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The impact on heart rate and blood pressure following exposure to ultrafine particles from cooking using an electric stove

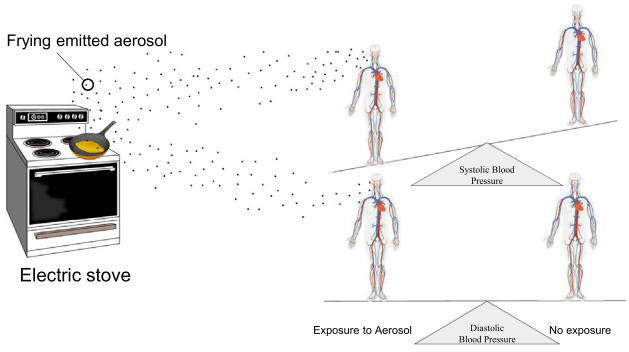
Raikhangul Gabdrashova [a], Sholpan Nurzhan [a], Motahareh Naseri [b], Zhibek Bekezhankyzy [c], Aidana Gimnkhan [c], Milad Malekipirbazari [d], Mahsa Tabesh [e], Reza Khanbabaie [e], Byron Crape [f], Giorgio Buonanno [g], Philip K. Hopke [h], Aliakbar Amouei Torkmahalleh [i], Mehdi Amouei Torkmahalleh [b,*]

[a] Department of Biology, School of Humanities and Social Sciences, Nazarbayev University, Nur-Sultan 010000, Kazakhstan
[b] Department of Chemical and Materials Engineering, School of Engineering and Digital Sciences, Nazarbayev University, Nur-Sultan 010000, Kazakhstan
[c] Department of Chemistry, School of Humanities and Social Sciences, Nazarbayev University, Nur-Sultan 010000, Kazakhstan
[d] Department of Industrial Engineering, Bilkent University, Bilkent, 06800 Ankara, Turkey
[e] Department of Physics, Babol Noshirvani University of Technology, Shariati Ave., Babol 47148-71167, Iran
[f] Department of Medicine, School of Medicine, Nazarbayev University, Nur-Sultan 010000, Kazakhstan
[g] Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, via Di Biasio 43, Cassino 03043, Italy
[h] Department of Public Health Sciences, University of Rochester Medical Center, Rochester, NY 14642, USA
[i] Kheradvarzan Center for Rehabilitation Services to Seniors, Ghaemshahr, Mazandaran, Iran

HIGHLIGHTS

- A low particle emission frying recipe still results in observable health effects.
- Systolic blood pressure increased 2 h after exposure to cooking aerosol.
- Systolic blood pressure decreased solely due to the lack of food and drink.
- Diastolic blood pressure did not change due to exposure to cooking aerosol.
- Heart rate varied both due to the exposure to aerosol and stress/anxiety.

GRAPHICAL ABSTRACT



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ABSTRACT

Cooking is a major source of indoor particulate matter (PM), especially ultrafine particles (UFPs). Long-term exposure to fine and ultrafine particles (UFPs) has been associated with adverse human health effects. Toxicological studies have demonstrated that exposure to $PM_{2.5}$ (particles with aerodynamic diameter smaller than 2.5 μm) may result in increased blood pressure (BP). Some clinical studies have shown that acute exposure to $PM_{2.5}$ causes changes in systolic (SBP) and diastolic blood pressure (DBP), depending on the source of particles. Studies assessing the effect of exposure to cooking PM on BP and heart rate (HR) using electric or gas stoves are not well represented in the literature. The aim of this investigation was to perform controlled studies to quantify the exposure of 50 healthy volunteer participants to fine and ultrafine particles emitted from a low-emissions recipe for frying ground beef on an electric stove. The BP and heart rate (HR) of the volunteers were monitored during exposure and after the exposure (2 h post-exposure). Maximum UFP and $PM_{2.5}$ concentrations were 6.5×10^4 particles/cm^3 and 0.017 mg/m^3, respectively. Exposure to UFPs from frying was associated with statistically significant increases in the SBP. The lack of food and drink during the 2 h post-cooking period was also associated with a statistically significant reduction in SBP. No statistically significant changes in DBP were observed. Physiological factors, including

* Corresponding author.
E-mail address: mehdi.torkmahalleh@nu.edu.kz (M. Amouei Torkmahalleh).

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heat stress over the stove, movements and anxiety, could be responsible for an elevation in HR at the early stages of the experiments with a subsequent drop in HR after 90 min post-cooking, when study participants were relaxed in a living room.

1. Introduction

The World Health Organization (WHO) reported that short-term exposure to particulate matter (PM) is associated with adverse health outcomes (WHO, 2013). Daily mortality and hospital admissions for cardiovascular diseases were shown to increase with PM concentrations (Zhang et al., 2018) and to be more important than hospitalization due to respiratory diseases (Basagaña et al., 2015).

Elevated blood pressure (BP) is associated with increased cardiovascular disease morbidity and mortality (Blacher et al., 2000; Brook et al., 2010; Guo et al., 2010; Kan et al., 2007). Studies on humans and animals have demonstrated that exposure to $PM_{2.5}$ and gases such as SO_2 and NO_2 may result in increased BP (Yang et al., 2018; Brook et al., 2010; Chang et al., 2004; Urch et al., 2005; Zanobetti et al., 2004), thus potentially increasing the risk of cardiovascular disease outcomes. Brook et al. (2011) reported an association between systolic BP (SBP) and short-term exposure to $PM_{2.5}$ concentrations (a mean of 15.4 μg/m^3) among 65 non-smoking subjects. A 10 μg/m^3 increase in $PM_{2.5}$ level was associated with a 1.41 mm Hg increase in SBP.

Liang et al. (2014) also found that acute exposure to $PM_{2.5}$ caused small increases in SBP and diastolic BP (DBP) of 1.393 mm Hg and 0.895 mm Hg, respectively. Human subjects without cardiovascular disease experienced a slight increase (0.99 mm Hg) in SBP during short-term exposure to increased $PM_{2.5}$ concentrations by 10 μg/m^3 (Auchincloss et al., 2008; Gong Jr et al., 2003). Soppa et al. (2017) reported that exposures to particles from toasting bread increased SBP while particles from frying sausages and candle burning did not affect BP during short-term exposure.

Negative (Chuang et al., 2007; Adar et al., 2007) and positive (Shields et al., 2013) associations between heart rate variability (specific change in the time between successive heart rate beats) and exposure to $PM_{2.5}$ have been reported. The inconsistencies in the literature regarding associations between exposure to fine particles and heart rate variability (HRV) were also found between ultrafine particle (UFP) concentrations (number concentration for particles smaller than 100 nm) and acute cardiovascular effects. For example, negative associations between exposure to UFPs and HRV were reported by Chan et al. (2004), while Samet et al. (2009) observed positive associations. Rizza et al. (2019) suggested that such discrepancies could result from several factors including the differences in the method of UFP exposure assessment (personal monitors vs. fixed-sites), differences in the type of studied population (adult vs. elder or healthy vs. unhealthy), and the lag time between the HRV recording and the exposure (discrete vs. continuous electrocardiogram (ECG) monitoring). Additionally, the effect of physical activities (standing, sitting, and laying down) and psychological moods during an exposure study may coincide with the impacts of exposure to particles on HR. Another key factor that may cause discrepancies among the previous cardiovascular studies could be the delay in measuring the cardiovascular effects after the exposure to UFPs due to the time required for the deposited materials to have an effect. Cardiovascular effects in exposure studies might be observed even if the UFP concentrations are at the background level (without a particle source). Controlled clinical exposure studies help to better understand the cardiovascular effects due to the exposure to UFPs and eliminate the influential factors on BP and HR that may coincide with the exposure.

The vast majority of people spend approximately 90% of their lifetime indoors and 60% in their home (Hu et al., 2012). Therefore, indoor PM may have a disproportionate impact on people's health and deserves further research.

Studies regarding the sources of indoor particles have identified cooking as one of the most significant indoor particle sources (Ozkaynak et al., 1996; Buonanno et al., 2009; Kan et al., 2007; Lazaridis et al., 2006; Liang et al., 2014; Massey et al., 2012; Wan et al., 2011; Amouei Torkmahalleh et al., 2018). Particle sizes emitted from cooking generally fall within the UFP and fine particle ($PM_{2.5}$) size ranges (Dennekamp et al., 2001; Wallace et al., 2008; Abdullahi et al., 2013; Amouei Torkmahalleh et al., 2017).

Blood pressure and brain wave pattern (Naseri et al., 2019) measurements have also been used as tools to assess the effects of exposure to cooking particles on human organs. However, blood pressure studies associated with exposure to indoor particles during cooking mostly focused on the impacts of biofuel combustion emissions. For example, rural Guatemalan women experienced statistically significant increases in their blood pressure and pulse rate during cooking using an open wood fire (Mann et al., 2013). Similarly, associations were observed between exposures to $PM_{2.5}$ emitted from biomass burning with increases in BP when rural Chinese women were studied (Huang et al., 2011).

The aims of this investigation were to conduct controlled clinical studies to quantify exposure of 50 study participants to ultrafine particles emitted from frying ground beef and to monitor their BP and HR variations up to 3 h (including 2 h post-exposure).

2. Methodology

Experiments were conducted in two phases. Initially, phase1 was undertaken to study the effect of the exposure and post-exposure (up to 30 min) periods on the heart rate and blood pressure. However, when no effects were observed during these periods, Phase2 was conducted with an extended post-exposure period, up to 120 min after the end of the cooking. The cooking recipe and the design of the experiments were identical for the two phases unless otherwise stated. The ethics committees of the Nazarbayev University approved the experimental procedure of this study under the approval code of 115/12022019. Some volunteers typically, student and faculty were invited to experiments after reviewing their physical and mental health conditions using a questionnaire. The exclusion criteria include but were not limited to tobacco and drug consumptions, neurological and psychological discomfort, and respiratory diseases (FS1).

2.1. Study participants

Seventeen healthy non-smoking adults (7 men and 10 women) with ages ranging from 18 to 46 years participated in the Phase 1 experiments. The study participants were provided with the necessary information before signing the consent form (FS2). The cooking habits of the study participants were recorded using a questionnaire (FS1). To ensure reliable measurements, participants were asked to have sufficient rest and food before the experiment to reduce stress levels and anxiety and not to take unnecessary medications or supplements that would disrupt measurements. Participants were asked to avoid eating or drinking during the experiments. To prevent exposing participants to levels of cooking fumes beyond their regular daily exposure, participants agreed to substitute one daily meal preparation with the experimental meal preparation.

Thirty-three non-smoking healthy adults (11 men and 21 women) with ages ranging from 18 to 51 years participated in the Phase 2 experiments. The instructions were the same as in the Phase 1 experiments except that 16 study participants were allowed to eat and drink during

the experiments, while the other 17 participants were not. Seven study participants who participated in the Phase 1 experiments also participated in the Phase 2 experiments.

To study the effect of other factors separate from the aerosol effects, we designed a control study. Sixteen study participants were selected to simulate the cooking and post-cooking procedure. The study participants stood next to the stove during the cooking period while the stove was off (no emissions) and sat in a living room during the post-cooking period. This control experiment (providing controls for the study) resulted in no additional exposure to particles beyond that which was normally in the room. The participants were also offered food and drinks. All of the participants in the control experiments participated in the Phase 2 experiments.

2.2. Cooking

Ground beef was purchased from a commercial market. A kitchen equipped with an electric stove in an apartment was selected to perform the experiments without mechanical ventilation. The kitchen's dimensions were 21.77 m^3 (height of 275 cm, length of 355 cm, and width of 223 cm). No mechanical ventilation was operated during cooking. We have used the same recipe developed in our recent study (Naseri et al., 2019). One hundred grams of ground beef was mixed with 20 g shredded, squeezed onions, 1 g salt, 1 g pepper, and 1 g turmeric. Three pieces of hamburger (pan kebab) roughly 40 g each were prepared. Some (approximately 21 mL) of sunflower oil was poured to a Teflon coated pan and heated. After eight minutes from the start of the heating, the hamburgers were placed in the pan to be fried by the heated oil. A wooden spatula was utilized to flip the hamburgers at minutes 11, 14, and 17. At minute 20, the stove was switched off, but measurements continued.

We did not see increased concentrations due to heating the pan whereas Wallace et al. (2015) previously reported the observation of UFPs when metal surfaces, such as heating elements in electric appliances, or empty cooking pans were heated. The source of these particles is adsorbed SVOCs (Wallace et al., 2015, 2017). Our observation of no additional particles could be due to repeatedly heating the pan over the course of the experiments preventing the SVOCs to build up. Thus, on average, these emissions became insignificant. Also, to observe the peak from the heated pan, the time at which the emission arises should be shorter than the time at which the meat is placed inside the pan. For our experiments, given the relatively large size of the pan, it could be possible that the meat was placed inside the pan before the pan became sufficiently hot to produce particles.

2.3. Instrumentation

A Condensation Particle Counter (CPC) model 3007 (TSI, St. Paul, MN, USA) was used to measure the particle number concentration. CPC is able to detect particles down to 10 nm up to maximum concentrations of 10^5 particles/cm^3. Concentrations higher than this value need to be corrected which will be explained later. The logging interval of CPC was 1 s. To quantify the particle mass concentration (PM_1, $PM_{2.5}$, PM_4, and PM_{10}), DustTrak DRX Model 8533 (TSI, St. Paul, MN, USA) was employed. This instrument has the lower size detection limit of 0.1 μm and is capable of measuring particle concentration up to 150 mg/m^3. The logging interval of 1 s was employed for DustTrak DRX. CPC and DustTrak were zero check before each experiment. An IAQ Model 7545 (TSI, St. Paul, MN, USA) was utilized to monitor indoor temperature, relative humidity (RH), and CO_2 concentrations with 1 minute logging intervals. Additionally, an ultrafine particle counter, the NanoTracer (Philips Aerasense, Netherlands), was utilized to study ultrafine particle concentrations. The lower detection limit of this instrument is 20 nm. The upper concentration limit of the instrument according to the manufacture, is 10^6 particles/cm^3. The logging interval for NanoTracer was 10s. The performance of the NanoTracer is limited to particles in the size range of 20 to 120 nm that can significantly reduce the particle counts if the particle size is below this range.

Since the NanoTracer (20 nm) has a different lower cutoff size compared to the CPC (10 nm), the two instruments need to be harmonized (Krecl et al., 2017). The CPC was selected as the reference instrument since it covers the wider range of particle sizes (>10 nm). To obtain the relationship between the two devices, the NanoTracer and CPC were deployed side-by-side in the living room of the experimental apartment after cooking to provide a cooking aerosol but without any volunteers present. During the study measurements, when the volunteers were present, the NanoTracer was similarly placed in the living room. Particles were generated using the cooking recipe (frying kebab (hamburger)) in the adjacent kitchen. The data from the two instruments were converted to minute average data. Three sets of the 30 minute measurements were made for approximately including a background period, cooking emissions (20 min), and decay through deposition and ventilation. The data from the three measurements are shown in Fig. S1. A regression analysis yielded a relationship between the two instruments as follows:

$$\mathrm{CPC} = 1.41(\mathrm{NT}) + 248 \left(R^2 = 0.85\right) \mathrm{N} = 86 \quad (1)$$

The NanoTracer measurement values were then adjusted using Eq. (1) to correspond to CPC-like values. The CPC- equivalent data (or corrected NanoTracer data) during the post exposure in the living room are presented in Fig. S11.

The temperature of the oil and meat were measured continuously with 1 minute logging intervals during the experiments using a digital thermometer (Model 54IIB, Fluke, Everett, USA) equip with K type thermocouple probe (THS-103–020, ThermoWorks, USA).

A blood pressure monitor (Omron Model BP786 N, USA) was employed to monitor systolic blood pressure (SBP), diastolic blood pressure (DBP) and heart rate (HR). According to the manufacturer, the accuracy of the blood pressure is ±3 mm Hg or 2% of the reading, and the accuracy of the heart rate measurement is ±5% of the display reading. A study showed that a different model of Omron BP monitor can be used for clinical BP measurements (El Assaad et al., 2002).

The three steps of BP and HR measurements were conducted in the living room.

2.4. Exposure assessment

The following parameters were continuously recorded during the Phase 1 and Phase 2: PM mass concentrations (PM_1, $PM_{2.5}$, PM_4, and PM_{10}), meat and cooking oil temperatures, room temperature, and relative humidity. For the Phase 2 experiment, UFP concentrations (particle number concentrations) were also monitored. The instrumentation is described below. The duration of the cooking was 20 min. All aerosol instrumentations, as well as CO2 and CO monitor, were located above the stove to assess the exposure of the study participant during the 20 minute cooking period, except for the Nanotracer that was operated in the living room where the participants stayed during the post-exposure period. Thus, CPC data represents the exposure of the participants during cooking while Nanotracer data represents the exposure during the post-cooking period. Three mixing fans were operated inside the apartment to ensure consistent concentrations among the study participants. Particle concentration varied less than 20% in different locations in the room. The windows and doors were closed during the experiments to reduce infiltration of ambient particles into the experimental home. The windows and doors were opened between experiments to reduce indoor particle concentrations to the background values. The average background UFP (potential other indoor sources) includes resuspended dust, secondary organic aerosol (SOA), etc. We asked the study participants to remove their shoes upon arriving to the test apartment to minimize the dust resuspension. To minimize

SOA formation, we excluded the storage of sources of volatile organic compounds (VOCs) in the apartment, including detergents, food additives, cosmetic materials, etc.

2.5. Health effects

For the Phase 1 experiments, HR and BP were measured at three different time points: before cooking, at the end of cooking, and 30 min after the end of cooking. For the Phase 2 experiments, HR and BP were measured 5 different time points: before cooking, at the end of cooking, 60, 90, and 120 min after the cooking. The measurements were made by trained researchers according to "Recommendations for Blood Pressure Measurement in Humans and Experimental Animals" from the American Heart Association Council on High Blood Pressure Research (Pickering et al., 2005). The BP and HR measurements were conducted under quiet conditions and controlled temperature and humidity. The study participants were at rest for approximately 5 min before the measurements. The arms of the study participants were placed at 90 degrees during the BP and HR measurements, and the cuff was wrapped over the left upper arm.

2.6. Data analysis

2.6.1. Correction

Corrections were made to the Dusttrak DRX and CPC measurements. The Dusttrak uses light scattering that depends on particle size, shape, and composition. The calibration factors (CF) for several cooking sources developed for the TSI SidePak were reported by Dacunto et al. (2013). The CF for frying a hamburger made of ground beef was used as the DustTrak's calibration factor (CF = 0.70) for this study since we also fried ground beef meat. We multiplied the PM concentrations measured by the DustTrak by 0.7 to calculate the estimated true mass concentration. Relative humidity (RH) and particle composition can affect the performance of a light scattering device. In this case, our assumptions of similar aerosol types and device between the current study and Dacunto et al. (2013) were reasonable. As for the relative humidity, in the study of by Dacunto et al. (2013) the RH varied from 30 to 64%, while in the present study, the relative humidity on average varied from 28 to 32%. However, the performance of the SidPak was independent of the RH up to 70% (Jiang, 2010). Thus, the impact of the RH on CF for the DustTrak is likely to be insignificant.

Eq. (2) was used to correct CPC recording in the range of 10^5–4×10^5 particles/cm^3 (Hämeri et al., 2002).

$$y = 6 \times 10^{-19}\, x^4 - 10^{-12}\, x^3 - 4 \times 10^{-8}\, x^2 + 0.9\, x + 9660.1 \qquad (2)$$

where x is a CPC measured concentrations above 10^5 particles/cm^3, and y is the corrected concentration (particles/cm^3). This equation was visually developed from Fig. 4of Hämeri et al. (2002).

2.6.2. Statistical method

2.6.2.1. Three-way ANOVA. A three-way ANOVA statistical test was utilized for this study for statistically testing associations for three independent categorical variables (food consumption, exposure chronology and exposure status) individually with the continuous dependent outcome variable (three separate analyses for the three different dependent outcome variables heart rate, systolic blood pressure, and diastolic blood pressure) and any two-way and three-way interactions between the three independent variables for the continuous dependent outcome variable (van Eeuwijk and Kroonenberg, 1998).

To analyze the data by three-way ANOVA test, we need to check the assumptions required for this test to be valid. Two of our independent variables (food consumption and exposure status) are two categorical groups. The third variable (exposure chronology) consists of five categorical groups. The observations were made independently so no relationships exist between the observations for each group or between the groups. There were no outliers in our dataset. To test for the assumption of homogeneity of variances across groups, we employed Levene's Test implemented in R (Fox, 2015), and no violations were detected. However, the final assumption of normality in the ANOVA model was violated in some of the data as indicated by the application of the Shapiro-Wilk Normality Test in R (Royston, 1982). Although the model is robust to violations of normality, once we incurred this violation, we transformed the data using an "ordered quantile normalizing transformation" (Bartlett, 1947). This transformation was performed with orderNorm function in the bestNormalize package in R. After the transformation, we repeated the modeling.

Since no significant interactions were found in this analysis, we then examined the relationship between changes detected and time of exposure. For this, we employed the Friedman's test (Zimmerman and Zumbo, 1993; Sheldon et al., 1996).

2.6.3. Friedman's test

The Friedman test is a non-parametric statistical tool applicable to test for differences when the same characteristic was measured on each subject at different times or under several different conditions (Friedman, 1937). This method is an alternative to the one-way ANOVA with repeated measures and is one of the alternatives that can be employed when the normality assumption has been violated. We apply this test via Friedman.test in R.

When the Friedman test showed statistically significant differences, we ran post hoc tests that identified where these differences occur. In our experiments, according to the structure of the data, we employed a Wilcoxon Test as our post-hoc test (Wilcoxon, 1992), which is implemented in R with function wilcox.test. Some of our data were not normally distributed and thus required the application of the Friedman statistical test. To better visualize the changes in the data, we presented error bar figures in our Supplementary materials section for the normalized data and not the original data. In this way, statistically significant changes can also be observed in the figures.

3. Results

3.1. Exposure assessment

Fig. S5 presents the $PM_{2.5}$ concentrations above the stove in the breathing zone as a function of time. The $PM_{2.5}$ concentration increased approximately from 0.010 to 0.013 mg/m^3 between minutes 6 and 8 of the experiments, when the meat was placed in the pan. This increase continued until minute 18 (0.017 mg/m^3). After that, the PM concentration decreased. This change corresponds to changes in meat temperature, which dropped due to being flipped. The mean (N = 31) UFP concentration variations with time (1 min logging intervals) recorded using CPC while frying the pan-kebabs using an electric stove during the Phase 2 experiments are presented in Fig. S10. This figure shows the UFP concentrations for exposure in the first 20 min, during the cooking time and up to 30 min during the post-exposure period above the stove. Thus, Fig. S10 presents the exposure of the study participants only during the 20 min of cooking since the participants left the stove area and stayed in the separated living room after the cooking ended. The initial background concentration recorded by CPC was approximately 8.7×10^3 particles/cm^3, while the peak concentration was found to be approximately 6.5×10^4 particles/cm^3. After approximately 48 min into the experiments, the background concentration was obtained. The concentration retained the background level during the 2 h of post-exposure period.

The results and discussions about exposure assessment are found in the Supplementary materials.

3.2. Cardiovascular effects

3.2.1. Friedman analysis

The mean BP values for Phase 1 and Phase 2 experiments are presented in Table S2. Mean SBP values in Phase 1 before cooking and

30 min after cooking started were 100.0 ± 9.8 and 100.2 ± 9.7 mm Hg, respectively. However, this value decreased to 98.2 ± 8.6 mm Hg by the end of the cooking period. Mean SBP values in Phase 2 experiments were found to be 105.0 ± 3.2 and 108.0 ± 3.8 mm Hg before cooking and at the end of the cooking period, respectively. After a drop to 107.0 ± 3.1 mm Hg 1 h after cooking, the SBP increased to 108.0 ± 1.8 mm Hg at 2 h after cooking. Mean DBP values in Phase 1 slowly decreased from 68.8 ± 1.6 mm Hg to 66.2 ± 1.5 mm Hg while in Phase 2, there was an increase at the end of cooking from 77.7 ± 2.7 mm Hg to 78.8 ± 3.5 mm Hg that then decreased and plateaued over the next 3 measurements.

Overall, there were no statistically significant changes (using a two-sided $\alpha > 0.05$ level) in DBP and SBP during the Phase 1 (N = 17) experiments and control experiments as compared to the before-cooking period (Table S2). Fig. 1 presents the distributions for the Phase 1 experiments. The Phase 1 experiments showed no significant changes in HR, suggesting that there was no immediate change in HR due to exposure to cooking $PM_{2.5}$ and UFPs.

For the Phase 2 experiments (N = 33), the overall statistical analyses showed significant reductions in HR during the post-cooking period as compared to the before- cooking period. The reductions became significant after 90 and 120 min during the post-cooking period, suggesting a time-dependent factor affecting the HR. Significant decreases were observed between the 1st and 4th ($p = 0.047$), 1st and 5th ($p = 0.003$), 2nd and 5th ($p = 0.007$), and 3rd and 5th ($p = 0.017$) measurements. SBP and DBP experienced no significant changes in the overall analysis (Table S2, Figs. 2 and S12). Two factors could affect the BP and HR during Phase 1 and Phase 2 experiments. They are exposure to particles and restrictions on eating and drinking during the experiments. The two factors may counteract each other and require further investigations. Heart rate is very much dependent on the position of the individuals (Rizza et al., 2019). Thus, another factor that influencing the HR is the physical activities during cooking, including standing near the stove and the subsequent sitting. Such activities are likely to increase the HR. However, due to the limitation of our instrument that does not continuously measure HR, we are unable to capture the dynamics of HR during the cooking period. To investigate the impact of the two factors (exposure and food/drink) on HR and BP, we divided the Phase 2 experiments into two subgroups, those who were not allowed to eat or drink (the "without food" subgroup) (N = 16) and those who were allowed to eat or drink (the "with food" subgroup) (N = 17) during the experiments. A Friedman analysis was applied to compare these subgroups in the Phase 2 experiments.

Figs. 3 and S13, Figs. 4 and S14, and Figs. S16 and S17 present variations of DBP, SBP, and HR over time for the control experiments, Phase 2 experiments with food and Phase 2 experiments without food, respectively. No statistically significant differences in HR, SBP, and DBP were observed for the control experiments over time (Table S2). The study participants in the control experiments were allowed food and drink during the experiments. These controls were compared to the Phase 2 experimental study population that was also allowed food or drink (with food). When the two study populations (the controls and the Phase 2 experiments with food) were compared, the confounding food/drink effect is eliminated, allowing for the unbiased evaluation of the effect of exposure to particles on HR, SBP, and DBP.

3.2.2. Systolic blood pressure (SBP)

Statistically significant increases were observed in SBP for the Phase 2 experiments with food (N = 17) after 90 min compared to before-cooking. This result suggests that UFP and PM exposures impacted SBP that occurred with a lag time of approximately 90 min following the exposure. Figs. S5 to S11 show that UFPs and PM concentrations had already achieved background levels, and there was no source of exposure that would contribute to increases in UFPs and PM concentrations at minutes 90 or 120. Thus, the observed impact with the lag time could be due to inhaled particles triggering a circulatory system effect after 90 to 120 min. This delayed effect is also supported by our Phase 1 experiments that showed no significant impact up to 60 min after cooking. The average SBP values during control and Phase 1 experiments were 101.68 and 99.4 mm Hg, respectively (Table S2). Table S2 shows that the average SBP increased from 105.0 ± 10.0 mm Hg before cooking to 109.0 ± 8.6 mm Hg and 109.0 ± 9.0 mm Hg after 90 and 120 min post-exposure, respectively.

Statistical analyses of the Phase 2 experiments without food/drink show no significant changes among different HR and DBP measurements (Table S2). However, SBP fluctuated with a statistically significant increase from 98.8 ± 8.5 (before cooking) to 102.0 ± 10.0 mm Hg ($p = 0.02$) 60 min after the end of cooking, followed by a statistically significant decrease to 98.8 ± 10.5 mm Hg ($p = 0.006$) at 90 min post-exposure, and a non-statistically significant increase to 102.2 ± 9.5 mm Hg at 120 min post-exposure. Since this study population was exposed to particles while not being allowed food and drink, the presence of the particles was expected to increase the SBP, as found earlier. However, the observed fluctuations or decreases in SBP suggest that lack of food/drink could decrease SBP with a lag time. When the entire Phase 2 study population, with-food/drink and without-food/drink, were statistically analyzed, no significant changes in SBP were observed. This observation could be due to opposing effects of particle exposure and lack of food/drink.

3.2.3. Heart rate (HR)

Decreasing HR with time was observed for the two subgroups (Phase 2 experiments with food and without food). For the Phase 2 experiments with food, HR decreased from 72 ± 9.9 BPM before cooking to 70 ± 9.7 BPM at 120 min after cooking. For the Phase 2 experiments without food/drink, the HR decreased from 74 ± 9.5 BPM before cooking to 68 ± 9.9 BPM 120 min after cooking. However, none of these changes were statistically significant (Table S2). Nonetheless, when the two subgroups were analyzed together (N = 33), statistically significant reductions were observed, such that HR decreased from 79.7 ± 9.31 BPM before cooking to 74.5 ± 8.0 BPM 120 min after cooking. Since both subgroups did cooking and both experienced reductions in HR, cooking could be responsible for observed reductions during the post-cooking period rather than the lack of food/drink. However, cooking itself encompasses several factors, including exposure to particles. Such factors, including physical activities (standing/sitting), anxiety in the early stages of the experiments, and heat stress from the stove are likely to elevate HR. When the study participants entered the experimental house for the first time, they have some anxiety due to unfamiliarity with the experimental conditions. As a result, HR could be elevated even before cooking, and the elevation could continue due to the standing and moving during the cooking period. Whereas following this period, HR dropped significantly after study participants adapted to the environment and relaxed in the living room on a sofa. The drop in HR during the post-cooking period could also be due to the post-effect of the inhaled particles. However, to completely understand the relative importance of these coexisting factors, further investigations are needed. Rizza et al. (2019) reported reductions in HR (not statistically significant) while sitting compared to standing suggesting possible reductions in HR during post-cooking period (sitting on sofa) in the present study compared to the cooking period (standing over the stove). The control group simulated cooking with the stove turned off. However, the control group was unlikely to have as much anxiety related to cooking, as they were all evaluated in the experimental exposure study before they participated in the control experiments, and thus, they were already familiar with the experimental conditions. Our observations are inconsistent with the findings of Rizza et al. (2019), who reported increased HR due to exposure to UFPs. Thus, the observed reductions in this study could be due to other influential factors coinciding with the cooking activity such as anxiety, stress, and thermal comfort.

The Friedman test indicated that cooking resulted in significant decreases in HR and significant increases in SBP. However, no significant

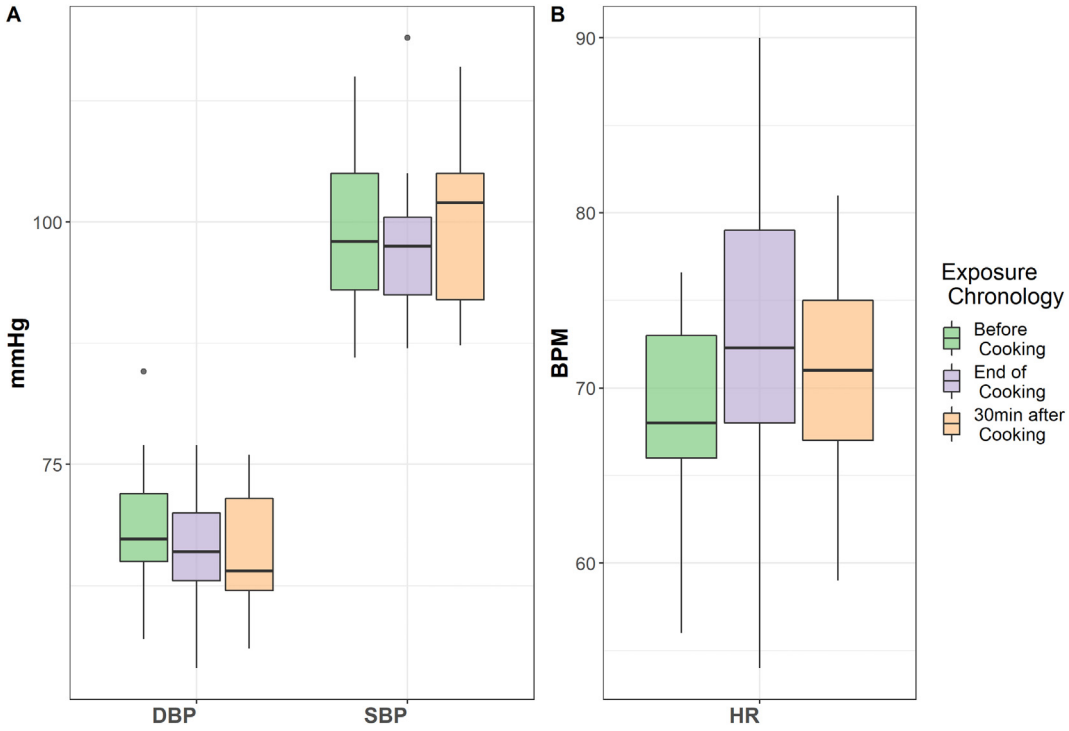

Fig. 1. Blood pressure and heart rate measurements for 17 study participants before, during and 30 min after exposure to $PM_{2.5}$ and UFPs produced during cooking (Box and Whisker Plot)-Phase 1 experiments - The bar in the figure represent maximum and minimum.

changes in DBP were observed. It was also found that reductions in SBP were associated with prolonged lack of food/drink.

A 3-way ANOVA was performed to determine interactions between the three coexisting factors, including cooking (exposure to particles), lack of food/drink and time. The analysis was performed for a population of 50 study participants (control and Phase 2 experiments). Analyses indicated that the food/drink restriction ($p = 0.0010$) and exposure to particles (UFP and PM) ($p = 0.0018$) caused statistically significant changes in SBP, consistent with our findings that indicated increases in SBP due to particle exposure and decreases in SBP due to lack of food/drink. The ANOVA analysis showed that the HR statistically significantly decreased with the effect of cooking ($p = 0.006$) (Table S2). This observation is consistent with our findings utilizing the Friedman test, showing that cooking was associated with significant decreases in HR. No statistically significant changes were observed in DBP due to particle exposure and lack of food/drink, consistent with the Friedman test results.

To better understand the impact of gender, age, and weight on HR, SBP, and DBP, we divided the population into two subgroups of male and female participants. A 3-way ANOVA test was performed on each of the subgroups. It was found that observed statistically significant changes in HR and SBP were among female participants, not among male participants (Table S3). Additional analyses on the impact of age and weight showed that changes in SBP were found among participants below 25 years old or weights below 65 kg. However, study participants below 25 years old or below 65 kg showed lower mean SBP as compared to study participants older than 25 or whose weights were higher than 65 kg, respectively (Figs. S18 and S19). These findings suggest that people with higher SBP were less susceptible to the effects of inhaled particles and lack of food/drink on SPB and HR. Similarly, study participants below the age of 25 years or below 65 kg have higher HR (Figs. S20 and S21) and are less susceptible to the inhaled particles (Table S2). Thus, volunteers with higher HR or SBP showed less susceptibility to the effects of inhaled particles and the lack of drink/food.

4. Discussion

In this study, the average SBP and DBP before exposure ($N = 33$) were 105 ± 10, and 77.7 ± 8.5 mm Hg, respectively, similar to baseline SBP and DBP values reported in the literature. Soppa et al. (2017) reported the average SBP and DBP for 54 healthy adults to be 116.0 ± 13.7, and 74.9 ± 9.7, mm Hg, respectively. In another study baseline SBP and DBP for 48 adults were reported to be 116 ± 19 and 69 ± 6, respectively (Fedak et al., 2019). Soppa et al. (2017) monitored the blood pressure of 54 healthy volunteers who were exposed to $PM_{2.5}$ and UFPs emitted from toasting bread and found that blood pressure increased with increasing particle mass concentration, particle surface area concentration, and size-specific particle number concentration. For example, an increase of 10 $\mu g/m^3$ PM_{10} and $PM_{2.5}$, increased SBP of 1.5 mm Hg (95%-CI: 1.1; 1.9) and of 2.2 mm Hg (95%-CI: 1.3; 3.1), respectively, with the largest changes occurring 1 h after exposure initiation. However, they reported that exposures to particles from frying sausages and candle burning did not affect BP during short-term exposures. These results are inconsistent with the findings of the current study for frying beef. Cosselman et al. (2012) reported increased SBP in healthy human volunteers 30 to 60 min after exposure to diesel exhaust, but no changes in DBP were reported, consistent with this study. Fedak et al. (2019) reported increases in SBP 24 h post-exposure to fumes from different cookstoves compared to the control experiment. They also reported no changes in DBP.

The mechanisms for the observed cardiovascular effects in this study are not clear. Systemic inflammation could be a factor for the observed increases in SBP. However, some clinical studies showed no indications of the systemic inflammation in blood samples of human volunteers up to 24 h after the exposure to diesel engine particles (Cliff et al., 2016) and cooking fumes (Svedahl et al., 2013; Pedata et al., 2016). Animal studies have demonstrated translocation of nanoparticles into the blood (Husain et al., 2015), and there have been recent reports of black carbon particles found on the fetal side of human placenta (Bové et al., 2019) and in the urine of healthy children (Saenen et al., 2017) representing the translocation of particles into the blood circulation

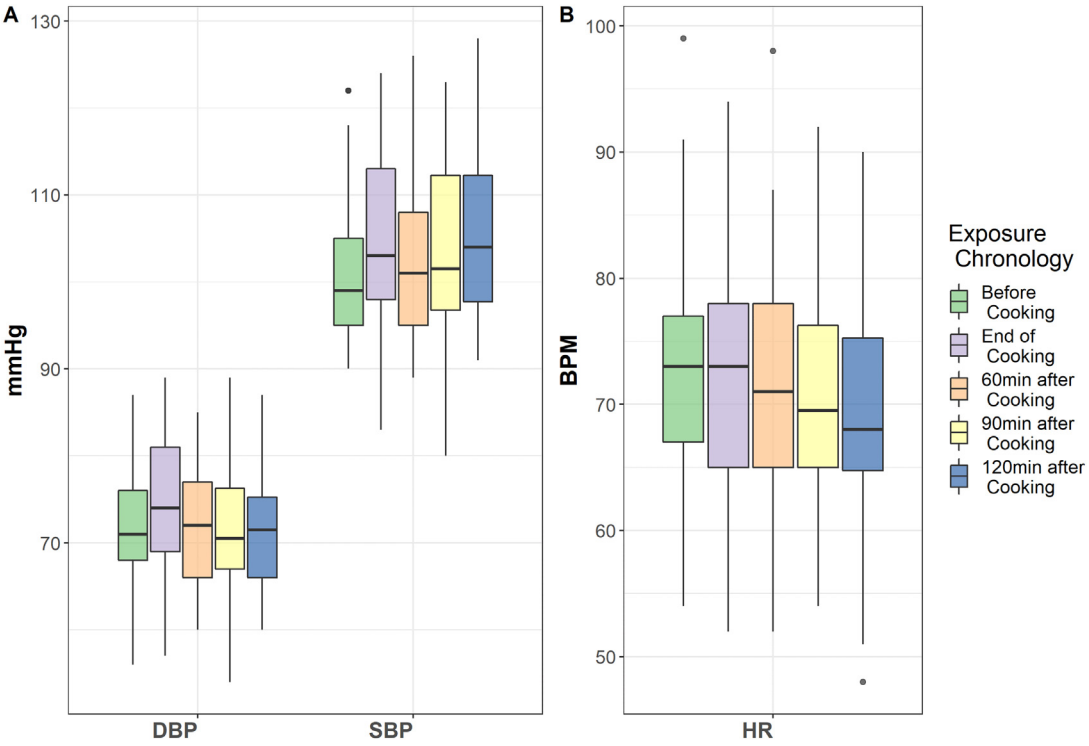

Fig. 2. Blood pressure and heart rate measurements for 33 study participants before, at the end of and 60 min, 90 min, and 120 min after cooking (Box and Whisker Plot)-Phase 2 experiments - The bar in the figure represent maximum and minimum.

during chronic exposure to ambient PM. However, there is no direct evidence that translocation is a relevant mechanism for the induction of these observed cardiovascular effects. Particularly no strong evidence of particle translocation into the human circulation during short-term exposure was reported (Brown et al., 2002; Mills et al., 2006; Wiebert et al., 2006).

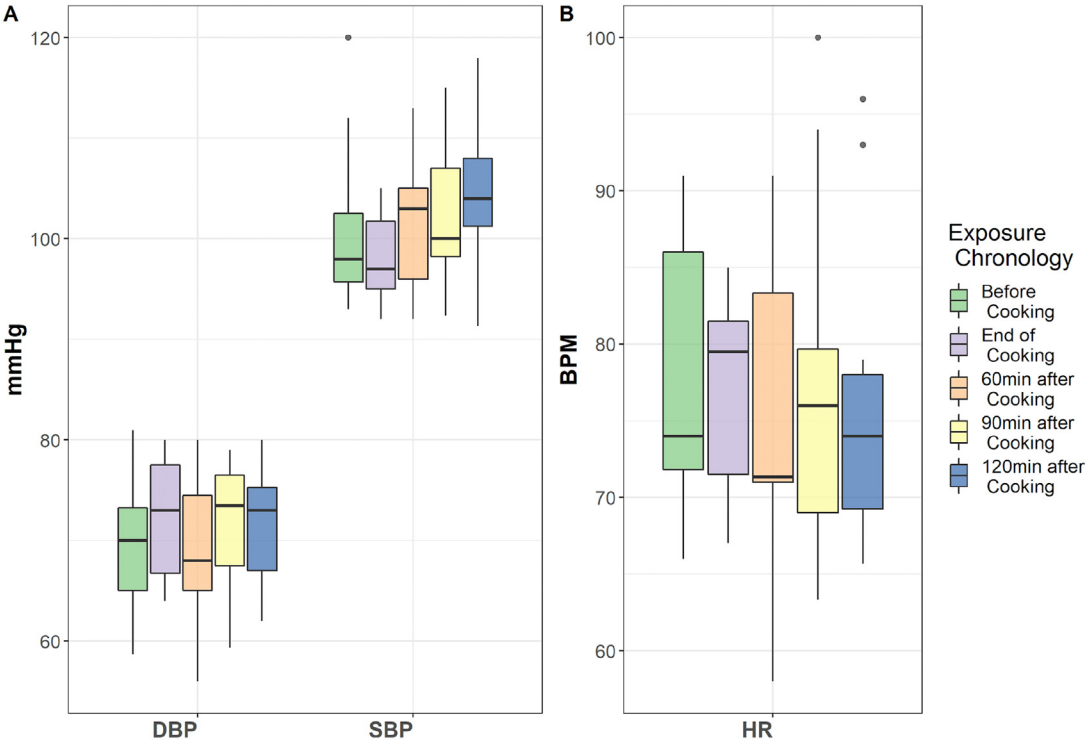

Fig. 3. Blood pressure and heart rate measurements for 16 study participants as controls (Box and Whisker Plot). [Control experiment] - The bar in the figure represent maximum and minimum.

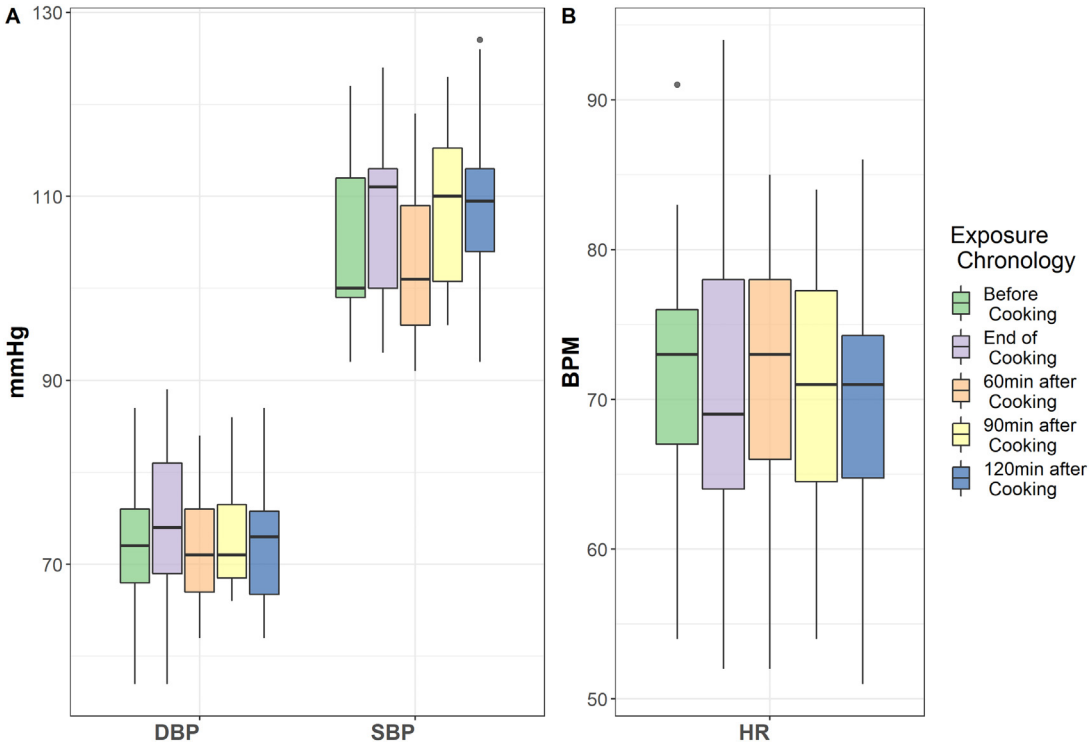

Fig. 4. Blood pressure and heart rate variations for 16 study participants who were provided food or drink as requested during the experiments - The bar in the figure represent maximum and minimum.

The translocation rate of particles into the blood circulation depends on the composition, size, and morphology. Few data are available regarding the morphology of PM from cooking. The dominant morphology of particles from gas and electric stove frying was an aggregated branched chain-like structure (Buonanno et al., 2009), and from the combustion of solid fuels without food was sub-micron soot particles (Shen et al., 2017). It is not clear if particles with such morphologies penetrate the blood circulation, particularly during short-term exposure at relatively low exposure levels.

A reason for the observed acute cardiovascular changes could be activation of the autonomic nervous system (Brook and Rajagopalan, 2009; Langrish et al., 2009). SBP and DBP can respond to the external stimuli differently due to their different regulatory pathways (Pieters et al., 2015). For example, increased arterial stiffness due to exposure to PM can result in greater changes in SBP compared to DBP (Fedak et al., 2019; Baumgartner et al., 2018). Inhaled particles can stimulate the nervous system in human airways leading to sympathetic activities (Widdicombe and Lee, 2001). The primary role of SBP is to push blood through the arteries when the heart is squeezing and respond to the sympathetic nervous system and stress stimuli (Paunovic et al., 2011). However, the DBP is the pressure in the vessels when the heart is in the resting position (Paunovic et al., 2011).

4.1. Limitations of this study

Health effect measurements started at the end of the cooking with subsequent measurements every 30 min. However, there might be immediate changes to HR and BP upon inhalation of particles that were not investigated study and needs further investigations.

The two instruments employed in this study (NanoTracer and Omron 10) were not reference instruments, and thus, their measurements are subject to uncertainties. This uncertainty is reflected in Eq. (1) for the NanoTracer. The Omron BP monitor was compared to a clinical BP cuff for 10 individuals (Figs. S22–S24). A 10% bias in measured SBP was found compared to the manufacturer's reported value of 2%. However, the bias in absolute values does not affect the analysis of the differences among the groups at the measurement points in this study. The reproducibility of either BP method is extremely difficult to determine, given the changing physiological responses of any given individual. While the current study addresses the changes in BP and HR during and after cooking, quantifying the true BP and HR values and performing the dose-response analyses using statistical tools, reference instruments such as a holter monitor and a clinical BP cuff would be required.

The experimental protocol of this study required the study participants to conduct cooking themselves. However, this methodology is subject to some confounders such as mental impact and physical activities (standing/moving/sitting) during cooking that makes it difficult to make a definitive conclusion regarding the impact of the inhaled particles on HR and BP. Thus, it is recommended that for future studies, a researcher of the study conducts the cooking instead of the study participants.

We did not measure the gas composition and concentrations emitted during the cooking. Controlled studies are required to investigate if such observed changes in BP were due to the particles or gases from cooking or both. An exposure-response statistical analysis is required to distinguish the impact of gases, particles, and environmental conditions such as temperature and humidity on the human heart. This correction is the objective of our new future study.

5. Conclusions

This study investigated the effect of inhaled aerosol from a low-emissions cooking recipe on blood pressure and heart rate of study participants volunteers. It was found that inhalation of particles consisting mainly of UFPs was statistically significantly associated with increases in SBP. The lack of food and drink during up to 2 h post-cooking was found to be an opposing factor that was associated with statistically significant reductions in SBP. No statistically significant changes were observed for DBP. Physiological effects of cooking such as anxiety, heat stress and physical activity during cooking were more likely to be responsible for elevating the HR and the subsequent reductions in HR 90 min after cooking when study participants were relaxed and sitting in the living room. Study participants with higher mean SBP, given

higher age and weight categories, were found to show lower changes in SBP and HR due to exposure to particles, lack of food/drink and physiological factors. Simultaneous measurements of heart and brain performance during and after exposure to particles could provide new insights on the mechanisms of cardiovascular impacts due to exposure to particles.

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CRediT authorship contribution statement

Raikhangul Gabdrashova: Writing - original draft, Investigation, Visualization. **Sholpan Nurzhan:** Writing - original draft, Investigation, Visualization. **Motahareh Naseri:** Investigation. **Zhibek Bekezhankyzy:** Investigation. **Aidana Gimnkhan:** Investigation. **Milad Malekipirbazari:** Formal analysis. **Mahsa Tabesh:** Investigation. **Reza Khanbabaie:** Supervision, Project administration. **Byron Crape:** Writing - review & editing. **Giorgio Buonanno:** Writing - review & editing, Methodology. **Philip K. Hopke:** Writing - review & editing. **Aliakbar Amouei Torkmahalleh:** Methodology, Formal analysis. **Mehdi Amouei Torkmahalleh:** Conceptualization, Writing - original draft, Writing - review & editing, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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