# Beetroot Juice versus Chard Gel: A Pharmacokinetic and Pharmacodynamic Comparison of Nitrate Bioavailability

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## Highlights

- When matched for nitrate content both beetroot juice and chard gels, known to be rich in nitrate, increased plasma nitrate and nitrite concentrations and reduced blood pressure to a similar extent.
- Inter-individual variability to reach maximal plasma nitrite levels was considerable and should be taken into account when utilizing acute dietary nitrate supplementation.
- Plasma concentrations of total nitrosated products were higher with beetroot juice than with chard gel despite comparable nitrate content.


## Abstract

Dietary supplementation with inorganic nitrate ($NO_3^-$) has been shown to induce a multitude of advantageous cardiovascular and metabolic responses during rest and exercise. While there is some suggestion that pharmacokinetics may differ depending on the $NO_3^-$ source ingested, to the best of our knowledge this has yet to be determined experimentally. Here, we compare the plasma pharmacokinetics of $NO_3^-$, nitrite ($NO_2^-$), and total nitroso species (RXNO) following oral ingestion of either $NO_3^-$ rich beetroot juice (BR) or chard gels (GEL) with the associated changes in blood pressure (BP). Repeated samples of venous blood and measurements of BP were collected from nine healthy human volunteers before and after ingestion of the supplements using a cross-over design. Plasma concentrations of RXNO and $NO_2^-$ were quantified using reductive gas-phase chemiluminescence and $NO_3^-$ using high pressure liquid ion chromatography. We report that, [$NO_3^-$] and [$NO_2^-$] were increased and systolic BP reduced to a similar extent in each experimental arm, with considerable inter-individual variation. Intriguingly, there was a greater increase in [RXNO] following ingestion of BR in

comparison to GEL, which may be a consequence of its higher polyphenol content. In conclusion, our data suggests that while differences in circulating $NO_2^-$ and $NO_3^-$ concentrations after oral administration of distinct $NO_3^-$-rich supplementation sources are moderate, concentrations of metabolic by-products may show greater-than-expected variability; the significance of the latter observation for the biological effects under study remains to be investigated.

**Key Words:** nitrite, nitric oxide, dietary supplementation, blood pressure

## 1. Introduction

Dietary nitrate ($NO_3^-$) supplementation has been demonstrated to positively influence parameters of exercise performance (2, 25, 36) and vascular health (26, 27, 50, 54). These effects have been achieved utilizing a variety of different vehicles for $NO_3^-$ delivery, including simple sodium (28) or potassium salts (23), $NO_3^-$-rich foods (44), concentrated beetroot juice (BR) (58), and chard gel (GEL) (37, 38). These studies have consistently shown that circulating plasma [$NO_3^-$] and nitrite ([$NO_2^-$]) concentrations are increased following ingestion of $NO_3^-$ supplements. Whilst the biological consequences of dietary $NO_3^-$ administration are not fully understood at present, it is known that $NO_3^-$ can be reduced to $NO_2^-$, which is believed to be subsequently further converted to bioactive nitric oxide (NO) (1, 31). The entero-salivary circulation plays a vital role in NO homeostasis with ~25% of all circulating $NO_3^-$ taken up by the salivary glands and concentrated in the saliva (51). The reduction of $NO_3^-$ to $NO_2^-$ takes place in the oral cavity where commensal facultative anaerobic bacteria on the surface of the tongue reduce $NO_3^-$ to $NO_2^-$ via $NO_3^-$ reductase enzymes (12, 29). Once

78 swallowed, $NO_2^-$ reaches the stomach where a proportion is then converted to NO, with
79 the remainder being absorbed into circulation via the intestinal tract (3, 32, 33).

80 It is well-established that increases in plasma [$NO_3^-$] and [$NO_2^-$] following dietary $NO_3^-$
81 supplementation occur in a dose-dependent manner (4, 19, 21, 23, 58, 59), however the
82 influence of the vehicle, if any, is less certain. Several studies have reported that plasma
83 [$NO_3^-$] and [$NO_2^-$] $^-$] reaches maximal quantities at ~ 1–1.5 h and 2.5–3h, respectively,
84 after ingestion of BR (23, 35, 54, 58). Recent work from our laboratory has shown that
85 consuming GEL results in similar plasma $NO_3^-$ pharmacokinetics but plasma [$NO_2^-$]
86 reaches maximal levels more quickly (~1.5 h) after ingestion (37). It is currently unclear
87 whether the variance in $NO_2^-$ pharmacokinetics between BR and GEL is simply due to
88 the vehicle of administration or profoundly influenced by inter-cohort differences in
89 the response to $NO_3^-$ supplementation. Understanding if the vehicle of $NO_3^-$
90 supplementation affects the fate of NO-related metabolites may allow for the
91 optimization of dosing strategies for sports performance and other contexts. Therefore,
92 the purpose of this study was to compare the effects of ingesting BR and GEL on plasma
93 NO metabolite pharmacokinetics and blood pressure (BP) pharmacodynamics in
94 healthy individuals.

95

96 **2. Methods**

97 **2.1 Participants**

98 Nine healthy adult males (age 28 ± 4 years, stature: 181 ± 8 cm, body mass: 83.4 ± 10.4
99 kg) volunteered to take part in the study, which was approved by the School of Science
100 and Sport Ethics Committee of the University of the West of Scotland. All participants
101 provided written informed consent and a medical questionnaire before the study began.

Healthy males between the ages of 18 and 45 who were physically active (taking part in recreational activity a minimum of 3 times per week) were eligible to participate in the study. Participants were excluded if they were currently taking dietary supplements or any medication, regularly used mouthwash, were smokers, had a current illness or virus within the previous month, had a known disorder or history of disorders of the hematopoietic system, were hypertensive (≥140/90 mmHg) or had a family history of premature cardiovascular disease. All procedures were conducted in accordance with the Declaration of Helsinki.

## 2.2 Experimental Design

Our study had a simple randomized cross-over design. Participants visited the laboratory on two separate occasions with a minimum 7-day washout period and a maximum of 14 days between visits. Participants consumed either concentrated BR (Beet It Organic Shot, James White Drinks, Ipswich, UK) or GEL (Science in Sport, GO+ Nitrates, Lancashire, UK) during each trial.

Participants were asked to refrain from the consumption of alcohol, caffeine, $NO_3^-$ rich foods as outlined by Hord and colleagues (22), and to avoid any strenuous exercise for 24 h before each trial. Participants were also asked to refrain from the use of anti-bacterial mouthwash and chewing gum for the duration of the study as they have been shown to disturb the oral bacterial flora required for the conversion of $NO_3^-$ to $NO_2^-$ in the saliva (17, 41). Compliance to these factors was determined at the start of each visit.

Following a 12 h overnight fast, participants reported to the lab in the morning where they were asked to void the contents of their bladder and lie supine on a medical bed. After 15 min, BP was determined using an automated sphygmomanometer (Omron M10, Kyoto, Japan) three times, at 1 min intervals. A cannula was then inserted into the antecubital vein of the arm or a superficial vein on the dorsal surface of the hand and the line was kept patent by regular flushing with intravenous 0.9% saline solution. A sample of venous blood was then collected in a vacutainer containing EDTA and immediately centrifuged at 4000 rpm at 4ºC for 10 min (Harrier 18/80, MSE, UK). The plasma was extracted carefully ensuring the cell layer was not disturbed and immediately frozen at -80ºC for later analysis of plasma [$NO_3^-$], [$NO_2^-$], and total nitrosospecies [RXNO]. Participants then ingested either the BR or GEL supplements within 1 min of pre supplementation blood sampling. The GEL supplement comprised 120 ml of peach flavored sports gel containing 500 mg of $NO_3^-$ from natural chard and rhubarb sources. In the BR trial, participants ingested 117 ml of concentrated BR that also contained 500 mg of $NO_3^-$. The $NO_3^-$ content of the supplements was later verified using high-pressure liquid ion chromatography (section 2.3).

As outlined in Fig. 1 venous blood samples were collected simultaneously with measurements of BP pre-supplementation then at 1, 1.5, 2, 2.5, 3, 3.5 and 6 h post-ingestion of each supplement. The measurement of BP was carried out in triplicate, with the measurement being performed as close as possible to blood draw. The BP Cuff was placed on the opposite arm to the cannula. Participants remained supine from the first blood sample until the 3.5 h sample, after which they were allowed to sit at a desk, returning 30 min before the final sample. During the experimental trials, participants were provided with standardized meals, which had a low $NO_3^-$ content. Specifically,

participants consumed a cereal bar after 1.5 h and a cheese sandwich 3.5 h after ingestion of BR or GEL. Participants were provided with *ad libitum* access to tap water. The volume consumed in trial 1 was recorded and kept consistent for trial 2.

### 2.3 Additional Experimental Arm

The aforementioned procedures were conducted to address the primary objective of this experiment whereby doses of GEL and BR matched for $NO_3^-$ content were compared. Whereas the dose of GEL used in this experiment comprised two full gels as provided by the manufacturer (2 x 60g), 23 ml of BR was removed from one 70 ml bottle to ensure a matched $NO_3^-$ content. Given that both researchers and end-users are more likely to utilize the full 140 ml (e.g. (21, 58) the dose of BR used in this experiment was considered to be lacking in ecological validity. To this end, eight of the participants completed an additional experimental trial where they received 140 ml of BR (600 mg of $NO_3^-$, H-BR) with the procedures repeated as previously described.

### 2.4 Analysis of Plasma NO Metabolites

High-pressure liquid ion chromatography was used to determine plasma [$NO_3^-$] and [$NO_2^-$]. Due to high variability in the $NO_2^-$ measurements, which may relate to lack of specific sample processing without addition of N-ethylmaleimide prior to centrifugation, the $NO_2^-$ data were re-analyzed using chemiluminescence and the latter was used in all calculations. Gas-phase chemiluminescence was used to determine plasma [RXNO]. Samples were thawed at room temperature in the presence of 5 mM N-ethylmaleimide and subsequently analyzed using an automated NOx detection system (Eicom, ENO-20, Kyoto, Japan, combined with a Gilson auto-sampler for [$NO_3^-$

])(46) and a NO analyzer (Sievers NOA 280i, Analytix, UK for [$NO_2^-$] and CLD 77AM sp, ECOphysicis, Durnten, Switzerland for [RXNO]) in conjunction with a custom-designed reaction chamber. $NO_2^-$ levels were determined using 1% potassium iodide in 5ml glacial acetic acid at room temperature for reduction of $NO_2^-$ to NO (42); RXNO levels were determined using the triiodide method (13). All samples were analyzed within 3 months of sample collection in order to minimize degradation of NO metabolites.

**2.5 Data Analysis**

All analyses were carried out using the Statistical Package for the Social Sciences, Version 22 (SPSS Inc., Chicago, IL, USA) or GraphPad Prism version 6 (GraphPad Software Inc., San Diego, USA) for kinetic analyses. For brevity, data from the additional H-BR trial are not displayed in figures. The sample size was determined *a priori* using a power calculation which revealed that a minimum of eight participants was required to detect differences in the time taken for $NO_2^-$ to peak between GEL and BR conditions. To establish the time to reach maximal [$NO_2^-$] and [$NO_3^-$] a log (Gaussian) non-linear regression model was applied to the data using the following equation:

*Y=Amplitude*exp(-0.5*(ln(X/Center)/Width)^2).*

Data are expressed as the change in the mean (Δ) ± standard error of the mean (S.E.M) as compared to baseline or the mean and 95% confidence interval (CI) for time to reach maximal values. The distribution of the data was tested using the Shapiro-Wilk test. A two-way repeated-measures ANOVA was used to examine the differences between condition and over time for plasma $NO_3^-$, $NO_2^-$, RXNO, and BP. *Post-hoc* analysis to

198 determine the difference from the baseline was conducted using a paired samples t-tests
199 with Bonferroni correction. Statistical significance was declared when $P < 0.05$.

200

201 **3. Results and Discussion**

202 Plasma [$NO_3^-$] and [$NO_2^-$] at baseline amounted to 26 ± 5.7 μM $NO_3^=$, 95 ± 31.9 nM
203 $NO_2^-$ for BR and 33 ± 3.4 μM $NO_3^-$ and 25 ± 6.7 nM $NO_2^-$ for GEL. As expected, oral
204 $NO_3^-$ supplementation significantly increased plasma [$NO_3^-$] and [$NO_2^-$] in each
205 experimental arm ($P < 0.001$) (Δ [$NO_3^-$] with BR: 319.4 ± 32.1 μM, with GEL: 383.9
206 ± 35.7 μM, Fig. 2; Δ [$NO_2^-$] with BR: 205.4 ± 51.9 nM, with GEL: 207.4 ± 58.1 nM,
207 Fig. 3). The magnitude of the increase, however, was not different between BR and
208 GEL ($P > 0.10$). In the H-BR arm, [$NO_2^-$] and [$NO_3^-$] increased to a greater extent than
209 BR and GEL (Δ [$NO_2^-$] 277 ± 161 nM, Δ [$NO_3^-$] 457 ± 22 μM, both $P < 0.01$).
210 Following ingestion of BR, [$NO_2^-$] reached maximal values at 3 h (95%CI 2.1 – 3.9 h),
211 which was not different to GEL (2.8 h, 95%CI 2.3 – 3.2 h, $P = 0.739$). Likewise, the
212 time taken for plasma [$NO_3^-$] to reach maximal concentrations was not different
213 between BR and GEL (BR: 1.4 h 95%CI 0.8 – 1.9 h, GEL: 1.4 h 95%CI 0.7 – 2.1 h, $P$
214 = 0.737). In the H-BR arm, [$NO_2^-$] and [$NO_3^-$] reached maximal concentration in the
215 plasma after 3.2 h (95%CI 2.1 – 4.2 h) and 1.5 h (95%CI 0.9 – 2.1 h), respectively.
216 These data collectively suggest that the vehicle of delivery, be it liquid or gel, does not
217 impact the kinetics of the reduction of $NO_3^-$ to $NO_2^-$ or the maximal plasma
218 concentrations of these metabolites. Nevertheless, it remains to be established whether
219 $NO_3^-$ supplementation in solid forms, such as whole vegetables or concentrated BR
220 flapjacks, results in different $NO_x$ pharmacokinetics.

221

In the present study, plasma [$NO_2^-$] and [$NO_3^-$] reached maximal quantities within a similar timeframe to previous research with BR (19, 29, 40, 43). However, on this occasion [$NO_2^-$] took substantially longer after GEL (2.8 h) compared with our own previous work (1.5 h) (37). Given that descriptive and anthropometric variables were similar between the two study cohorts, it seems likely that physiological variations between individuals may account for these differences in time. Although plasma [$NO_2^-$] is likely to be substantially elevated in most individuals 2.5 h after ingestion of either BR or GEL, the peak may reasonably occur anywhere between 2.1 and 3.9 h. To further highlight this Figure 4 displays the individual variability in the plasma $NO_2^-$ response to both vehicles of supplementation. Another important factor to acknowledge when comparing different studies is the methods of analysis for NO metabolites. The sensitivity of chemiluminescence and HPLC has been highlighted with factors such as sample preparation, type of analyzer used, and duration of sample storage, all potentially influencing the result acquired (8, 42). Whilst the precise mechanisms explaining the disparity in plasma [$NO_2^-$] pharmacokinetics between these studies are unclear, we speculate that this may at least be partially explained by variances in the gut microbiota (14), pH of oral cavity and stomach (18, 43), and differences in the composition of the oral bacterial flora required for $NO_3^-$ reduction (11, 18). The importance of the oral microbiome for $NO_3^-$ reduction has been clearly established, with the oral reductase capacity substantially interrupted when using anti-bacterial mouthwash (5, 41, 55) or spitting of saliva following $NO_3^-$ supplementation (30, 54). Equally, physical fitness has been suggested to affect the individual response to $NO_3^-$ supplementation (18). In contrast to the direct association between endothelial NO production (as measured by plasma $NO_2^-$) and exercise performance (47, 53). Porcelli and colleagues (45) demonstrated that there was a negative association between aerobic

capacity ($VO_{2peak}$) and the increase in plasma [$NO_2^-$] following ingestion of a $NO_3^-$ supplement. Although not measured in either the present study or our previous work on $NO_3^-$ pharmacokinetics (37), it is conceivable that individual differences in physical fitness, diet, or other lifestyle habits may contribute to the between-group variation reported here and elsewhere within the literature (18). Although it has not been thoroughly investigated, it is also conceivable that oral (and gut) microbial flora changes as a result of frequent $NO_3^-$ supplementation. It has been recently demonstrated following 2 weeks of $NO_3^-$ supplementation via BR there is an increase in salivary pH suggesting a role of $NO_3^-$ supplementation in altering composition of the oral microbiome (20).

Whilst the $NO_3^-$ and $NO_2^-$ responses were similar between experimental arms, an unexpected finding was that ingestion of BR tended to increase plasma [RXNO] to a greater extent in comparison to GEL (Δ in BR: 408.1 ± 127.9 nM vs. Δ in GEL: 148.1 ± 35.1 nM, $P = 0.08$, Fig. 5.). Plasma [RXNO] at baseline amounted to 79.5 ± 13.1 nM for BR and 71.9 ± 10.9 nM for GEL. There was, however, a high degree of variability in the change in [RXNO] between individuals and the small sample size likely explains why this finding was not statistically significant. The increase in [RXNO] was even greater in the H-BR trial (Δ563.8 ± 116.7 nM) at 2 h post ingestion than in GEL ($P = 0.004$) and BR ($P=0.03$). Although plasma [RXNO] is not measured routinely in $NO_3^-$ supplementation studies, the magnitude by which [RXNO] increased following BR in the present study is greater than what has been previously reported [6]. Equally surprising was that the rise in [RXNO] exceeded that of [$NO_2^-$] following ingestion of BR. The explanation for this is presently uncertain and while differences in supplementation regimen, $NO_3^-$ dose, and study participants may explain the disparity

272 with previous research, further work is required to explore the changes in [RXNO] and
273 [$NO_2^-$] following ingestion of BR.

274

275 What is also unclear is why ingestion of BR increases [RXNO] to a greater extent (at
276 least in the H-BR trial) compared to GEL. Although care was taken to match the
277 supplements for total $NO_3^-$ content, differences in the polyphenol content between
278 beetroot and chard may account for this outcome (24, 57). Furthermore, alongside the
279 primary sources of $NO_3^-$ the BR supplement contained additional ingredients including
280 lemon juice and the GEL contained rhubarb juice, gelling agents, preservatives, and
281 flavorings. While the total antioxidant and polyphenol content of BR has been defined
282 (56, 57) there is no comparable data on GEL. The total polyphenol content of each
283 supplement may be important for overall NO bioavailability. Ingestion of flavonoid
284 rich apples, for example, has been shown to increase [RXNO] in healthy adults (6), and
285 nitrated polyphenols are formed from acidified $NO_2^-$ under simulated stomach
286 conditions (40). Moreover, it has been shown that polyphenols augment the reduction
287 of $NO_2^-$ to NO in the gut (48, 49). Given that S-nitrosothiols (RSNO), a component of
288 RXNO, act as a carrier and store of NO in the blood, a polyphenol-induced increase in
289 the bioavailability of NO may reasonably be exhibited by an increase in total nitroso
290 products following BR. The importance of the polyphenol content of $NO_3^-$ supplements
291 and the role of RXNO in the translation to consequent physiological outcomes has yet
292 to be established. However, the high polyphenol content of BR (56, 57), may explain
293 the greater reduction in oxygen consumption following BR compared to sodium $NO_3^-$
294 (15). RXNOs are protected from direct NO scavenging by reactive oxygen species
295 allowing NO to be transported by e.g. serum albumin and red blood cells (7, 52). This
296 establishes an NO reservoir for the sustained release of NO from these biological

297 storage forms (9, 16, 34). Potentially allowing for the targeted delivery of NO to where
298 it is required such as sites of ischemia during exercise.

299

300 Systolic (SBP), diastolic (DBP), and mean arterial pressure (MAP) at baseline were as
301 follows SBP: 123 ± 2 mmHg, DBP: 70 ± 1 mmHg, MAP: 88 ± 1 mmHg for BR and
302 SBP: 124 ± 2 mmHg, DBP: 73 ± 2 mmHg, MAP: 90 ± 2 mmHg for GEL. In the present
303 study, both BR and GEL reduced SBP and MAP (Δ SBP with BR: -10 ± 2 mmHg, $P <$
304 0.001, vs. Baseline; with GEL: -12 ± 2 mmHg, $P < 0.001$; Δ MAP with BR: -5 ± 2
305 mmHg, $P = 0.012$ vs Baseline; with GEL: -7 ± 2 mmHg, $P = 0.010$, Fig. 6). The
306 magnitude of the reductions in SBP and MAP were not different between BR and GEL
307 ($P \geq 0.12$). Neither GEL nor BR significantly altered DBP ($P = 0.18$) nor was there any
308 difference between experimental arms ($P = 0.197$). Likewise, SBP (Δ -11 ± 2 mmHg,
309 $P < 0.001$) and MAP (Δ -8 ± 3 mmHg, $P < 0.001$) were reduced and DBP remained
310 unchanged from baseline in the H-BR arm. It must be acknowledged that maintenance
311 of the supine position for a prolonged period of time also likely contributed to a
312 reduction in BP. Without a control condition, however, it is impossible to determine
313 the extent of this effect. Nevertheless, these findings are consistent with previous
314 literature demonstrating that ingestion of either BR or GEL reduces SBP and MAP
315 among healthy individuals (23, 37, 54, 58). The response in DBP appears to be more
316 variable, however, although several previous studies have reported comparable data (2,
317 10, 23). Given the data presented here, it appears that the plasma [$NO_3^-$] and [$NO_2^-$]
318 mirrors acute hemodynamic response to dietary $NO_3^-$ closely. Of notable interest,
319 however, is that the changes in [RXNO] did not appear to be associated with the
320 magnitude of the reduction in BP. This is in contrast to work by Oplander and
321 colleagues (39) who demonstrated that reductions in BP were associated with an

increased plasma availability of RXNO but not $NO_2^-$ following exposure of the skin to ultraviolet radiation. It is conceivable, therefore, that the method by which NO bioavailability is augmented will alter the mechanisms by which BP is reduced.

## 4. Conclusion

Our data suggests that dietary $NO_3^-$ supplementation via BR and GEL elicits similar plasma [$NO_2^-$] and [$NO_3^-$] pharmacokinetics when examined within the same participant cohort. Likewise, both BR and GEL are capable of reducing SBP and MAP with little difference in the magnitude of these effects. Nevertheless, we here present data demonstrating that the time course of ingesting the $NO_3^-$ supplements to maximal [$NO_2^-$] in blood plasma is profoundly variable between individuals. This is of major relevance for researchers wishing to determine the same. We also report, for the first time, that ingesting BR leads to a greater availability of RXNO compared to GEL, which we speculate may be attributed to the higher polyphenol content of the BR supplement.

## References


1. Bailey JC, Feelisch M, Horowitz JD, Frenneaux MP, Madhani M. Pharmacology and therapeutic role of inorganic nitrite and nitrate in vasodilatation. *Pharmacol Ther* 2014;144(3):303–20.

2. Bailey SJ, Winyard P, Vanhatalo A, et al. Dietary nitrate supplementation reduces the O2 cost of low-intensity exercise and enhances tolerance to high-intensity exercise in humans. *J Appl Physiol* 2009;107(4):1144–55.

3. Benjamin N, O'Driscoll F, Dougall H, et al. Stomach NO synthesis. *Nature* 1994;368(6471):502.

4. Bondonno CP, Croft KD, Puddey IB, et al. Nitrate causes a dose-dependent augmentation of nitric oxide status in healthy women. *Food Funct* 2012;3(5):522.

5. Bondonno CP, Liu AH, Croft KD, et al. Antibacterial mouthwash blunts oral nitrate reduction and increases blood pressure in treated hypertensive men and women. *Am J Hypertens* 2015;28(5):572–5.

6. Bondonno CP, Yang X, Croft KD, et al. Flavonoid-rich apples and nitrate-rich spinach augment nitric oxide status and improve endothelial function in healthy men and women: A randomized controlled trial. *Free Radic Biol Med* 2012;52(1):95–102.

7. Bryan NS, Fernandez BO, Bauer SM, et al. Nitrite is a signaling molecule and regulator of gene expression in mammalian tissues. *Nat Chem Biol* 2005;1(5):290–7.

8. Bryan NS, Grisham MB. Methods to detect nitric oxide and its metabolites in biological samples. *Free Radic Biol Med* 2007;43(5):645–57.

9. Bryan NS, Rassaf T, Maloney RE, et al. Cellular targets and mechanisms of nitros(yl)ation: an insight into their nature and kinetics in vivo. *Proc Natl Acad Sci U S A* 2004;101(12):4308–13.

10. Coles LT, Clifton PM. Effect of beetroot juice on lowering blood pressure in free-living, disease-free adults: a randomized, placebo-controlled trial. *Nutr J* 2012;11(1):106.

11. Doel JJ, Benjamin N, Hector MP, Rogers M, Allaker RP. Evaluation of bacterial nitrate reduction in the human oral cavity. *Eur J Oral Sci* 2005;113(1):14–9.

12. Duncan C, Dougall H, Johnston P, et al. Chemical generation of nitric oxide in the mouth from the enterosalivary circulation of dietary nitrate. *Nat Med* 1995;1(6):546–51.

13. Feelisch M, Rassaf T, Mnaimneh S, et al. Concomitant S-, N-, and heme-nitros(yl)ation in biological tissues and fluids: implications for the fate of NO in vivo. *FASEB J* 2002;16(13):1775–85.

14. Flint HJ, Scott KP, Louis P, Duncan SH. The role of the gut microbiota in

nutrition and health. *Nat Rev Gastroenterol Hepatol* 2012;9(10):577–89.

15. Flueck JL, Bogdanova A, Mettler S, Perret C. Is beetroot juice more effective than sodium nitrate? The effects of equimolar nitrate dosages of nitrate-rich beetroot juice and sodium nitrate on oxygen consumption during exercise. *Appl Physiol Nutr Metab* 2016;41(4):421–9.

16. Ford PC, Wink DA, Stanbury DM. Autoxidation kinetics of aqueous nitric oxide. *FEBS Lett* 1993;326(1–3):1–3.

17. Govoni M, Jansson EA, Weitzberg E, Lundberg JO. The increase in plasma nitrite after a dietary nitrate load is markedly attenuated by an antibacterial mouthwash [Internet]. *Nitric Oxide* 2008;19(4):333–7.

18. Hezel MP, Weitzberg E. The oral microbiome and nitric oxide homoeostasis. *Oral Dis* 2015;21(1):7–16.

19. Hobbs DA, Kaffa N, George TW, Methven L, Lovegrove JA. Blood pressure-lowering effects of beetroot juice and novel beetroot-enriched breads in normotensive male subjects. *Br J Nutr* 2012;108(11):2066–74.

20. Hohensinn B, Haselgrübler R, Müller U, et al. Sustaining elevated levels of nitrite in the oral cavity through consumption of nitrate-rich beetroot juice in young healthy adults reduces salivary pH [Internet]. *Nitric Oxide* 2016;Ahead of Print

21. Hoon MW, Jones AM, Johnson NA, et al. The effect of variable doses of inorganic nitrate-rich beetroot juice on simulated 2000-m rowing performance in trained athletes. *Int J Sports Physiol Perform* 2014;9(4):615–20.

22. Hord NG, Tang Y, Bryan NS. Food sources of nitrates and nitrites: the physiologic contact for potential health benefits. *Am J Clin Nutr* 2009;90(6):1–10.

23. Kapil V, Milsom AB, Okorie M, et al. Inorganic Nitrate Supplementation Lowers Blood Pressure in Humans: Role for Nitrite-Derived NO. *Hypertension* 2010;56(2):274–81.

24. Kazimierczak R, Hallmann E, Lipowski J, et al. Beetroot (Beta vulgaris L.) and naturally fermented beetroot juices from organic and conventional production: Metabolomics, antioxidant levels and anticancer activity. *J Sci Food Agric* 2014;94(13):2618–29.

25. Lansley KE, Winyard PG, Bailey SJ, et al. Acute dietary nitrate supplementation improves cycling time trial performance. *Med Sci Sports Exerc* 2011;43(6):1125–31.

26. Lara J, Ashor AW, Oggioni C, Ahluwalia A, Mathers JC, Siervo M. Effects of inorganic nitrate and beetroot supplementation on endothelial function: a systematic review and meta-analysis. *Eur J Nutr* 2016;55(2):451–9.

27. Larsen FJ, Ekblom B, Sahlin K, Lundberg JO, Weitzberg E. Effects of Dietary Nitrate on Blood Pressure in Healthy Volunteers To the Editor : Nitric oxide , generated by nitric. *N Engl J Med* 2006;355(26):2792–3.

28. Larsen FJ, Weitzberg E, Lundberg JO, Ekblom B. Effects of dietary nitrate on oxygen cost during exercise. *Acta Physiol* 2007;191(1):59–66.

29. Li H, Duncan C, Townend J, et al. Nitrate-reducing bacteria on rat tongues. *Appl Environ Microbiol* 1997;63(3):924–30.

30. Lundberg JO, Govoni M. Inorganic nitrate is a possible source for systemic generation of nitric oxide. *Free Radic Biol Med* 2004;37(3):395–400.

31. Lundberg JO, Weitzberg E, Gladwin MT. The nitrate-nitrite-nitric oxide pathway in physiology and therapeutics. *Nat Rev Drug Discov* 2008;7(2):156–67.

32. Lundberg JO, Weitzberg E, Lundberg JM, Alving K. Intragastric nitric oxide production in humans: measurements in expelled air. *Gut* 1994;35(11):1543–6.

33. McKnight GM, Smith LM, Drummond RS, Duncan CW, Golden M, Benjamin N. Chemical synthesis of nitric oxide in the stomach from dietary nitrate in humans. *Gut* 1997;40(2):211–4.

34. Miersch S, Mutus B. Protein S-nitrosation: Biochemistry and characterization of protein thiol-NO interactions as cellular signals. *Clin Biochem* 2005;38(9):777–91.

35. Miller GD, Marsh AP, Dove RW, et al. Plasma nitrate and nitrite are increased by a high-nitrate supplement but not by high-nitrate foods in older adults. *Nutr Res* 2012;32(3):160–8.

36. Muggeridge DJ, Howe CCF, Spendiff O, Pedlar C, James PE, Easton C. A single dose of beetroot juice enhances cycling performance in simulated altitude. *Med Sci Sports Exerc* 2014;46(1):143–50.

37. Muggeridge DJ, Sculthorpe N, Grace FM, et al. Acute whole body UVA irradiation combined with nitrate ingestion enhances time trial performance in trained cyclists. *Nitric Oxide - Biol Chem* 2015;48:3–9.

38. Muggeridge DJ, Sculthorpe N, James PE, Easton C. The effects of dietary nitrate supplementation on the adaptations to sprint interval training in previously untrained males. *J Sci Med Sport* 2016;Ahead of Print

39. Oplander C, Volkmar CM, Paunel-go A, et al. Whole Body UVA Irradiation Lowers Systemic Blood Pressure by Release of Nitric Oxide From Intracutaneous Photolabile Nitric Oxide Derivates. *Circ Res* 2009;105(10):1031–40.

40. Peri L, Pietraforte D, Scorza G, Napolitano A, Fogliano V, Minetti M. Apples increase nitric oxide production by human saliva at the acidic pH of the stomach: A new biological function for polyphenols with a catechol group? *Free Radic Biol Med* 2005;39(5):668–81.

41. Petersson J, Carlström M, Schreiber O, et al. Gastroprotective and blood pressure lowering effects of dietary nitrate are abolished by an antiseptic mouthwash. *Free Radic Biol Med* 2009;46(8):1068–75.

42. Pinder AG, Rogers SC, Khalatbari A, Ingram TE, James PE. The Measurement of Nitric Oxide and Its Metabolites in Biological Samples by Ozone-Based Chemiluminescence. In: *Redox-Mediated Signal Transduction: Methods and Protocols.* NJ: Humana Press; 2008 p. 11–28.

43. Pinheiro LC, Amaral JH, Ferreira GC, et al. Gastric S-nitrosothiol formation drives the antihypertensive effects of oral sodium nitrite and nitrate in a rat model of renovascular hypertension. *Free Radic Biol Med* 2015;87:252–62.

44. Porcelli S, Pugliese L, Rejc E, et al. Effects of a Short-Term High-Nitrate Diet on Exercise Performance. *Nutrients* 2016;8(9):534. 5

45. Porcelli S, Ramaglia M, Bellistri G, et al. Aerobic Fitness Affects the Exercise Performance Responses to Nitrate Supplementation. *Med Sci Sports Exerc* 2014;47(8); 1643-1651.

46. Rassaf T, Bryan NS, Kelm M, Feelisch M. Concomitant presence of N-nitroso and S-nitroso proteins in human plasma. *Free Radic Biol Med* 2002;33(11):1590–6.

47. Rassaf T, Lauer T, Heiss C, et al. Nitric oxide synthase-derived plasma nitrite predicts exercise capacity. *Br J Sport Med* 2007;41(2):669–73; discussion 673.

48. Rocha BS, Gago B, Barbosa RM, Laranjinha J. Dietary polyphenols generate nitric oxide from nitrite in the stomach and induce smooth muscle relaxation. *Toxicology* 2009;265(1–2):41–8.

49. Rocha BS, Nunes C, Pereira C, Barbosa RM, Laranjinha J. A shortcut to wide-ranging biological actions of dietary polyphenols: modulation of the nitrate-nitrite-nitric oxide pathway in the gut. *Food Funct* 2014;5(8):1646–52.

50. Siervo M, Lara J. Inorganic nitrate and beetroot juice supplementation reduces blood pressure in adults: a systematic review and meta-analysis. *The Journal of Nutrition* 2013;143(6):818–26.

51. Spiegelhalder B, Eisenbrand G, Preussmann R. Influence of dietary nitrate on nitrite content of human saliva: Possible relevance to in vivo formation of N-nitroso compounds. *Food Cosmet Toxicol* 1976;14(6):545–8.

52. Stamler JS, Jaraki O, Osborne J, et al. Nitric oxide circulates in mammalian plasma primarily as an S-nitroso adduct of serum albumin. *Proc Natl Acad Sci U S A* 1992;89(16):7674–7.

53. Totzeck M, Hendgen-Cotta UB, Rammos C, et al. Higher endogenous nitrite levels are associated with superior exercise capacity in highly trained athletes. *Nitric Oxide - Biol Chem* 2012;27(2):75–81.

54. Webb AJ, Patel N, Loukogeorgakis S, et al. Acute blood pressure lowering, vasoprotective, and antiplatelet properties of dietary nitrate via bioconversion to nitrite. *Hypertension* 2008;51(3):784–90.

55. Woessner M, Smoliga JM, Tarzia B, Stabler T, Van Bruggen M, Allen JD. A

stepwise reduction in plasma and salivary nitrite with increasing strengths of mouthwash following a dietary nitrate load. *Nitric Oxide* 2016;54(16):1–7.

56. Wootton-Beard PC, Moran A, Ryan L. Stability of the total antioxidant capacity and total polyphenol content of 23 commercially available vegetable juices before and after in vitro digestion measured by FRAP, DPPH, ABTS and Folin-Ciocalteu methods. *Food Res Int* 2011;44(1):217–24.

57. Wootton-Beard PC, Ryan L. A beetroot juice shot is a significant and convenient source of bioaccessible antioxidants. *J Funct Foods* 2011;3(4):329–34.

58. Wylie LJ, Kelly J, Bailey SJ, et al. Beetroot juice and exercise: pharmacodynamic and dose-response relationships. *J Appl Physiol* 2013;115(3):325–36.

59. Wylie LJ, Ortiz de Zevallos J, Isidore T, et al. Dose-dependent effects of dietary nitrate on the oxygen cost of moderate-intensity exercise: Acute vs. chronic supplementation. *Nitric Oxide* 2016;

**Figure Captions**

**Figure 1:** Study overview: time-points for beetroot juice/chard gel administration, venous blood sampling, blood pressure measurements and food intake.

**Figure 2:** Changes in plasma nitrate concentrations following supplementation with BR and GEL (Δ Mean ± S.E.M). * Significant difference from baseline (pre-supplementation) ($P < 0.001$).

**Figure 3:** Changes in plasma nitrite concentrations following supplementation with BR and GEL (Δ Mean ± S.E.M). * Significant difference from baseline (pre-supplementation)

**Figure 4:** Individual plasma nitrite pharmacokinetics and Systolic BP for BR and GEL. Each participant is represented by the same different colour in each figure.

**Figure 5:** Changes in total nitroso species concentrations following supplementation with BR and GEL (Δ Mean ± S.E.M). * Significant difference from baseline (pre-supplementation)

**Figure 6:** Systolic (A), diastolic (B) and mean arterial pressure (C) changes following supplementation with BR and GEL (Δ Mean ± S.E.M). * Significant difference from baseline (pre-supplementation)