COVID-19 epidemic, when consumers are buying more than then they need and potentially overfill home refrigerators, increasing the risk of cross-contamination, date of durability expiration, and high refrigerator temperatures if cooling settings are not adjusted.

Food distribution is, as observed in the current study, related to the refrigerator load; more space enables the more optimal distribution of food items in terms of adequate temperatures and in terms of cross-contamination prevention. Although the risk of cross-contamination, based on the observed food items (mostly pre-packed) might be mitigated, the observed situation reveals improper housekeeping practice observed especially in overpacked refrigerators. As reported by others, consumers mostly do not have any preferences or priorities regarding how to store food in the refrigerator except if the questions compel them to answer (James et al., 2017). Improper practices among Slovenian consumers arranging foodstuffs in the refrigerator in a random manner were reported previously by Ovca and Jevšnik (2009a). They also reported that consumers buy high-risk food items (e.g., fresh meat) mostly for daily use, which could also explain the absence of high-risk food items in refrigerators of the current study.

Although pre-packed food items are labelled with durability dates (in addition to required storage temperature), we determined that expired durability date was not related to the refrigerator load or any of

demographic characteristic. It is important to point out that improper refrigerator storage conditions may significantly shorten shelf-life, which cannot be assuring in terms of food safety (Jofré et al., 2019; Laguette, Duret, Hoang, & Flick, 2014). Additionally, improper practices were detected, based on informal conversations with responsible householders, regarding the verification of foods after the expiration of durability date (checking the smell and colour), which is especially risky in the case of “use-by” if consumers do not distinguish it from “best-before” date. This risky practise was also observed among Swedish consumers Marklinder and Eriksson (2015).

Unclean surfaces inside refrigerators are another potential risk factor for cross-contamination due to the biofilms that microorganisms may form on them (Carrasco, Morales-Rueda, & García-Gimeno, 2012). Despite low temperatures, some microorganisms can grow or survive below 5 °C. Therefore, regular cleaning and maintenance are recommended by NIPH (2011). Most refrigerators in the current study contained glass shelves, which are easier to clean. Based on self-reports in the current study, a relatively small share does not remember when the last time they cleaned their refrigerator was. Surprisingly, the self-reports from urban area significantly differ from those of the rural area, which is comparable to the findings by Kennedy et al. (2005), reporting significantly higher total viable counts and incidences of pathogens in the refrigerators of urban consumers. The difference is not a consequence of reported cleaning method, which did not differ according to the area of residence. Although James et al. (2017) reported the rarity of refrigerator cleaning in previous studies, they also emphasise the absence of a clear link between refrigerator cleanliness and food poisoning. However, the absence of systematic cleaning and appropriate cleaning agents increases the risk of cross-contamination.

#### 4.3. Household characteristics

The current study confirmed gaps in food safety practices related to the importance of cold chain maintenance and cross-contamination prevention, which were highlighted previously among Slovenian consumers (Jevšnik, Hlebec, & Raspor, 2008a,b), raising the risk for microbiological food poisoning. The majority of women among household members who mostly buy food demonstrates that women are mostly responsible for food supply. Comparing ITTP and RAT based on demographic characteristics revealed no significant differences. The biggest difference of ITTP was observed considering gender, for which average ITTP was lower in households with women as the household member who mostly buys the food. This finding is in line with a previous, larger study among Slovenian consumers, which showed that women adhered to safer food handling practices to a greater degree than men did (Jevšnik, Hlebec, & Raspor, 2008a,b). However, Case nr. 1 (Table 2) confirms the findings of a recent European study in which young men were not confirmed to be risk-takers in relation to cooling practices (Dumitraşcu et al., 2020). Nevertheless, other than gender, reasons for different household practices should be investigated in line with different consumer profiles in terms of lifestyle, attitude, and behaviours towards food and food safety (Kendall, Kuznesof, Seal, Dobson, & Brennan, 2013).

The average frequency of door openings was probably lower because of the season (winter) but still comparable to the previous studies reviewed by James et al. (2017). Although the frequency and length of door opening are generally recognised as factors that could influence the refrigerator temperature, James et al. (2017) reported a poor correlation between these two factors and the mean air temperature at any position within a refrigerator or the mean food temperatures in previous studies. Even during the simulation of power failure, different frequencies of door openings did not correlate with internal temperatures (Ovca & Jevšnik, 2009b). In the current study, door opening correlated much more with the number of household members than with ITTP and RAT. That is most probably related to the recovery time of the refrigerator. As reported by Brennan, Kuznesof, Kendall, Olivier, and Ladha (2013), the

refrigerator took up to 123 s to recover to within 5% of the starting temperature after a door opening.

#### 4.4. Research limitations

There are several well-known disadvantages of snowball sampling. Most critical among these is the non-random nature of respondent selection (Johnson, 2014). The impact of contacting participants in advance and the method of performing measurements on the temperature and storage conditions because of consumer behaviour during the measurements could not be completely prevented despite detailed instructions. Measuring the temperatures inside refrigerators solely at one location increases the reliability of comparisons between the refrigerators; however, temperature variation in different areas of the same refrigerator is ignored with this approach. We measured only 24 h, which does not enable determining a long-term situation.

#### 5. Conclusions

Based on measurements, one third of monitored refrigerators provided product temperatures as recommended by public health authorities, but only one fifth did so consistently throughout the monitoring period. While refrigerator age and load had a noticeable but not significant impact on temperatures, it seems, based on all comparisons done, that thermostat setting has a key impact on refrigerator temperatures. However, the absence of temperature displays, control thermometers and/or consumers' knowledge prevent correct refrigerator setting. High temperatures combined with the non-systematic distribution of food in the refrigerator, expired dates of durability, non-systematic cleaning strategies and, consequently, potential cross-contamination allow favourable preconditions for food infections occurring at the end of the food supply chain, representing a significant share of FBO.

#### CRedit authorship contribution statement

**Andrej Ovca:** Conceptualization, Methodology, Writing - original draft, Formal analysis. **Tina Škufca:** Investigation, Data curation, Formal analysis. **Mojca Jevšnik:** Writing - review & editing.

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#### Appendix A. Supplementary data

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#### References

- Anderson, B. A., & Singh, R. P. (2005). Moisture diffusivity in tylose gel (karlsruhe test material). *Journal of Food Science*, *70*(5), E331–E337.
- Barthel, C., & Götz, T. (2012). *The overall worldwide saving potential from domestic refrigerators and freezers*. Wuppertal Institute for Climate, Environment and Energy. [https://energypedia.info/images/c/c9/Bigee\\_refrigerators\\_freezers\\_worldwide\\_potential.pdf](https://energypedia.info/images/c/c9/Bigee_refrigerators_freezers_worldwide_potential.pdf). (Accessed 7 July 2020).
- Borda, D., Mihalache, O. A., Nicolau, A. I., Teixeira, P., Langsrud, S., & Dumitrascu, L. (2020). Using tactile cold perceptions as an indicator of food safety—a hazardous choice. *Food Control*, *111*, 107069.
- Brennan, M., Kuznesof, S., Kendall, H., Olivier, P., & Ladha, C. (2013). *Activity recognition and temperature monitoring (ART) feasibility study (FS244026)*. [https://www.food.gov.uk/sites/default/files/media/document/819-1-1498\\_FSA\\_ART\\_Final\\_Report\\_10-07-13.pdf](https://www.food.gov.uk/sites/default/files/media/document/819-1-1498_FSA_ART_Final_Report_10-07-13.pdf). (Accessed 2 July 2020).

- Carrasco, E., Morales-Rueda, A., & García-Gimeno, R. M. (2012). Cross-contamination and recontamination by Salmonella in foods: A review. *Food Research International*, *45*(2), 545–556.
- Creswell, J. W. (2007). *Qualitative inquiry & research design: Choosing among five approaches* (2<sup>nd</sup> ed.). London: Thousand Oaks, CA: Sage Publications.
- Davenport, M. L., Qi, D., & Roe, B. E. (2019). Food-related routines, product characteristics, and household food waste in the United States: A refrigerator-based pilot study. *Resources, Conservation and Recycling*, *150*, 104440.
- Derens-Bertheau, E., Osswald, V., Laguerre, O., & Alvarez, G. (2015). Cold chain of chilled food in France. *International Journal of Refrigeration*, *52*, 161–167.
- Dumitraşcu, L., Nicolau, A. I., Neagu, C., Didier, P., Maître, I., Nguyen-The, C., ... Borda, D. (2020). Time-temperature profiles and *Listeria monocytogenes* presence in refrigerators from households with vulnerable consumers. *Food Control*, *111*, 107078.
- EFSA, & ECDC. (2019). The European union one health 2018 zoonoses report. *EFSA Journal*, *17*(12), 276.
- Gemmel, A., Foster, H., Siyanbola, B., & Judith, E. (2017). *Study of over-consuming household cold appliances*. [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/585520/Cold\\_appliances\\_field\\_trial\\_report\\_FINAL\\_230117\\_2\\_.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/585520/Cold_appliances_field_trial_report_FINAL_230117_2_.pdf). (Accessed 12 July 2020).
- George, R. M., Burgess, P. J., & Thorn, R. D. (2010). *Reducing food waste through the chill chain*. <http://www.wrap.org.uk/sites/files/wrap/Reducing%20food%20waste%20through%20the%20chill%20chain.pdf>. (Accessed 10 July 2020).
- Hartnoll, R., Griffiths, P., Taylor, C., Vincent, H., Blanken, P., Nolimal, D., ... Ingold, R. (1997). *Handbook on snowball sampling*. Strasbourg.
- Hassan, H. F., Dimassi, H., & El Amin, R. (2015). Survey and analysis of internal temperatures of Lebanese domestic refrigerators. *International Journal of Refrigeration*, *50*, 165–171.
- James, S. J., Evans, J., & James, C. (2008). A review of the performance of domestic refrigerators. *Journal of Food Engineering*, *87*(1), 2–10.
- James, C., Onarinde, B. A., & James, S. J. (2017). The use and performance of household refrigerators: A review. *Comprehensive Reviews in Food Science and Food Safety*, *16*(1), 160–179.
- Janjić, J., Katić, V., Ivanović, J., Bošković, M., Starčević, M., Glamočlija, N., et al. (2016). Temperatures, cleanliness and food storage practises in domestic refrigerators in Serbia, Belgrade. *International Journal of Consumer Studies*, *40*(3), 276–282.
- Jevšnik, M., Hlebec, V., & Raspor, P. (2008). Consumers' awareness of food safety from shopping to eating. *Food Control*, *19*(8), 737–745.
- Jevšnik, M., Hoyer, S., & Raspor, P. (2008). Food safety knowledge and practices among pregnant and non-pregnant women in Slovenia. *Food Control*, *19*(5), 526–534.
- Jevšnik, M., Ovca, A., Bauer, M., Fink, R., Oder, M., & Sevssek, F. (2013). Food safety knowledge and practices among elderly in Slovenia. *Food Control*, *31*(2), 284–290.
- Jofré, A., Latorre-Moratalla, M. L., Garriga, M., & Bover-Cid, S. (2019). Domestic refrigerator temperatures in Spain: Assessment of its impact on the safety and shelf-life of cooked meat products. *Food Research International*, *126*, 108578.
- Johnson, T. P. (2014). *Snowball sampling: Introduction*. Wiley StatsRef: Statistics Reference Online.
- Kendall, H., Kuznesof, S., Seal, C., Dobson, S., & Brennan, M. (2013). Domestic food safety and the older consumer: A segmentation analysis. *Food Quality and Preference*, *28*(1), 396–406.
- Kennedy, J., Jackson, V., Blair, I. S., McDowell, D. A., Cowan, C., & Bolton, D. J. (2005). Food safety knowledge of consumers and the microbiological and temperature status of their refrigerators. *Journal of Food Protection*, *68*(7), 1421–1430.
- Laguerre, O., Derens, E., & Palagos, B. (2002). Study of domestic refrigerator temperature and analysis of factors affecting temperature: A French survey. *International Journal of Refrigeration*, *25*(5), 653–659.
- Laguerre, O., Duret, S., Hoang, H. M., & Flick, D. (2014). Using simplified models of cold chain equipment to assess the influence of operating conditions and equipment design on cold chain performance. *International Journal of Refrigeration*, *47*, 120–133.
- Laguerre, O., & Flick, D. (2004). Heat transfer by natural convection in domestic refrigerators. *Journal of Food Engineering*, *62*(1), 79–88.
- Ledesma, S., & Belman-Flores, J. M. (2017). Mathematical application to analyze the thermal behavior of a domestic refrigerator: Influence of the location of the shelves. *International Journal of Refrigeration*, *74*, 360–368.
- Marklinder, I., & Eriksson, M. (2015). Best before date - food storage temperatures recorded by Swedish students. *British Food Journal*, *117*(6), 1764–1776.
- NIPH. (2011). *Higienska priporočila za varnost živil za potrošnike (Hygienic recommendations for food safety for consumers)*. Retrieved from [https://www.nijz.si/sites/www.nijz.si/files/publikacije-datoteke/higienska\\_priporocila\\_za\\_varnost\\_zivil\\_za\\_potrosnike\\_2011.pdf](https://www.nijz.si/sites/www.nijz.si/files/publikacije-datoteke/higienska_priporocila_za_varnost_zivil_za_potrosnike_2011.pdf). (Accessed 12 July 2020).
- O'Brien, G. D. (1997). Domestic refrigerator air temperatures and the public's awareness of refrigerator use. *International Journal of Environmental Health Research*, *7*(2), 141–148.
- Ovca, A., & Jevšnik, M. (2009a). Maintaining a cold chain from purchase to the home and at home: Consumer opinions. *Food Control*, *20*(2), 167–172.
- Ovca, A., & Jevšnik, M. (2009b). Temperature and time impact on food safety in domestic refrigerator. *International Journal of Sanitary Engineering Research*, *3*(1), 17–25.
- Ovca, A., Jevšnik, M., & Raspor, P. (2014). Food safety awareness, knowledge and practices among students in Slovenia. *Food Control*, *42*, 144–151, 0.
- Ricci, A., Allende, A., Bolton, D., Chemaly, M., Davies, R., Fernández Escámez, P. S., ... Hazards, E. P. B. (2018). *Listeria monocytogenes* contamination of ready-to-eat foods and the risk for human health in the EU. *EFSA Journal*, *16*(1).
- WHO. (2006). *Five keys to safer food manual*.
- WHO, & FAO. (2009). *Food hygiene (basic texts)* (4th ed.). Rome, Italy: World Health Organization, Food and Agriculture Organization of the United Nations.