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Acute black tea consumption improves cutaneous vascular function in healthy middle-aged humans.

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1 ABSTRACT

2 **Background & Aims.** Dietary flavonoids, such as those present in black tea, are
3 associated with reduced risk of cardiovascular disease (CVD), possibly through
4 improving nitric oxide (NO) mediated vascular function. The aim of this study was to
5 examine the effect of acute black tea ingestion on cutaneous microvascular function.

6 **Methods.** Twenty healthy participants (58 ± 5 yr, 9 men) attended two experimental
7 trials (tea, placebo), 7-days apart in a randomised, controlled, double-blind, cross-over
8 design. Participants ingested a single dose of 200ml black tea or placebo, followed by
9 assessment of forearm cutaneous perfusion using laser-Doppler flowmetry (LDF)
10 using three distinct heating protocols, enabling us to distinguish between axon- and
11 endothelium-dependent vasodilation: 1. *rapid 42°C*, 2. *rapid 39°C* and 3. *gradual 42°C*.
12 On the contralateral arm, full-field laser perfusion imaging (FLPI) was used to assess
13 forearm perfusion during *gradual 42°C*. Data were presented as cutaneous vascular
14 conductance (CVC; flux/mean arterial pressure, MAP) and CVC expressed as a
15 percentage of maximal CVC (%CVC_{max}).

16 **Results.** Rapid local heating to 39°C or 42°C demonstrated no effect of tea for flux,
17 CVC or %CVC_{max} (all $P > 0.05$). Gradual local heating to 42°C, however, produced a
18 higher skin blood flow following black tea ingestion for absolute CVC ($P = 0.04$) when
19 measured by LDF, and higher absolute flux ($P < 0.001$) and CVC ($P < 0.001$) measured
20 with FLPI. No effect of tea was found for %CVC_{max} when assessed by either LDF or
21 FLPI.

22 **Conclusions.** Acute tea ingestion enhanced cutaneous vascular responses to
23 gradual local heating to 42°C in healthy, middle-aged participants, possibly through a
24 mechanism related to activation of endothelium-derived chemical mediators, such as

25 NO. These improvements may contribute to the cardiovascular health benefits of
26 regular tea ingestion.

27

28 **Key words: tea; flavonoids; cardiovascular health; vascular function;**
29 **microcirculation.**

30 INTRODUCTION

31 Cardiovascular disease (CVD) remains the leading cause of global mortality,
32 representing ~30% of all deaths.¹ The role of dietary factors on CVD risk has been
33 frequently explored in recent years, with a high dietary flavonoid intake being
34 associated with a reduction in CVD risk.² Tea, produced from the plant *Camillia sinensis*,
35 is the major dietary source of flavonoids in many countries globally³ and can be found
36 as catechins and flavonols in green tea and theaflavins, thearubigins and flavonols in
37 black tea.⁴ Accordingly, several studies have revealed a strong, inverse relation
38 between regular intake of tea and cardiovascular risk.^{5, 6}

39

40 A frequently cited explanation for the cardioprotective effects of black and green tea
41 ingestion relates to the reduction in blood pressure following chronic consumption.⁵⁻⁷
42 Further research found that acute and regular tea ingestion improves nitric oxide-
43 mediated, endothelium-dependent dilation of conduit arteries.^{6, 8-11} Both conduit and
44 resistance vessels have demonstrated improved endothelial function following tea
45 ingestion in both healthy individuals^{6, 8} and in those with CVD.¹⁰ Thus, the general
46 consensus is that regular tea ingestion improves blood pressure by virtue of a
47 generalised improvement of endothelial function and lowering of peripheral vascular
48 resistance.^{6, 8, 10-12}

49

50 Despite encouraging data supporting a beneficial effect of tea ingestion in larger
51 (conduit) vessels, no previous study has explored the effect of black tea on small
52 vessels (skin microcirculation). Therefore, our aim was to examine cutaneous vascular
53 responses to local skin heating. Given the complexity of the cutaneous vascular
54 system and contribution of distinct mechanisms for skin dilation when gradually or

55 rapidly heating the skin, we adopted a comprehensive approach of using rapid *and*
56 gradual local skin heating protocols simultaneously. We hypothesised that black tea
57 ingestion would be associated with increased cutaneous microcirculation responses
58 for both rapid and gradual heating protocols.

59

60 **MATERIALS AND METHODS**

61 **Participants**

62 Twenty middle-aged male (n=9) and post-menopausal female (n=11) participants
63 were recruited through local advertisement. All participants were healthy and non-
64 smokers (58±5yrs, height 1.70±0.1m, weight 75.9±16.1kg, BMI 26±4 kg/m², baseline
65 mean arterial pressure 104±8mmHg). Individuals with a medical history of
66 hypercholesterolaemia (total cholesterol >6.5mmol/l),¹³ cardiovascular disease and
67 hypertension (systolic blood pressure ≥140mmHg, diastolic blood pressure
68 ≥90mmHg)¹⁴ were excluded. Participants were not taking any vasoactive medications
69 or supplements. After being fully informed of the methods, written informed consent
70 was obtained from all participants. The study conformed to the Declaration of Helsinki
71 and was approved by the Research Ethics Committee of Liverpool John Moores
72 University.

73

74 **Experimental Design**

75 All participants performed two experimental trials (tea and control), 7-days apart in a
76 randomised, controlled, double-blind, cross-over design (figure 1). The cross-over
77 design was chosen to eliminate between-participant variability, taking into account a
78 6-day washout period between the two interventions to avoid any carry-over effects,
79 which is in accordance with previous similar designed cross-over tea vascular function

80 studies.^{6,7} Computer-generated randomisation was used to reduce potential selection
81 bias. Upon arrival to the laboratory, and 2h prior to microvascular assessment,
82 participants ingested a tea drink (containing 300 mg flavonoids, 75 mg caffeine and
83 2.8 g sucrose) or a taste and appearance matched placebo drink (0 mg flavonoids, 75
84 mg caffeine, 2.7 g sucrose, tea flavour and caramel colour), prepared by dissolving
85 two sachets in 200 ml hot water. Participants subsequently rested for 2h prior to
86 commencement of testing to match peak plasma concentrations of flavonoids and
87 other metabolites such as phenolic acids, with testing of skin microcirculation. During
88 each testing day, baseline and thermally stimulated forearm cutaneous blood flow was
89 examined simultaneously using rapid (to 39 and 42°C) and gradual (to 42°C) local
90 heating protocols. Since these protocols reflect different dilator mechanisms and a
91 distinct role of the NO-pathway, they provide complementary insight into the impact of
92 black tea on cutaneous microvasculature. Rapid local heating was performed at two
93 different sites (i.e. two different local heating protocols) on the dominant forearm and
94 examined using laser Doppler flowmetry (LDF). Gradual local heating to 42°C was
95 performed on the dominant forearm using LDF and on the contralateral (non-dominant)
96 arm using laser speckle imaging to provide whole forearm cutaneous microcirculation
97 function.

98

99 **Experimental Measures**

100 All participants fasted for at least six hours and refrained from alcohol, food products
101 high in polyphenols (dark chocolate, red wine), caffeine and exercise for 24h prior to
102 testing.¹⁵ Participants were asked to refrain from drinking all types of tea for a period
103 of one week prior to each trial. Sips of water were permitted prior to testing to ensure

104 that participants were well hydrated. All trials were conducted in a quiet, temperature
105 controlled environment ($23.4\pm 0.6^{\circ}\text{C}$)^{15, 16} and at the same time of day to reduce any
106 circadian influences on vascular function.¹⁵ Following a 20-minute stabilisation period,
107 the LDF equipment was calibrated using two generic points, 0 and 250 PU, a zeroing
108 disk and motility standard, according to manufacturer's guidelines (Perimed AB,
109 Järfälla, Stockholm, Sweden). Two hours following tea ingestion, participants
110 assumed a comfortable, supine position on a bed, with the head slightly elevated and
111 the hand of each testing arm relaxed, supinated and supported by a vacuum cushion
112 to minimise microcirculatory fluctuations resulting from motion artefact.^{15, 16} If
113 necessary, forearm measurement sites were shaved 24h prior to testing to avoid any
114 inflammatory response that may affect cutaneous blood flow; we inspected the
115 forearms prior to each trial to ensure that no skin damage was present that may
116 adversely influence cutaneous blood flow responses. Participants were instrumented
117 for LDF measurements on the dominant forearm; three heating discs (Perimed 355,
118 Perimed AB, Järfälla, Stockholm, Sweden) were placed ~5cm apart on the dominant
119 forearm, with a 7-laser array probe (PF 413, Perimed AB, Järfälla, Stockholm, Sweden)
120 placed into each heater and firmly attached to the skin using adhesive stickers and
121 medical tape. Following sterilisation of the non-dominant arm measurement site,
122 participants were instrumented for laser speckle imaging using the technique of full-
123 field laser perfusion imaging (FLPI); a water-filled clear heating probe (Moor VHP3,
124 Moor Instruments, Axminster, UK) was placed on the skin and attached using an
125 adhesive sticker to obtain a good seal. Measurement sites were randomly chosen,
126 avoiding visible veins, hair follicles and dermatological lesions.¹⁶ Upon completion of
127 the first experimental trial, the location of the LDF and FLPI assessment sites was
128 marked on the skin, with digital photographs and measurements taken to the nearest

129 millimetre using anatomical and skin-surface landmarks for reference, to ensure
130 accurate re-selection of probe sites for the second trial. Stature (seca 217 stadiometer,
131 seca UK, Birmingham, UK) and body mass (seca 767 calibrated electronic scales,
132 Germany) were recorded using standardised protocols. Body mass index was
133 calculated (BMI) as the body weight (kg) divided by the height squared (m^2).

134

135 Both LDF and FLPI provide non-invasive, continuous measures of cutaneous blood
136 flow.¹⁷ By using a combination of these techniques, it is possible to simultaneously
137 evaluate superficial (<300 micron) and deeper (1-1.5mm) skin blood flow via FLPI and
138 LDF, respectively. Rather than assessing overall microvascular function, using local
139 thermal hyperaemia provides a more comprehensive assessment of microvascular
140 reactivity to acute tea ingestion and the complex neural and chemically-mediated
141 pathways underlying microvascular function. Distinct rapid and gradual local heating
142 protocols all provide a different type of vasodilation that likely relates to different
143 vasodilator pathways.

144

145 *Rapid local heating.* First, we adopted the classic local heating protocol *rapid 42°C*
146 (0.5°C per 5s, 30-min at 42°C, 20-min at 44°C), which induces a rapid, transient axon-
147 reflex, followed by a more gradual, but sustained, heating response. The plateau
148 phase represents 80-90% of the maximal response, and is partly (60-70%) NO-
149 mediated.^{18, 19} Secondly, we examined a more recently introduced protocol; *rapid 39°C*
150 (0.5°C per 5s, 30-min at 39°C, 20-min at 44°C), that also induces an axon-reflex and
151 gradual plateau during the heating response. By stopping the heating protocol at 39°C,
152 the plateau phase is largely NO-mediated and only represents 50% of the maximal

153 response.²⁰ The *rapid 42°C* and *rapid 39°C* protocols were examined simultaneously
154 on the dominant arm using LDF.

155

156 *Gradual local heating.* We examined an adapted version of the *gradual* local heating
157 protocol that increases to 42°C (0.5°C per 2min30s, 30-min at 42°C, 20-min at 44°C),
158 and induces a slow heating response that is largely NO-mediated and reflects 80-90%
159 of the maximal response.²¹ This protocol was examined on the dominant arm using
160 LDF, covering 6mm² of skin at a penetration depth of ~1-1.5mm, and on the
161 contralateral arm using FLPI, which covers an area of skin up to 30,000mm² at a depth
162 of ~0.3mm.²²

163

164 *Laser Doppler Flowmetry (LDF).* Laser Doppler flowmetry is a non-invasive technique
165 that is routinely used to study microvascular function,^{16, 18, 22} and is sensitive in
166 detecting changes in skin perfusion over a period of time and in response to a stimulus,
167 such as local thermal hyperaemia.¹⁶ LDF is concerned with the reflection of a laser
168 beam that undergoes a change in wavelength, or Doppler shift, when it detects moving
169 red blood cells, the magnitude and frequency of which is related to the concentration
170 and velocity of blood cells and is recorded as a signal of red blood cell flux (RBCF).^{16,}
171 ²² Following a 20-minute acclimation period, cutaneous blood flow was measured as
172 RBCF at the chosen probe sites using a laser Doppler flowmeter (Periflux system 5000,
173 Perimed AB, Järfälla, Stockholm, Sweden). The local heating discs were connected
174 to a heating unit (Peritemp 4005 heater, Perimed AB, Järfälla, Stockholm, Sweden)
175 which was manually controlled to perform the temperature stages of the local heating
176 protocols. Baseline skin RBCF was recorded with the local heating disc temperature

177 set at 33°C for 10-minutes for each measurement site. Subsequently, local skin
178 temperature was heated using the three distinct protocols.

179

180 *Full-field Laser Perfusion Imaging (FLPI)*. The FLPI technique, also known as laser
181 speckle contrast imaging, exploits the fact that the random speckle pattern that is
182 generated when tissue is illuminated by laser light, changes when blood cells move
183 within the region of interest.²³ High levels of movement (fast flow) produce a more
184 blurred pattern, associated with a reduction in contrast in that region. Low contrast
185 corresponds with high flow and high contrast corresponds with low flow. The strengths
186 of this technique are that video frame rate blood flow images (up to 25 per second)
187 enable the tracking of fast transient blood flow changes and provides high spatial and
188 temporal resolution. This device works with a near infra-red laser diode (785nm) and
189 is able to scan skin surfaces from 5mm x 7mm to 15cm x 20cm, to a depth of
190 approximately 150-300 micron and is safe for human use. Following a 20-minute
191 acclimation period, FLPI recordings of the non-dominant forearm were performed
192 using a blood flow imaging system (moorFLPI-1, Moor Instruments, Axminster, UK)
193 with a laser wavelength of 785nm and sampling frequency of 25Hz. The distance
194 between the laser head and skin surface was fixed at 15cm.²⁴ A skin heater module
195 (moorVMS-HEAT, Moor Instruments, Axminster, UK) was used to manually set the
196 baseline temperature at 33°C for 10-minutes and to perform the incremental local
197 heating protocol; *gradual 42°C_{FLPI}* (0.5°C per 2min30s, 30-min at 42°C, 20-min at
198 44°C).²¹

199

200 *Haemodynamics*. Heart rate (HR) and blood pressure were recorded at the beginning
201 and at the end of the 20-minute acclimation period using an automated
202 sphygmomanometer (Dinamap V100, GE Healthcare, UK) positioned on the ankle,
203 corresponding to the same laterality as their dominant arm. Thereafter, mean arterial
204 pressure (MAP, mV/mmHg) and HR were recorded at 5-minute intervals throughout
205 the local heating protocols. MAP was used to calculate cutaneous vascular
206 conductance ($CVC=RBCF/MAP$), thereby accounting for changes in skin blood flow
207 resulting from variations in blood pressure.^{16, 18, 25}

208

209 **Data Analysis**

210 Data analysis was performed blind. Cutaneous RBCF (PU) was expressed as
211 cutaneous vascular conductance (CVC), as described previously.¹⁶ Artefact in the
212 data, due to unwanted subject movement, was identified and removed prior to
213 analysis. Baseline laser Doppler RBCF was averaged over a stable 10-minute
214 baseline period. For the *rapid 42°C* and *rapid 39°C* protocols, following initiation of
215 heating, initial peak and nadir CVC values were calculated over a stable 60-second
216 period,¹⁸ with the initial peak identified as the highest value and the nadir as the lowest
217 value during the first 5-10 minutes of local heating.²⁶ A clear nadir was not detected in
218 all measurement traces, which is typical of this type of thermal provocation test. In
219 those traces (~5%), data was included from a 60-second period, 1-minute after the
220 initial peak. This value was always lower than the initial peak. CVC was calculated
221 over a stable 60-second period for the final minute of each temperature increment (34-
222 41°C) of the *gradual 42°C* local heating protocol. For each of the three protocols, *rapid*
223 *42°C*, *rapid 39°C* and *gradual 42°C*, plateau phases during heating (42°C, 39°C and
224 maximal 44°C) were averaged over the last 5-minutes of each phase. Data at baseline

225 and at the various plateau phases were also normalised to the maximal CVC achieved
226 at 44°C ($\%CVC_{max}=[CVC/CVC_{max}] \times 100$).²⁵ All data were collected in LabChart 7.0
227 (ADInstruments, Dunedin, New Zealand).

228

229 **Statistical Methods**

230 Data were expressed as mean \pm SD and statistical significance was set at $P<0.05$. For
231 all protocols, linear mixed models (main effects of condition and time) were used to
232 examine the impact of acute tea ingestion on blood pressure and forearm skin
233 microcirculation. The repeated covariance type was Unstructured and Condition, Time
234 and Condition*Time was specified as Fixed Effects (intercept was included) and as
235 Estimated Marginal Means. We interpreted the Test of Fixed Effects Condition*Time
236 interaction. Significant main effects of Time or Condition or a Time*Condition
237 interaction were followed up with a simple main effects analysis and the least
238 significant difference (LSD) approach to multiple comparisons.²⁷ Data were stored and
239 transformed within Microsoft Excel (Microsoft Office 2010, Microsoft Corporation), and
240 statistical analyses were performed using SPSS 22.0 (SPSS, Chicago, IL, USA).

241

242

243 **RESULTS**

244 One participant was removed from the *gradual 42°C_{LDF}* analysis for both experimental
245 trials (due to probe failure) and five participants were removed from the *gradual*
246 *42°C_{FLPI}* analysis for both trials (linked to excessive movement artefacts), giving a
247 population of $n=19$ and $n=15$, respectively. No participants were removed from the
248 *rapid 39°C* and *rapid 42°C* analysis (both $n=20$). Baseline MAP was not different
249 between conditions (108 ± 11 , 108 ± 11 , $P=0.73$) and showed no change across time

250 (P=0.52). There were no differences in baseline cutaneous perfusion between trials
251 for measurement sites that underwent *rapid 39°C* or *rapid 42°C* local heating for
252 absolute flux, CVC or %CVC_{max} (Table 1). Also the site that underwent *gradual 42°C*
253 local heating using LDF showed no difference in baseline cutaneous blood flow
254 between trials for absolute flux, CVC or %CVC_{max} (Table 2). However, using FLPI, a
255 significantly higher baseline perfusion was found after tea ingestion for cutaneous flux
256 and CVC, but not for %CVC_{max} (Table 2).

257

258 *Rapid local heating: impact of tea*

259 *Rapid 39°C*. Local heating induced a typical pattern of an initial peak, nadir and plateau
260 in cutaneous blood flow. Therefore, a main effect of time was demonstrated for
261 absolute flux, CVC and %CVC_{max} (Table 1). However, we found no effect of the
262 intervention or a timeXintervention-interaction for absolute flux, CVC or %CVC_{max}
263 (Table 1).

264 *Rapid 42°C*. Local heating induced a typical pattern of an initial peak, nadir and plateau
265 in cutaneous blood flow. Consequently, a main effect of time was demonstrated for
266 absolute flux, CVC and %CVC_{max} (Table 1), whilst no main effect of intervention or
267 timeXintervention-interaction was found for absolute flux, CVC or %CVC_{max} (Table 1).

268

269 *Gradual local heating: impact of tea*

270 *Gradual 42°C_{LDF}*. Local heating induced a gradual, slow heating response with no
271 detectable initial axon reflex-induced peak or nadir with a main effect of time (Table 2).
272 A higher skin blood flow throughout the heating protocol was observed during the trial
273 preceded by black tea for absolute CVC (P=0.04), with a trend towards significance
274 when data were presented as absolute flux (P=0.06, Table 2). No effect of tea was

275 found when CVC was normalised for maximum perfusion (%CVC_{max}, P=0.82, Table
276 2). No timeXintervention-interaction was found for absolute flux (P=0.93), CVC
277 (P=0.95) or %CVC_{max} (P=0.98, Table 2).

278 *Gradual 42°C_{FLPI}*. Local heating induced a gradual, slow heating response with no
279 detectable initial axon reflex-induced peak or nadir (Table 2). Tea ingestion was
280 associated with a significantly higher absolute flux (P=0.00) and CVC (P=0.00), but
281 not when CVC was normalised to maximum CVC (%CVC_{max}, P=0.35, Table 2). No
282 timeXintervention-interaction was present for absolute flux (P=0.50), CVC (P=0.66)
283 or %CVC_{max} (P=1.00, Table 2).

284

285 Our statistical analysis revealed no presence of a carry-over effect.

286

287 **DISCUSSION**

288 The aim of this study was to test the hypothesis that a single dose of black tea
289 ingestion improves cutaneous microcirculation following both rapid and gradual local
290 skin heating. We found that gradual local heating of the skin to 42°C induced a greater
291 vasodilatory response following tea ingestion compared to placebo when expressed
292 as absolute flux and CVC. The ability of tea to improve local gradual heating responses
293 in the skin was reinforced by the observation that both LDF and FLPI, two distinct but
294 accepted techniques to assess skin perfusion, detected this effect. Conversely, rapid
295 local heating did not demonstrate a significant increase in cutaneous microcirculation
296 with tea ingestion, either for the *rapid 39°C* or *rapid 42°C* protocols. Taken together,
297 our study provides some further evidence that regular tea ingestion may mediate its
298 potential cardiovascular benefits via improvements in (cutaneous) microvascular
299 function.

300

301 Our study is the first to explore the acute effects of tea ingestion on the cutaneous
302 microcirculation whilst adopting a rigorous protocol involving blind analysis of rapid
303 and gradual heating protocols as well as two distinct, accepted techniques. This
304 observation fits with the general observation of tea being able to enhance endothelial
305 function in conduit vessels when assessed by flow-mediated dilation (FMD).^{6, 9} Taken
306 together, these findings suggest that acute tea ingestion improves vascular function
307 across the vascular tree, including skin microvessels, possibly via upregulation of
308 vasodilator mechanisms.

309

310 In contrast to gradual local heating, rapid heating of the skin did not alter cutaneous
311 vascular function following tea ingestion when compared to placebo. Our findings were
312 similar for both rapid heating protocols (*rapid 39°C* and *rapid 42°C*). Interestingly, a
313 recent observational study²⁸ found improved microvascular function following regular
314 consumption of green tea (14 days) using rapid heating (whilst no measure of gradual
315 heating was included). Important differences were present between studies, especially
316 since this previous study did not include a placebo control, did not fully adhere to
317 guidelines for vascular assessment (e.g. control of menstrual cycle),¹⁵ and was limited
318 by a lack of control of dietary habits.⁶ Furthermore, whilst our study investigated the
319 acute (2h) effects of tea, they examined a protocol of 14 days of green tea. Despite
320 the *rapid 39°C* and *gradual 42°C* protocols both being linked to the release of NO,
321 distinct responses are clearly evident between the gradual and rapid heating protocols
322 in our study. Different vasodilator pathways directly influence the cutaneous
323 microcirculation, including neurogenic reflexes and local chemical mediators.^{18, 21, 25}
324 The rate at which the skin is heated, alters the contribution of these vasodilator

325 pathways, with rapid (0.5°C per 5s) local heating inducing a transient axon-reflex
326 mediated vasodilation that is produced via activation of heat sensitive
327 sensory/nociceptive nerves releasing calcitonin gene-related peptide (CGRP) and
328 substance P and adrenergic nerves releasing norepinephrine and neuropeptide Y.¹⁸
329 ²⁹ This initial neurogenic response is followed by a more gradual, sustained
330 vasodilation. In both phases, vasodilation occurs through complex pathways that lead
331 to the production of NO and smooth muscle relaxation via hyperpolarization from
332 endothelial derived hyperpolarization factors (EDHFs),²⁹ with a greater (but not
333 exclusive) contribution of NO during the plateau phase.^{18, 20} Furthermore, the relative
334 contribution of NO to the vasodilation during the plateau phase of the rapid heating
335 protocols depends upon the target heating temperature, as the heating response to
336 39°C seems to depend more on NO than the response to 42°C.^{18, 20} These studies,
337 therefore, demonstrate that the underlying mechanism for cutaneous vasodilation
338 differ based on the rate and maximum level of heating. The different vasodilator
339 pathways for these heating protocols may contribute to the distinct findings in our study.
340 From a methodological perspective, the differences between rapid and gradual local
341 heating highlight the importance of using multiple heating protocols simultaneously
342 when exploring the impact of an intervention on skin perfusion.

343

344 The higher vasodilatory responses that we observed following gradual heating of the
345 skin were demonstrated for arbitrary flux and CVC values, for both LDF and FLPI
346 techniques. However, the difference in responses between the tea and placebo trials
347 was not significant when data were expressed as %CVC_{max}. The skin is commonly
348 heated to 44°C to reach maximal vasodilation and expressing CVC as a percentage
349 of maximal perfusion is often considered the preferred method of data expression,¹⁶

350 with improved reproducibility compared to flux or CVC.²⁵ Despite a main effect of tea
351 on flux and CVC, post-hoc analyses revealed no differences between trials at 44°C
352 (LFD: flux=0.17 and CVC=0.19; FLPI: flux=0.09 and CVC=0.08). However, the
353 magnitude of differences in flux and CVC between tea and placebo are larger than
354 one may expect based on day-to-day variation.²⁵ This provides some indication that
355 the tea intervention may have altered cutaneous perfusion at 44°C local heating.

356

357 *Clinical Relevance.* Tea consumption is known to have cardiovascular benefits,
358 including a reduction in blood pressure after short- to long-term intervention, possibly
359 mediated (in part) by improved endothelial function of conduit vessels.^{8, 9, 12} In our
360 study, cutaneous microcirculation responses to gradual heating improved following tea
361 ingestion. We speculate that these findings may have implications for individuals with
362 microvascular complications and skin endothelial dysfunction, such as type 2 diabetes
363 mellitus. Interestingly, consumption of tea has been associated with a reduced risk for
364 type 2 diabetes mellitus.³⁰ Our findings thus support the hypothesis that regular tea
365 consumption may have potential benefit in such patient groups. Future studies are
366 warranted to explore this hypothesis.

367

368 *Limitations.* Due to our modest sample size, we are unable to generalise our findings
369 towards the wider populace. Furthermore, although we included a middle-aged
370 population who likely are at an increased risk of CVD, we cannot simply extrapolate
371 our findings to clinical groups. Moreover, our population may have impaired
372 endothelial function as blunted cutaneous NO-mediated vasodilation has been
373 demonstrated in older individuals,²¹ suggesting that young healthy volunteers may
374 exhibit different results than our older population. Therefore, future work is required to

375 explore the potential impact of acute as well as chronic tea ingestion on cutaneous
376 vascular function in both individuals with compromised endothelial function and in
377 young, healthy individuals. A further limitation is that we did not obtain plasma
378 measures of flavonoids or NO compounds and, therefore, our study does not provide
379 any biochemical or biomolecular insight into the mechanisms underlying the
380 improvement in cutaneous microvascular function. However, it is important to
381 emphasise that this was not the purpose of our study, particularly given that we are
382 the first to explore the effects of acute tea ingestion on the cutaneous microcirculation.

383

384 In conclusion, our findings suggest that acute tea ingestion enhances cutaneous
385 vascular function in a healthy, middle-aged population, when measured following
386 gradual local heating to 42°C. Therefore, these data suggest that acute tea ingestion
387 has a beneficial impact on vascular function at the microcirculatory level, which is likely
388 achieved through a mechanism related to activation of endothelium-derived
389 vasodilators. These improvements in cutaneous microvascular function may
390 contribute to the potential cardiovascular health benefits of regular tea ingestion.
391 Future studies are required to explore the acute and chronic effects of tea on
392 individuals with increased CVD risk and in clinical populations with *a priori* endothelial
393 dysfunction.

394

395 **STATEMENT OF AUTHORSHIP**

396 K. A. W., D. A. L., D. H. J. T., N. D. H., R. D. and Y. d. G. designed research; K. A.
397 W. conducted research; K. A. W., D. A. L. and Y. d. G. analysed data; K. A. W., D. A.
398 L., D. H. J. T., R. D. and N. D. H. wrote the paper; R. D. and D. H. J. T. had primary
399 responsibility for final content. All authors read and approved the final manuscript.

400

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404 Kirsty A. Woodward, Nicola D. Hopkins, David A. Low and Dick H. J. Thijssen had no
405 personal or financial conflict of interest.

406

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482

483 **Table 1.** Laser Doppler flowmetry cutaneous blood flow responses to local heating
 484 for the *rapid 39°C* and *rapid 42°C* protocols for placebo and tea interventions.

485

Rapid 39°C	Intervention (mean ± SD)		LMM		
	Placebo	Tea	time	tea	time*tea
<i>Absolute flux(PU)</i>					
Baseline	22 ± 11	21 ± 8			
Axon-reflex	108 ± 38	103 ± 50			
Nadir	57 ± 25	52 ± 26	<0.001*	0.14	0.76
Plateau 39°C	136 ± 53	123 ± 70			
Plateau 44°C	288 ± 61	263 ± 61			
<i>Absolute CVC (PU/mmHg)</i>					
Baseline	0.21 ± 0.12	0.21 ± 0.10			
Axon-reflex	1.03 ± 0.39	0.99 ± 0.47			
Nadir	0.54 ± 0.25	0.50 ± 0.26	<0.001*	0.27	0.91
Plateau 39°C	1.29 ± 0.52	1.17 ± 0.65			
Plateau 44°C	2.70 ± 0.67	2.52 ± 0.59			
<i>Maximal CVC (%CVC_{max})</i>					
Baseline	8 ± 4	8 ± 3			
Axon-reflex	39 ± 15	39 ± 15			
Nadir	20 ± 10	20 ± 10	<0.001*	0.76	0.99
Plateau 39°C	48 ± 15	46 ± 21			
Rapid 42°C					
<i>Absolute flux(PU)</i>					
Baseline	22 ± 9	25 ± 16			
Axon-reflex	199 ± 60	208 ± 60			
Nadir	165 ± 64	177 ± 74	<0.001*	0.51	0.99
Plateau 42°C	252 ± 72	253 ± 67			
Plateau 44°C	300 ± 79	302 ± 63			
<i>Absolute CVC (PU/mmHg)</i>					
Baseline	0.21 ± 0.10	0.25 ± 0.16			
Axon-reflex	1.90 ± 0.61	2.00 ± 0.61			
Nadir	1.57 ± 0.64	1.71 ± 0.74	<0.001*	0.29	1.00
Plateau 42°C	2.39 ± 0.74	2.43 ± 0.66			
Plateau 44°C	2.81 ± 0.81	2.91 ± 0.74			
<i>Maximal CVC (%CVC_{max})</i>					
Baseline	8 ± 3	8 ± 4			
Axon-reflex	67 ± 11	68 ± 11			
Nadir	55 ± 16	57 ± 19	<0.001*	0.65	0.95
Plateau 42°C	85 ± 8	83 ± 12			

486 Data are mean ± SD. *Main effect of time $P < 0.001$ vs baseline.

487 **Table 2.** Cutaneous blood flow responses to local heating for the *gradual_{LDF}* (42°C)
 488 and *gradual_{FLPI}* (42°C) protocols for placebo and tea interventions.

489

<i>Gradual_{LDF}</i> (42°C)	Intervention (mean ± SD)		LMM		
	Placebo	Tea	time	tea	time*tea
<i>Absolute flux(PU)</i>					
Baseline	26 ± 11	24 ± 9			
Plateau 42°C	268 ± 79	278 ± 61	<0.001*	0.06	0.93
Plateau 44°C	302 ± 84	319 ± 45			
<i>Absolute CVC (PU/mmHg)</i>					
Baseline	0.25 ± 0.11	0.23 ± 0.09			
Plateau 42°C	2.51 ± 0.76	2.61 ± 0.64	<0.001*	0.04 [^]	0.95
Plateau 44°C	2.80 ± 0.82	2.93 ± 0.51			
<i>Maximal CVC (%CVC_{max})</i>					
Baseline	9 ± 5	8 ± 3			
Plateau 42°C	90 ± 7	89 ± 14	<0.001*	0.82	0.98
<i>Gradual_{FLPI}</i> (42°C)					
<i>Absolute flux(PU)</i>					
Baseline	30 ± 9	36 ± 8			
Plateau 42°C	197 ± 51	222 ± 50	<0.001*	<0.001 [^]	0.50
Plateau 44°C	216 ± 65	253 ± 68			
<i>Absolute CVC (PU/mmHg)</i>					
Baseline	0.29 ± 0.09	0.36 ± 0.07			
Plateau 42°C	1.85 ± 0.55	2.10 ± 0.57	<0.001*	<0.001 [^]	0.66
Plateau 44°C	2.01 ± 0.64	2.34 ± 0.72			
<i>Maximal CVC (%CVC_{max})</i>					
Baseline	17 ± 11	17 ± 8			
Plateau 42°C	94 ± 10	91 ± 6	<0.001*	0.35	1.00

490 Data are mean ± SD. *Main effect of time $P < 0.001$ vs baseline. [^]Main effect of intervention; placebo

491 vs. tea $P < 0.05$.

492 **FIGURE LEGENDS**

493 **Figure 1.** CONSORT diagram showing the flow of participants through each stage of
494 the randomised trial.

495

496 **Figure 2.** Study overview and schematic depicting the stages of the local heating
497 protocols. Light grey shading denotes local heating, mid grey shading
498 represents the plateau and dark grey shading represents the maximal
499 plateau.

500

501 **Figure 3.** Cutaneous vascular conductance (CVC) responses across time points
502 (baseline at 33 °C, axon peak, axon nadir, plateau at 39/42 °C and maximal
503 plateau at 44 °C) following rapid local heating for **A.** *rapid 39°C* and **B.**
504 *rapid 42°C* in 20 healthy volunteers when heating was preceded by
505 ingestion of placebo (open squares) or tea (solid triangles). Data are
506 presented as means, with error bars representing SE.

507

508 **Figure 4.** Cutaneous vascular conductance (CVC) responses across time points
509 (from baseline at 33 °C to maximal plateau at 44 °C) following gradual local
510 heating using **A.** laser-Doppler flowmetry (LDF) and **B.** full-field laser
511 perfusion imaging (FLPI) in 20 healthy volunteers when heating was
512 preceded by ingestion of placebo (open squares) or tea (solid triangles).
513 Data are presented as means, with error bars representing SE. *Main effect
514 of condition $P < 0.05$ placebo vs tea.