Nitrate, the oral microbiome, and cardiovascular health: a systematic literature review of human and animal studies

Lauren C. Blekkenhorst
*Edith Cowan University*

Nicola P. Bondonno

Alex H. Liu

Natalie C. Ward

Richard L. Prince

*See next page for additional authors*

Follow this and additional works at: https://ro.ecu.edu.au/ecuworkspost2013

Part of the Human and Clinical Nutrition Commons

10.1093/ajcn/nqx046

Available here.

This Journal Article is posted at Research Online.

https://ro.ecu.edu.au/ecuworkspost2013/4269
Authors

This journal article is available at Research Online: https://ro.ecu.edu.au/ecuworkspost2013/4269
Nitrate, the oral microbiome and cardiovascular health: a systematic literature review of human and animal studies

Lauren C Blekkenhorst1,6*, Nicola P Bondonno1*, Alex H Liu1, Natalie C Ward1,2, Richard L Prince3, Joshua R Lewis3,4,5, Amanda Devine6, Kevin D Croft1, Jonathan M Hodgson1,6, Catherine P Bondonno1,6

1Medical School, Royal Perth Hospital Unit, University Western Australia, Perth, WA, Australia (LCB, NPB, AHL, NCW, KDC, JMH, CPB)
2School of Biomedical Sciences & Curtin Health Innovation Research Institute, Curtin University, Perth, WA, Australia (NCW)
3Medical School, Queen Elizabeth Medical Centre Unit, University of Western Australia, Nedlands, WA, Australia (RLP, JRL)
4Centre for Kidney Research, Children's Hospital at Westmead, Westmead, NSW, Australia (JRL)
5School of Public Health, Sydney Medical School, University of Sydney, Sydney, NSW, Australia (JRL)
6School of Medical and Health Sciences, Edith Cowan University, Joondalup, WA, Australia (AD, JMH, CPB)

*These authors contributed equally to this work

Authors’ last names: Blekkenhorst, Bondonno, Liu, Ward, Prince, Lewis, Devine, Croft, Hodgson, Bondonno

Corresponding author:
Lauren Blekkenhorst
Medical School, Royal Perth Hospital Unit (M570)
The University of Western Australia
35 Stirling Highway
Sources of support: The salary of JMH was supported by a National Health and Medical Research Council of Australia Senior Research Fellowship, and a Royal Perth Hospital Medical Research Foundation Fellowship. The salary of JRL was supported by a National Health and Medical Research Council Career Development Fellowship.

Short running head: Nitrate, oral microbiome and cardiovascular health

Abbreviations: ABP, ambulatory blood pressure; AC, adenylate cyclase; Ach, acetylcholine; ADI, acceptable daily intake; AIx, augmentation index; BH4, tetrahydrobiopterin; cGMP, cyclic guanosine monophosphate; CKD, chronic kidney disease; DASH, dietary approaches to stop hypertension; DBP, diastolic blood pressure; eNOS, endothelial nitric oxide synthase; FMD, flow-mediated dilatation; GTP, guanosine triphosphate; nitrous acid, HNO2; MAP, mean arterial pressure; NO, nitric oxide; NOS, nitric oxide synthase; PI3K, phosphoinoside 3-kinase; PWV, pulse wave velocity; sGC, soluble guanylate cyclase; SBP, systolic blood pressure.
ABSTRACT

Background: Dietary nitrate is an important source of nitric oxide (NO), a molecule critical for cardiovascular health. Nitrate is sequentially reduced to NO through an enterosalivary nitrate-nitrite-NO pathway that involves the oral microbiome. This pathway is considered an important adjunct pathway to the classical L-arginine-NO synthase pathway. The objective of this study was to systematically assess the evidence for dietary nitrate intake and improved cardiovascular health from both human and animal studies.

Methods: A systematic literature search was performed according to PRISMA guidelines using key search terms in Medline and EMBASE databases and defined inclusion and exclusion criteria.

Results: Thirty-seven articles were included on humans and fourteen articles on animals from 12,541 screened references. Data on the effects of dietary nitrate on blood pressure, endothelial function, ischaemic reperfusion injury, arterial stiffness, platelet function, and cerebral blood flow in both human and animal models were identified. Beneficial effects of nitrate on vascular health have predominantly been observed in healthy human populations while effects in populations at risk of cardiovascular disease are less clear. Few studies have investigated the long-term effects of dietary nitrate on cardiovascular disease clinical endpoints. In animal studies, there is evidence that nitrate improves blood pressure and endothelial function particularly in animal models with reduced NO bioavailability. Nitrate dose seems to be a critical factor as there is evidence of cross-talk between the two pathways of NO production.

Conclusion: Evidence for a beneficial effect in humans at risk of cardiovascular disease is limited. Furthermore, there is a need to investigate the long-term effects of dietary nitrate on cardiovascular disease clinical endpoints. Further animal studies are required to elucidate the mechanisms behind the observed effects.
Keywords: vegetables, nitrate, nitric oxide, oral microbiome, cardiovascular diseases
Introduction

Cardiovascular disease is the number one cause of death globally and contributes a major burden to public health systems worldwide (1). Several observational cohort studies have found plant-based diets rich in vegetables to be associated with a lower incidence of cardiovascular disease clinical endpoints (2-4). Specific vegetable groups, such as green leafy vegetables, have been shown to be the most beneficial (5-9). There are many bioactive components in green leafy vegetables that may benefit cardiovascular health. One component that has gained research interest in the last decade is nitrate (10).

Nitrate is present in all vegetables at various concentrations; however, the richest sources of nitrate are beetroot and green leafy vegetables (11). Increasing nitrate intake through the diet is one potential strategy to increase nitric oxide (NO) bioavailability (12). NO plays an important role in vascular tone and integrity, and is a vital molecule for cardiovascular health (12). Reduced NO bioavailability has been observed in individuals with cardiovascular disease (13). Strategies to increase NO in healthy individuals and those at risk of cardiovascular disease may reduce cardiovascular-related events in the wider population.

Due to the increased research interest in the vascular benefits of dietary nitrate, the aim of this review is to provide an overview of dietary nitrate as a source of NO, the importance of the oral microbiome in the nitrate-nitrite-NO pathway, and dietary sources of nitrate. We have also systematically compiled evidence to date on the effects of nitrate ingestion on blood pressure, arterial stiffness, endothelial function, platelet function, and cerebral blood flow in human and animal studies. This systematic literature search was conducted using criteria outlined in the PRISMA checklist. Key search terms used in Medline and EMBASE databases are outlined in Supplemental Table 1 and inclusion and exclusion criteria in Supplemental Table 2. The PRISMA flow charts for human studies can be found in
Supplemental Figure 1 and animal studies in Supplemental Figure 2. Articles were excluded if full texts could not be accessed or the articles were not in English.

Two pathways to nitric oxide

Nitric oxide is an important cell signalling molecule critical for vascular homoeostasis (13). A powerful vasodilator, NO relaxes smooth muscle tissue and increases regional blood flow (14). Nitric oxide also inhibits platelet and leukocyte adhesion to the vessel wall, delaying the onset of atherogenesis (15). Nitric oxide is generated through the L-arginine-NOS pathway and the recently described enterosalivary nitrate-nitrite-NO pathway.

L-arginine-NOS pathway

Nitric oxide is synthesised predominantly through the classical L-arginine NO synthase (NOS) pathway (16) which involves three types of NOS isoforms. These include neuronal NOS (nNOS or NOS-1), cytokine-inducible NOS (iNOS or NOS-2), and endothelial NOS (eNOS or NOS-3) (17). Due to the large mass of the endothelium within the body, eNOS is a major contributor to NO production. The regulation of eNOS activity is via intracellular calcium (Ca$^{2+}$) (18) and several signal transduction pathways, including phosphoinoside 3-kinase (PI3K) and adenylate cyclase (AC) pathways (19). An increase in shear stress, cyclic strain or receptor activation of vascular endothelium by biochemical stimuli (bradykinin, acetylcholine, thrombin, adenosine diphosphate, and serotonin) causes a release of Ca$^{2+}$ from intracellular stores, stimulating eNOS activity (17, 20). Phosphorylation of several residues on the eNOS dimer is also an important requirement for activation (19). Equimolar amounts of NO and L-citrulline are produced using L-arginine and molecular oxygen together with tetrahydrobiopterin (BH$_4$) in a complex oxygen-dependent five electron-transfer reaction (18, 21).

Nitric oxide synthesised from L-arginine in the endothelium diffuses across the cell membrane to nearby smooth muscle cells stimulating soluble guanylate cyclase (sGC) (18).
This results in the synthesis of cyclic guanosine monophosphate (cGMP) from guanosine triphosphate (GTP), triggering the relaxation of smooth muscle cells (18). Uncoupling of eNOS, by reduced bioavailability of BH₄ or the substrate L-arginine, can lead to the production of superoxide or H₂O₂ (22). Furthermore, studies have demonstrated that reduced tissue levels of BH₄ and increased superoxide generation are associated with risk factors for atherosclerosis (23-25).

**Nitrate-nitrite-NO pathway**

Historically, nitrate and nitrite have been considered to be environmental pollutants and potential carcinogenic residues in the food chain (26). Now, however, nitrate and nitrite are considered important molecules for cardiovascular health (27).

Vegetables are a major source of nitrate consumed in the human population (28). When nitrate is ingested, it is absorbed in the proximal area of the small intestine (12). Nitrate then enters the bloodstream and mixes with endogenous sources of nitrate (mainly derived from oxidation of NO through the L-arginine-NOS pathway). Approximately 75% of circulating nitrate is excreted by the kidneys. The rest (~25%) is actively taken up by the salivary glands where nitrate is concentrated in saliva and secreted in the oral cavity (29, 30). Nitrate is then reduced to nitrite by facultative anaerobic bacteria found in the deep clefts on the dorsal surface of the tongue (31). The commensal bacteria in the oral cavity use nitrate as an alternative electron acceptor to oxygen during respiration, reducing nitrate to nitrite by nitrate reductases (32). Once swallowed, a proportion of nitrite is rapidly protonated forming nitrous acid (HNO₂) in the acidic environment of the stomach (33). Nitrous acid decomposes further to form NO, having localised benefits (33). This non-enzymatic reduction of nitrite to NO is enhanced by vitamin C and polyphenols (34, 35). The remaining nitrate and nitrite in the stomach enter the small intestine and are absorbed into the bloodstream where they mix with
endogenous forms of nitrate and nitrite (mainly derived from oxidation of NO through the L-arginine-NOS pathway). The one-electron reduction of nitrite to NO in the blood and tissues is catalysed by both enzymatic and non-enzymatic pathways (10). Enzymatic pathways include a number of proteins and enzymes including globins (such as haemoglobin, myoglobin, cytoglobin, and neuroglobin), xanthine oxidoreductase, cytochrome P450, mitochondrial proteins, carbonic anhydrase, aldehyde oxidase and eNOS (10). Non-enzymatic pathways include protons, polyphenols, and vitamin C (10). Both enzymatic and non-enzymatic reductions of nitrite to NO are enhanced during hypoxia and at a low pH (10, 36). Recent evidence suggests that the acidic environment of the stomach plays an important role in the reduction of nitrite to NO (37).

The nitrate-nitrite-NO pathway and the L-arginine-NOS pathway are interconnected through the anions, nitrate and nitrite. Nitrate and nitrite are the oxidation end products of NO metabolism through the L-arginine-NOS pathway but can also be derived from the diet (32). Nitrate and nitrite, derived from the diet and derived as oxidation end products of NO metabolism, are both recycled through the nitrate-nitrite-NO pathway. Both pathways become a storage pool for NO production. Because the L-arginine-NOS pathway requires molecular oxygen to produce NO, nitrite reduction to NO via the nitrate-nitrite-NO pathway may form as a backup system for NO production during hypoxia. A crucial step in the nitrate-nitrite-NO pathway is nitrate to nitrite reduction by the oral microbiome.

The oral microbiome

The oral microbiome is the second most diverse microbial community in the human body comprising 50 – 100 billion bacteria, from over 700 prokaryotic taxa, as well as a fungal and viral flora (38). Disturbances to the composition, and therefore function, of the oral microbiome are thought to play a role in a number of diseases, including cardiovascular
Whether this link is related in part to the nitrate-nitrite-NO pathway is garnering research interest. An important step in the nitrate-nitrite-NO pathway is the reduction of nitrate to nitrite by facultative anaerobic bacteria found in the oral cavity. Reduced oral bacterial nitrate to nitrite reduction, both in the presence and absence of dietary nitrate intake, could have detrimental effects on the circulating NO pool with subsequent vascular effects. In the presence of nitrate intake, interrupting the nitrate-nitrite-NO pathway with an antibacterial mouthwash or spitting out of saliva, prevented the resultant increase in salivary and plasma nitrite and the associated decrease in blood pressure (39, 40). In the absence of dietary nitrate intake, increases in blood pressure with concomitant decreases in salivary and plasma nitrite were observed with daily chlorhexidine based antibacterial mouthwash use in both healthy volunteers (41) and treated hypertensives (42). This could be explained by the fact that nitrate and nitrite, produced as end-products of NO metabolism, are recycled through the nitrate-nitrite-NO pathway back into the circulating NO pool. Thus nitrate to nitrite reduction by the oral microbiome could play a key role in blood pressure control. The influence on other measures of vascular health has yet to be determined.

The fundamental role of the oral microbiome in the nitrate-nitrite-NO pathway and possibly blood pressure control makes understanding all the factors that influence oral nitrate to nitrite reduction an important research area. Indeed, there is evidence of a considerable variation between individuals in the nitrate-reducing capacity of the oral microbiome (43). The first set of factors to consider is the use of anti-bacterial mouthwashes, anti-bacterial toothpastes, and antibiotics. Given the results of the studies described above, the widespread use of daily mouthwash in the general population is of potential concern. The mouthwash used in these studies, however, contained chlorhexidine, a strong antibacterial agent. Different effects have been observed with other types and strengths of antibacterial mouthwashes (44). To date only one study has examined the effect of antibacterial toothpaste, containing triclosan, on oral
nitrate to nitrite reduction (45), with no effect observed. These results need to be confirmed in additional studies examining the effect of mouthwash and toothpaste on oral nitrate reduction. Interestingly, epidemiological studies show that regular tooth brushing and mouthwash use, indicative of good oral hygiene, is associated with a decreased risk of hypertension and cardiovascular disease (46, 47). The effect of antibiotic use on oral nitrate to nitrite reduction has yet to be ascertained.

Other important factors are those inherent to the complex oral microbial community such as bacterial genetics, the presence and influence of other microorganisms and environmental pressures. There are a number of potential nitrate-reducing taxa present in the oral microbiome. Doel et al (48) identified Veillonella spp as the most abundant nitrate-reducing genus followed by Actinomyces, Rothia and Staphylococcus spp (48). Hyde et al (49) confirmed Veillonella spp as the most abundant nitrate-reducing genus present but also detected Prevotella, Neisseria and Haemophilus at a higher abundance than Actinomyces spp.

Nitrate to nitrite reduction by these bacteria is highly variable both within and between bacterial species and needs to be examined in the context of the huge interdependent microbial network in which they exist. This network comprises a heterogeneous microbial community within a biofilm which communicates using a process called quorum sensing. These communities are highly complex, with all members influencing its health and vitality. Interestingly, the presence of nitrite reducers may prevent the accumulation of nitrite in the saliva and as such have a negative influence on the nitrate-nitrite-NO pathway (49).

Microbial nitrate metabolism can also be altered by environmental influences such as pH and oxygen tension. A low pH in an oral microenvironment together with increased nitrate and nitrite concentration, can select for nitrate-reducing bacteria (50). Nitrate-reducing bacteria are facultative anaerobes. A low or no oxygen environment will therefore result in the nitrate reductive pathway being utilised for respiration. Other potential factors influencing nitrate to
nitrite reduction that requires future investigation include host factors such as age, diet, and oral health.

The evidence of the link between oral health and cardiovascular disease being related to the nitrate-nitrite-NO pathway is strongly suggestive. Future studies will need to examine this relationship in the context of the large number of factors that could influence oral nitrate to nitrite reduction.

**Dietary sources of nitrate and nitrite**

Vegetables contribute approximately 80% of dietary nitrate intake in the human population (28, 51-54). Nitrate ingested in the diet can also be derived from other food sources such as fruits, grains, and animal products with the remainder coming from drinking water. Many countries have strict regulations to maintain low levels of nitrate in drinking water due to underlying health concerns, such as methaemoglobinaemia (55). High levels, however, have been detected in private wells in rural areas due to nitrogen-based fertiliser use in agricultural areas (56). Another controversial health concern is the addition of nitrate and nitrite to meat and their potential to form N-nitrosoamines, which are potential carcinogens (29).

Compounds such as polyphenols, vitamins C and E and other antioxidants inhibit the formation of N-nitrosoamines (56). These compounds are abundant in vegetables. A large number of countries have also set maximum levels for nitrate in vegetables, particularly for lettuce and spinach, which are known to accumulate high amounts of nitrate (57). These maximum levels vary across harvest period, being higher in winter and if grown under cover, and lower in summer and if grown in open air (57).

Dietary nitrite, on the other hand, contributes only a small amount to human exposure and is mainly consumed from animal-based foods such as cured meats and bacon (52). Nitrite is added to these products as a preservative and to enhance taste and appearance (52). Although a small amount of nitrite is consumed from these food sources, the majority of nitrite
exposure (70-90%) is derived from the in vivo conversion of nitrate to nitrite through endogenous pathways (58).

The nitrate content of vegetables depends on many different factors including the biological properties of plants, fertiliser use, soil conditions, sun exposure, and cooking and storage methods. The biological properties of plants can influence the amount of nitrate that accumulates in that plant. For example, nitrate accumulates in different parts of the plants with the leaf and stem having the highest concentrations, and the bulb and fruit having the lowest (28). In our recently developed reference database for assessing dietary nitrate in vegetables (11), leafy vegetables were found to have the highest nitrate content, with Chinese flat cabbage and arugula containing the highest concentrations of nitrate (3000 mg/kg fresh weight). Corn, mushroom, and peas had the lowest nitrate content (<50 mg/kg fresh weight).

Nitrate concentration in vegetables also differs between varieties. For example, Chinese lettuce has a 3-fold higher nitrate value than iceberg lettuce (11). Nitrogen-based fertilisers enhance the growth of plants, and thus, have an impact on how much nitrate accumulates in vegetables. Nitrate located in the soil of a growing vegetable is transported via the plant xylem system to the leaves of the vegetables (52). As organic vegetables tend to be grown in fertilisers containing less nitrogen, by comparison conventionally grown vegetables tend to accumulate higher nitrate levels (11, 59).

Other factors such as handling, storage, and processing, as well as temperature and light intensity can also influence the amount of nitrate in vegetables (52). Higher nitrate levels are observed in vegetables grown in winter compared to summer, and vegetables grown under cover contain higher nitrate levels than those grown outdoors in the same season and the same region (11, 52).

Storage in ambient temperature can also reduce the nitrate content of fresh vegetables. Under refrigerated and frozen storage conditions nitrate levels appear to be unaffected (52).
Endogenous nitrate reductase activity and the amount of bacterial contamination due to post-harvest storage and wilting processes reduce nitrate and subsequently increase nitrite in fresh vegetables (52). Being water soluble, nitrate is also reduced with washing and cooking methods by approximately 10-15% and 50%, respectively (52). As nitrate is also found in the skin of vegetables, peeling of the skin can also reduce nitrate levels by roughly 20-34% (52).

**Nitrate ingestion and its effects on vascular function**

Dietary nitrate is now considered an important alternative source of NO. Human and animal studies to date have focused on the effects of nitrate ingestion on blood pressure, arterial stiffness, endothelial function, platelet function, and cerebral blood flow, as discussed below.

A summary of the beneficial effects of nitrate ingestion on these cardiovascular-related outcomes in human and animal studies is shown in **Figure 1**. Benefits of nitrate ingestion on exercise performance will not be covered in this review.

**Blood pressure**

Evidence that decreased NO production was associated with hypertension raised the possibility that nitrate, through the nitrate-nitrite-NO pathway, could partially account for the blood pressure lowering effects of green leafy vegetables. Randomised controlled trials such as the Dietary Approaches to Stop Hypertension (DASH) trial have been shown to reduce blood pressure (60). It has been suggested that the high nitrate content of the DASH diet contributes to the blood pressure lowering effects observed (28). The DASH diet has been estimated to include as much as 1,222 mg (19.7 mmol) of nitrate per day (28). This amount can, however, differ by as much as 700% due to the wide variation of nitrate in vegetables (28). An Acceptable Daily Intake (ADI) of 3.7 mg nitrate per kg body weight was set by the Joint Food and Agricultural Organisation and World Health Organisation (52). For an average person weighing 70 kg, this is calculated to be 259 mg of nitrate. The DASH diet can provide up to 500% more nitrate than this ADI.
The DASH diet is associated with reductions of 4.5 mmHg in systolic blood pressure (SBP) (61). This blood pressure reduction is similar to that seen in a meta-analysis demonstrating that consumption of inorganic nitrate and nitrate-rich beetroot juice is associated with a SBP reduction of 4.4 mmHg (62). There is now substantial evidence from human intervention trials to demonstrate blood pressure reductions with short-term intake of dietary nitrate in healthy populations (62). However, the effects of chronic nitrate intake on blood pressure in older populations and populations at risk of cardiovascular disease remain uncertain (50, 63-68).

**Human studies**

Our systematic literature search revealed 27 acute studies (≤24 hours) (Table 1) (40, 50, 63, 69-85) and 15 chronic studies (>1 day) (Table 2) (50, 65-68, 86-93) in 32 publications investigating the effects of nitrate ingestion on blood pressure. Beetroot juice was the most common nitrate source used in both acute and chronic studies. Twenty-four hour ambulatory blood pressure (24-hour ABP), the preferred diagnostic method for assessing hypertension (94, 95), was used in 10 studies (65-68, 77, 80-82, 87, 90). Clinic blood pressure was used in 34 studies (40, 50, 63, 65, 67, 69-76, 78, 79, 83-93) and four studies used home blood pressure monitoring (66, 67, 87, 90).

**Acute studies**

The acute effects of nitrate ingestion on blood pressure were investigated between 2-24 hours with nitrate doses ranging from 68-1488 mg (1.1-24 mmol) (Table 1). Five studies showed a significant reduction in SBP only (78, 82-85) and four studies showed a significant reduction in only diastolic blood pressure (DBP) (71, 77, 79, 80). Eleven studies showed significant reductions in both SBP and DBP (40, 50, 71, 72, 81, 85). Acute reductions in SBP ranged from 2.7 to 22.2 mmHg and 2.6 to 23.6 mmHg for DBP. Reductions in blood pressure were seen across the entire range of nitrate doses investigated and in subjects that were healthy (40,
71, 72, 77, 78, 80-85), overweight (79), and hypercholesterolaemic (50). Sample sizes of these populations ranged from 6 to 67 participants. Blood pressure reductions were not seen in seven studies (63, 69, 70, 73-76). These populations consisted of subjects that were healthy (69, 70, 73-76) and subjects with heart failure (63). Sample sizes of these populations ranged from 5 to 40 participants.

**Chronic studies**

The chronic effects of nitrate ingestion on blood pressure were investigated in 15 studies from 3 to 42 days (6 weeks) with nitrate doses ranging from 155-1104 mg/d (2.5-17.8 mmol/d) (Table 2). Three studies showed a significant reduction in SBP (88-90) and three other studies showed a significant reduction in DBP (86, 92, 93). Only one study showed a significant reduction in both SBP and DBP (87). In total, seven studies demonstrated a significant reduction in blood pressure. It is worth noting, the study conducted by Ashworth et al (88) was not clear whether the significant reductions in blood pressure were acute or chronic as the subjects were advised to eat high nitrate vegetables 2-3 hours before blood pressure was taken on the final day. Reductions in SBP ranged from 4.0 to 8.1 mmHg and reduction in DBP ranged from 2.4 to 12 mmHg with nitrate doses ranging from 165-1104 mg/d (2.7-17.8 mmol/d). Reductions in blood pressure were seen in one study using 24-hour ABP monitoring (87), two studies using home blood pressure (87, 90) and six studies using clinic blood pressure (86-89, 92, 93). Blood pressure reductions were seen in subjects that were healthy (86, 88, 92, 93), at moderate cardiovascular risk (89), older and overweight (90), and grade 1 hypertensive (treated and untreated) (87). These studies were a mix of young (mean age <37 y) (86, 88, 92, 93) and older cohorts (mean age >56 y) (87, 89, 90). Most studies demonstrating reductions in blood pressure were of low sample size (n range 6-25), except Kapil et al (87), which had a sample size of n=64.
Blood pressure reductions were not seen in eight studies (50, 65-68, 91). These populations consisted of subjects that were older (91), pre-hypertensive (67), treated hypertensive (66), overweight and obese (65), type 2 diabetic (68), and hypercholesterolemic (50). These populations were all older adult populations (mean age >60 y) with larger sample sizes (n range 27-67) (50, 65-68), apart from one study which had a sample size of n=8 (91).

There is now clear and convincing evidence that nitrate reduces blood pressure within hours of ingestion. The evidence of chronic ingestion of nitrate on blood pressure is less clear. Studies suggest that chronic intake of nitrate lowers blood pressure in young healthy individuals; however, these blood pressure lowering effects are not seen in older individuals and individuals at risk of cardiovascular disease. Recent evidence suggests possible interactions between sulphate and nitrate which may explain some of these inconsistencies (96). However, research is in need to further investigate this theory.

**Animal studies**

We identified 17 studies, in 12 publications, that assessed the effect of nitrate supplementation on blood pressure in an animal model (Table 8). Nitrate sources included NaNO₃ (n=10), KNO₃ (n=1), and Mg(NO₃)₂ (n=1) supplemented drinking water. Nitrate doses ranged from 0.1-4.27 mmol/kg/d and treatment time ranged from 1 week to 12 months. The number of animals in each treatment group ranged from 5 to 23. Nine studies reported a decrease in blood pressure after nitrate supplementation and five studies reported no change in blood pressure. Only one study reported an increase in blood pressure; Carlstrom et al reported a significant increase in mean arterial pressure (MAP) in healthy rats after 8 weeks of nitrate supplementation (1 mM/kg/d) (97). In the same study, a decrease in blood pressure was seen with a 0.1 mM dose of nitrate. In two studies where high blood pressure was induced, either by the use of spontaneously hypertensive rats (98, 99) or by administration of a high-fructose diet (100), nitrate supplementation prevented the increase in blood pressure.
observed in the control group. In a study by Henzel et al, a decrease in MAP and SBP was only seen in old (22 months) Sprague-Dawley rats and not in young (3 months) rats (101). It is important to note that although both groups were receiving the same concentration of nitrate in their drinking water, the younger rats were receiving a much higher dose of nitrate (776 µmol/kg/d vs 290 µmol/kg/d), due to their higher water intake and lower body weight. In a study by Khalifi et al, a decrease in SBP was only seen in diabetic Wistar rats and not their healthy counterparts (102). This may be due to positive effects of nitrate supplementation on NO status and oxidative stress, which would have been compromised in the diabetic rats but not the healthy rats. Other studies have shown that higher doses of nitrate can reduce blood pressure in animal models that have been shown to have reduced NO bioavailability (100, 101, 103).

Endothelial function

The endothelium lines the entire vascular system and plays an essential role in the maintenance of vascular homoeostasis (104). Dysfunction of the endothelium has been identified in the development of atherosclerotic-related diseases (105). Flow-mediated dilatation (FMD) via non-invasive ultrasound measures the endothelial function of the brachial artery (106, 107). It is the gold standard method for assessing conduit artery endothelial function (106) and is significantly associated with cardiovascular disease events (108, 109). It has previously been shown from a meta-analysis of 14 prospective cohort studies that the risk of experiencing a cardiovascular event is reduced by 13% for every 1% higher in FMD (110). The degree of endothelial function is determined by the change in brachial artery diameter before and after a shear stress stimulus, induced by reactive hyperaemia (108). In the forearm vasculature, FMD provides a measure of endothelium-derived NO bioavailability (111).

Human studies
Our systematic literature search revealed seven acute studies (≤24 hours) (Table 3) (50, 75, 76, 79, 83, 84, 112) and four chronic studies (>1 day) (Table 4) (50, 68, 87, 89) in 10 publications investigating the effects of nitrate ingestion on FMD. Beetroot juice was the most common nitrate source used in both acute and chronic studies.

**Acute studies**

The acute effects of nitrate ingestion on FMD were investigated between 1.5-4 hours with nitrate doses ranging from 6-772 mg (0.1-12.4 mmol) (Table 3). The lower nitrate dose in this range was estimated using the global average body weight of 62 kg as no average body weight was reported in this study (75). Six studies demonstrated a significant improvement in FMD (50, 75, 76, 79, 83, 112) and one study demonstrated no effect (84). Improvements in FMD ranged from 0.5 to 4.0% were seen across the entire range of nitrate doses investigated. Beetroot juice was also found to attenuate the postprandial impairment of FMD following a high-fat meal (79). Improvements in FMD were seen in mainly healthy populations (75, 76, 83, 112). Other populations where improvements in FMD were seen included hypercholesterolaemic (50) and overweight (79) subjects. These healthy and at risk populations consisted of three studies in younger cohorts (mean age ≤27 y) (75, 76, 112) and three studies in older cohorts (mean age >45 y) (50, 79, 83) with an overall sample size ranging from 5 to 67. No effects on FMD were observed in one healthy population of 14 participants aged 28 y (84).

**Chronic studies**

The chronic effects of nitrate ingestion on FMD were investigated ranging from 14 to 42 days (2 to 6 weeks) with nitrate doses ranging from 375 to 577 mg/d (6.0 to 9.3 mmol/d) (Table 4). The higher nitrate dose in this range was estimated using the global average body weight of 62 kg as no average body weight was reported in this study (89). Three studies showed a significant improvement in FMD (50, 87, 89) and one study had no effects (68). In particular,
Rammos et al (89) demonstrated dietary nitrate reversed vascular dysfunction in older adults with moderately increased cardiovascular risk. Improvements in FMD ranged from 0.5 to 1.1% and were seen across the entire range of nitrate doses investigated. Increases in FMD (~1%) were seen in two studies (50, 87) using similar nitrate doses from beetroot juice (375 mg/d and 398 mg/d). Ingestion of a slightly higher nitrate dose of 577 mg/d (9.3 mmol/d) using sodium nitrate showed a 0.5% improvement (89). Improvements in FMD were seen in subjects with hypercholesterolemia (50), treated and untreated hypertension (87), and moderate cardiovascular risk (89). All populations were older adult populations (mean age >50 y) with large sample sizes (>60), except one study that had a sample size of 11 (89). No effects on FMD were observed after 14 days of nitrate ingestion (beetroot juice) in 27 subjects with type 2 diabetes mellitus (68).

Animal studies
Numerous studies have reported that blood vessels with a damaged endothelium have impaired vasorelaxation in response to acetylcholine (ACh) (Table 8) (113, 114). We identified three animal studies, from two publications, investigating the effects of dietary nitrate supplementation on endothelial function (97, 115). Bakker et al (115) demonstrated that although supplementation with very high dose nitrate (10 mmol/kg/d) had no effect on Ach-mediated vessel relaxation in a mouse model of atherosclerosis, low (0.1 mmol/kg/d) and moderate (1 mmol/kg/d) dose nitrate supplementation significantly improved the endothelial dysfunction associated with this mouse model. In addition, Carlstrom et al (97) reported that dietary supplementation with a high dose of nitrate (1 mmol/kg/d) was associated with attenuated acetylcholine-mediated vasorelaxation. These observations are in support of the theory proposed by Carlstrom et al that there is cross-talk between the two pathways of NO production. They suggest that high doses of dietary nitrate may inhibit production of NO through the L-arginine-NOS pathway, leading to a net decrease in the
amount of NO reaching the smooth muscle cells of the blood vessel (97). Although Bakker et al showed improvements with a 1 mmol/kg/d dose of nitrate and Carlstrom et al reported no improvements with the same dose, the animal model used is likely an important factor as the Apolipoprotein-E knock-out mice used in the study by Bakker et al (115) have reduced NO bioavailability.

Ischaemic reperfusion injury

Ischaemic reperfusion injury is tissue damage caused by a period of ischemia or lack of oxygen. Lack of oxygen during an ischaemic period results in inflammation and oxidative damage leading to microvascular dysfunction (116). Local and systemic tissue ischemia remains the major cause of death from cardiovascular disease (1). As the nitrate-nitrite-NO pathway is enhanced in times of hypoxia, this pathway may provide a back up to the classical L-arginine-NO synthase pathway.

Human studies

Our systematic literature search revealed three acute studies (two publications) investigating the effects of nitrate ingestion on ischaemic reperfusion injury (Table 5) (40, 85). Beetroot juice was the most common nitrate source used. The acute effects of nitrate ingestion on ischaemic reperfusion injury were investigated between 2-3 hours with nitrate doses ranging from 341-1488 mg (5.5-24 mmol) (Table 5). Benefits were also seen in all studies where beetroot juice (40, 85) and potassium nitrate (85) attenuated ischaemia reperfusion-induced endothelial dysfunction measured using FMD. Improvements were seen in young (mean age <28 y), healthy populations (40, 85) with an overall sample size ranging from 10 to 12.

Animal studies

We found only one study describing the effects of dietary nitrate supplementation on ischaemia-induced revascularisation in an animal model (Table 8). In a study by Hendgen-Cotta et al, mice were treated with either nitrate (1 g/L NaNO₃ in drinking water) or NaCl
(control) for 14 days (117). Perfusion recovery in the ischaemic hind limb was significantly improved in mice treated with nitrate compared with controls via a significant increase in capillary density. These results suggest that dietary nitrate supplementation may represent a novel strategy to enhance ischaemia-induced revascularization.

**Arterial stiffness**

Pulse wave velocity (PWV) is a measure of aortic stiffness and is a strong predictor of cardiovascular events (118-120). Pulse wave velocity is recognised as the most simple, non-invasive, robust and reproducible technique to determine arterial stiffness and is considered the gold-standard measurement of arterial stiffness (121). Pulse wave velocity measures arterial stiffness by dividing the estimated distance between the carotid and femoral arteries by the pulse transit time, the time delay between the carotid and femoral waveforms. A tonometer is used to capture the carotid waveform and a cuff is placed around the femoral artery to capture the femoral waveform. Augmentation index (AIx) is another measure of arterial stiffness which provides a composite measure of elastic plus muscular artery stiffness and wave reflection. Augmentation index has also been shown to be an independent predictor of future cardiovascular disease events (122).

**Human studies**

Our systematic literature search revealed seven acute studies (≤24 hours) (50, 70, 72, 78-80, 84) and 5 chronic studies (>1 day) (50, 65, 67, 87, 89) in 10 publications investigating the effects of nitrate consumption on arterial stiffness (Table 6). Beetroot juice was the most common nitrate source used in both acute and chronic studies.

**Acute studies**

The acute effects of nitrate ingestion on arterial stiffness were investigated between 2-6 hours with nitrate doses ranging from 68-583 mg (1.1-9.4 mmol) (Table 6). Three studies demonstrated a significant decrease in arterial stiffness (50, 72, 84) and four studies
demonstrated no effect (70, 78-80). A significant decrease of 0.3 m/s in PWV was observed in two studies (50, 84) with a nitrate dose of 375 mg (6 mmol) from beetroot juice (50) and 496 mg (8 mmol) from potassium nitrate (84). The study by Velmurugan et al (50) consisted of a large sample size of 67 hypercholesterolaemic men and women with a mean age of 53 y, whereas the study by Bahra et al (84) consisted of a smaller sample of 14 healthy individuals with a mean age 28 y. Hughes et al (72) demonstrated a reduced AIx in young, but not old, adults following a nitrate dose of 583 mg (9.4 mmol). No effect was seen in four studies with nitrate doses ranging from 68-500 mg (1.1-8.1 mmol) using beetroot juice (70, 79), beetroot-enriched bread (80), and spinach (78). These studies consisted of healthy (70, 78, 80) and overweight (79) subjects.

Chronic studies

The chronic effects of nitrate ingestion on arterial stiffness were investigated from 7 to 42 days (1 to 6 weeks) with nitrate doses ranging from 300-600 mg/d (4.8-9.7 mmol/d) (Table 6). Three studies demonstrated a significant decreased in arterial stiffness after nitrate ingestion (50, 87, 89) and two studies demonstrated no effect (65, 67). Studies found a significant decrease of 0.2-1.2 m/s in PWV with nitrate doses ranging from 375-577 mg/d (6-9.3 mmol/d) using beetroot juice and sodium nitrate (577 mg/d was estimated using the global average body weight of 62 kg as no average body weight was reported in this study (89)). The populations where an effect was observed had moderate cardiovascular risk (89), untreated and treated hypertension (87), and hypercholesterolemia (50). No effect was seen in two studies with nitrate doses of 300 mg/d (4.8 mmol/d) from green leafy vegetables (67) and 600 mg/d (9.7 mmol/d) from beetroot juice (65); populations that were overweight and obese (65) and pre-hypertensive (67). It has been demonstrated that for every 3.4 m/s in increase in PWV, the risk of experiencing a cardiovascular event is increased by 17% (118). Therefore, a
decrease of 0.2-1.2 m/s in PWV is likely to provide a small but significant reduction in the risk of experiencing a cardiovascular disease event.

**Animal studies**

Upon search of the literature, we found no animal studies investigating the effects of dietary nitrate supplementation on arterial stiffness.

**Platelet function**

Platelets play a major role in the acute complications of atherosclerosis in the late stages of the disease, which can subsequently lead to atherosclerotic-related events (123). Nitric oxide has been shown to inhibit platelet aggregation and adhesion to the endothelial wall (124) and there is now evidence to suggest dietary nitrate may repress platelet reactivity.

**Human studies**

Our systematic literature search identified five acute studies (≤24 hours) (40, 125, 126) and one chronic study (>1 day) (50), in four publications, investigating the effects of nitrate intake on platelet function (Table 7). Potassium nitrate was the most common nitrate source used in acute studies whilst beetroot juice was used in the chronic study.

**Acute studies**

The acute effects of nitrate ingestion on platelet function were investigated between 2.5-3 hours with nitrate doses between 31-1054 mg (0.5-17 mmol) (Table 7). All five studies demonstrated reductions in platelet aggregation and reactivity (40, 125, 126). Velmurugan et al (125) demonstrated that nitrate ingestion decreased platelet reactivity in healthy males, but not in healthy females. This was observed with both beetroot juice (192 mg or 3.1 mmol) and potassium nitrate (496 mg or 8 mmol). Further studies using beetroot juice (1054 mg or 17 mmol) (40) and potassium nitrate (31 mg and 124 mg or 0.5 and 2 mmol) (126) demonstrated reductions in platelet aggregation. All cohorts consisted of young healthy populations and
were of small sample sizes (n<25). Further acute studies are needed to replicate these findings in older adult populations at risk of developing cardiovascular disease.

**Chronic studies**

The chronic effects of nitrate ingestion on platelet function were investigated in only one study (Table 7) (50). Velmurugan et al (50) demonstrated a reduction in platelet-monocyte aggregates after 42 days of daily beetroot juice ingestion with a nitrate dose of 375 mg/d (6 mmol/d). This study had a large sample size (n=67) of older male and female adults aged 53 y with hypercholesterolemia. There is a strong need for further chronic studies to investigate the effects of nitrate ingestion on platelet function in healthy populations and to replicate findings in older adult populations at risk of cardiovascular disease.

**Animal studies**

Only one animal study has been published investigating the effects of dietary nitrate supplementation on platelet function (Table 8). In this study, wild-type C57BL/6 mice were supplemented with 1 g/L NaNO₃ in their drinking water for 1 week, placed on a low nitrate diet or continued on standard mice chow (control) (127). Platelet aggregation was significantly decreased in the group supplemented with nitrate and was significantly increased in the group on the low nitrate diet, in comparison to the control group. These findings demonstrate that manipulation of nitrate levels in blood, via supplementation or dietary restriction, could affect platelet function in mice, although further studies are required to corroborate this finding.

**Cerebral blood flow**

The effect of dietary nitrate on cerebral blood flow has been investigated in several studies due to the observed effects of dietary nitrate on vasodilation and increases in blood flow. Diminished blood flow to the brain is likely to contribute to the pathophysiological processes underlying vascular cognitive impairment (128).
**Human studies**

Our systematic literature search identified one acute study (≤24 hours) (129) and one chronic study (>1 day) (130) in two publications investigating the effect of nitrate ingestion on cerebral blood flow (**Table 9**). Sodium nitrate and a high nitrate diet were used as nitrate sources.

**Acute studies**

Presley et al (129) demonstrated consuming a high nitrate diet (769 mg or 12.4 mmol of nitrate) over a 24 hour period increased regional cerebral perfusion in frontal lobe white matter, in older adults with a mean age of 75 y (**Table 9**). This was particularly evident in the dorsolateral prefrontal cortex and anterior cingulate cortex. In the same study, however, the acute effects of a high nitrate diet did not modify global cerebral perfusion.

**Chronic studies**

Aamand et al (130) demonstrated no effects after 3 days of sodium nitrate ingestion (477 mg/d or 7.7 mmol/d of nitrate, based on study mean weight of 77kg) on cerebral blood flow in 20 healthy men (**Table 9**).

**Animal studies**

No animal studies investigating the effects of dietary nitrate supplementation on blood flow were found.

**Summary: nitrate ingestion and its effects on vascular function**

Human intervention studies have now demonstrated ingestion of nitrate lowers blood pressure and improves endothelial function. These studies are predominantly in healthy populations and are of short duration. It is yet to be established whether nitrate ingestion has the same effects in populations at higher risk of cardiovascular disease as few studies have been conducted and findings are inconsistent. Further research is also needed to understand the long-term effects of nitrate intake on cardiovascular clinical endpoints.
Epidemiological evidence

Epidemiological studies have found plant-based diets rich in vegetables are associated with lower rates of cardiovascular disease (2, 4, 131-136). In particular, cohort studies have shown specific vegetable groups high in nitrate, such as green leafy vegetables, to be most beneficial (6-9). The exact mechanisms for the protective effects shown in these studies are still unknown. The Mediterranean diet (3, 137), the DASH diet (60, 138) and a vegetarian diet (139, 140), all rich in vegetables, have been shown to be particularly beneficial towards cardiovascular health. These diets are likely to contain substantially higher amounts of nitrate than the average Western diet. Thus, nitrate is one possible candidate for explaining cardiovascular health benefits seen with higher vegetable intakes (141).

There are very few observational epidemiological studies investigating nitrate intake and cardiovascular-related health outcomes (Table 10). Although databases have been established to calculate the nitrate intake in observational epidemiological studies (142-144), there was a strong need for a more comprehensive database with compiled up-to-date data. Our recently developed database on the nitrate content of vegetables (11) now gives researchers the opportunity to conduct more observational epidemiological studies with an adequate assessment of nitrate intake.

To date, there have been two articles published utilising the nitrate content of vegetables database (11). We have demonstrated nitrate intake to be inversely associated with atherosclerotic vascular disease mortality in a cohort of older adult women (mean age 75 ± 3 y) (53). In comparison to lower intakes of nitrate from vegetables <53 mg/d (median 39 mg/d), the inverse relationship with atherosclerotic vascular disease mortality plateaued at intakes of 53-76 mg/d (median 63 mg/d) (53). In the same cohort of older adult women, we also observed an inverse relationship between nitrate intake from vegetables and common carotid artery intima-media thickness, as well as ischaemic cerebrovascular disease events
The inverse relationship with ischaemic cerebrovascular disease events also plateaued at intakes of 53-76 mg/d (median 63 mg/d) (54).

Prior to these studies being published, the Tehran Lipid and Glucose Study reported on the relationship between consumption of nitrate-containing vegetables and risk of hypertension (145) and chronic kidney disease (CKD) (146), both risk factors for cardiovascular disease. These studies investigated nitrate intake by assessing whole vegetables containing nitrate. The authors further categorised nitrate-containing vegetables into low-nitrate, medium-nitrate and high-nitrate vegetables. It is worth noting that these studies essentially investigated whole vegetables and then different types of vegetables according to their nitrate levels and not nitrate as a separate entity. It is, however, difficult to separate nitrate intake from vegetable intake as the two can be highly correlated; as we have previously demonstrated ($r=0.75$, $P<0.001$) (53). Golzarand et al (145) found a significant inverse association between the intake of nitrate-containing vegetables and 3-year incidence of hypertension in the highest tertile compared with the lowest tertile of nitrate-containing vegetables. There were no significant associations observed between low-nitrate, medium-nitrate and high-nitrate containing vegetables and 3-year risk of hypertension. As no associations were found between categories of nitrate-containing vegetables, it is difficult to determine whether the inverse association demonstrated with total nitrate-containing vegetables is due to vegetable intake alone. This cohort consisted of 1,546 Iranian men and women (57% women), aged 38±12 years, without hypertension at baseline. In the same cohort, Mirmiran et al (146) found that the highest compared to the lowest tertile of nitrate-containing vegetables was associated with a lower estimated glomerular filtration rate and a higher prevalence of CKD at baseline. This could be a demonstration of reverse causality bias where the diagnosis of chronic disease has altered dietary intake. There was no association with the occurrence of CKD after 3 years of follow-up after excluding patients with CKD at baseline. Lastly, Bahadoran et al
recently reported findings on the potential effects of dietary nitrate and nitrite on the occurrence of type 2 diabetes in the same cohort of Iranian men and women (Tehran Lipid and Glucose Study). Bahadoran et al (147) reported on 2,139 adults free of type 2 diabetes at baseline with a median follow-up of 5.8 y. Nitrate and nitrite values were determined from a recent survey conducted on frequently consumed food items among Iranians (148). Nitrate and nitrite concentrations of 87 foods were determined using spectrophotometric methods. The authors found no associations between nitrate intake and the risk of developing type 2 diabetes. However, the authors demonstrated an increased risk of type 2 diabetes among participants with higher intakes of total and animal-based nitrite in the presence of low vitamin C intake. The same was not observed in participants with high intakes of vitamin C (>108 mg/d) (147), suggesting that diets high in vitamin C may counteract the suggested adverse effects of nitrite on type 2 diabetes. However, higher intakes of total and animal-based nitrite in the presence of low vitamin C intake may be a marker of an unhealthy diet and lifestyle that may also be associated with a higher prevalence of type 2 diabetes.

There is a lingering concern that nitrate and nitrite may form cancerous compounds such as nitrosamines (10). The majority of epidemiological studies to date have investigated relationships between nitrate intake and cancer outcomes. A report compiled by the International Agency for Research on Carcinogenicity concluded “Ingested nitrate or nitrite under conditions that result in endogenous nitrosation is probably carcinogenic to humans (Group 2A)” (149). Conditions that increase endogenous nitrosation are complex but could involve interactions between the amount of nitrate and nitrite consumed, stomach acidity, smoking status, medical conditions and the low intakes of nutrients that are likely to decrease the potential for nitrosation such as polyphenols, vitamin C and vitamin E (56). Now that there is a comprehensive database on the nitrate content of vegetables available, researchers have the opportunity to further investigate the associations between chronic
intake of nitrate and health outcomes. Further research is needed to elucidate the relationships amongst different populations including young vs. older age groups, low vs. higher background nitrate intakes, and healthy vs. at risk populations.

Conclusion

There is now strong evidence to suggest that dietary nitrate derived from vegetables can reduce blood pressure and other markers of vascular function in healthy populations. There is a need for further research to investigate whether similar effects are observed in populations at risk of developing cardiovascular disease. Few studies have investigated the long-term effects of dietary nitrate on cardiovascular disease clinical endpoints; large observational follow-up studies are required to address this. Further animal studies are required to elucidate the mechanisms behind the observed beneficial effects. Increasing nitrate in the diet through the consumption of nitrate-rich vegetables may prove to be an achievable and cost effective way to reduce the risk of cardiovascular disease.
ACKNOWLEDGEMENTS

Conflict of interest statement: All authors have no potential conflict of interest to report.

Statement of authorship: LCB, NPB, AHL, NCW, RLP, JRL, AD, KDC, JMH and CPB designed research; LCB, NPB, AHL and CPB conducted research; LCB, NPB, JMH and CPB wrote paper; LCB, NPB and CPB had primary responsibility for final content; all authors critically revised the manuscript for important intellectual content. All authors read and approved the final manuscript.
REFERENCES


52. European Food Safety Authority. Opinion of the scientific panel on contaminants in the food chain on a request from the European Commission to perform a scientific risk assessment on nitrate in vegetables. The EFSA Journal 2008;689:1-79.


49


152. Carlström M, Larsen FJ, Nyström T, Hezel M, Borniquel S, Weitzberg E, Lundberg JO. Dietary inorganic nitrate reverses features of metabolic syndrome in endothelial


Table 1. Intervention studies investigating the acute effects of inorganic nitrate on blood pressure in humans.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Blood pressure effect</th>
<th>Nitrate source</th>
<th>Nitrate dose</th>
<th>Duration</th>
<th>Subjects</th>
<th>Screening/baseline blood pressure</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>↓ Clinic SBP</td>
<td>Beetroot juice</td>
<td>583 mg (9.4 mmol)</td>
<td>3 h</td>
<td>Young: 25±4 y (10 M; 3 F) Old: 64±5 y (9 M; 3 F) Healthy</td>
<td>Optimal/normal</td>
<td>Hughes 2016 (72)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic DBP</td>
<td>Sodium nitrate</td>
<td>800 mg (12.9 mmol)</td>
<td>5 h</td>
<td>28±1 y (11 M; 7 F) Healthy</td>
<td>Optimal/Normal</td>
<td>Jonvik 2016 (71)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic SBP</td>
<td>Beetroot juice</td>
<td>375 mg (6 mmol)</td>
<td>3 h</td>
<td>Nitrate: 53±10 y (12 M; 21 F) Placebo: 53±12 y (12 M; 22 F) Hypercholesterolaemic</td>
<td>Normal</td>
<td>Velmurugan 2016 (50)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic DBP</td>
<td>Spinach</td>
<td>220 mg (3.5 mmol)</td>
<td>3.5 h</td>
<td>58.8±7.6 y (6 M; 20 F) Healthy</td>
<td>Optimal</td>
<td>Liu 2013 (78)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic SBP</td>
<td>Beetroot juice</td>
<td>500 mg (8.1 mmol)</td>
<td>2 h</td>
<td>61±7 y (20 M) Overweight</td>
<td>High-normal</td>
<td>Joris 2013 (79)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic SBP</td>
<td>Spinach</td>
<td>182 mg (2.9 mmol)</td>
<td>3.3 h</td>
<td>47±14 y (6 M; 24 F) Healthy</td>
<td>Optimal</td>
<td>Bondonno 2012 (83)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic SBP</td>
<td>Potassium nitrate</td>
<td>496 mg (8 mmol)</td>
<td>3 h</td>
<td>28±2 y (14) Healthy</td>
<td>Optimal</td>
<td>Bahra 2012 (84)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic SBP</td>
<td>Potassium nitrate</td>
<td>1488 mg (24 mmol)</td>
<td>24 h</td>
<td>23±1 y (8 M; 12 F) Healthy</td>
<td>Optimal</td>
<td>Kapil 2010 (85)</td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>Potassium Nitrate</td>
<td>Administration Time</td>
<td>Clinic SBP</td>
<td>Clinic DBP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------------</td>
<td>---------------------</td>
<td>------------</td>
<td>------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potassium nitrate</td>
<td>248 mg, 744 mg</td>
<td>3 h</td>
<td>29±2 y (6)</td>
<td>Healthy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4 mmol, 12 mmol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beetroot juice</td>
<td>341 mg</td>
<td>3 h</td>
<td>25±1 y (9)</td>
<td>Normal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(5.5 mmol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beetroot juice</td>
<td>1395 mg</td>
<td>24 h</td>
<td>26±5 y (9 M; 5 F)</td>
<td>Optimal</td>
<td>Webb 2008 (40)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(22.5 mmol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beetroot bread</td>
<td>68 mg</td>
<td>6 h</td>
<td>34±9 y (14 M)</td>
<td>Normal</td>
<td>Hobbs 2014 (77)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.1 mmol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beetroot bread</td>
<td>68 mg</td>
<td>6 h</td>
<td>31±2 y (23 M)</td>
<td>Normal</td>
<td>Hobbs 2013 (80)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.1 mmol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beetroot juice</td>
<td>0-707 mg</td>
<td>24 h</td>
<td>31±3 y (18 M)</td>
<td>High-normal</td>
<td>Hobbs 2012 (81)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0-11.4 mmol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beetroot juice</td>
<td>99 mg</td>
<td>24 h</td>
<td>25±1 y (14 M)</td>
<td>High-normal</td>
<td>Coles and Clifton 2012 (82)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.6 mmol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red beetroot-enriched bread</td>
<td>112 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.8 mmol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beetroot juice</td>
<td>465 mg</td>
<td>24 h</td>
<td>43±3 y (15 M; 15 F)</td>
<td>High-normal</td>
<td>Coles and Clifton 2012 (82)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(7.5 mmol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No effect on clinic BP</td>
<td>No effect on clinic BP</td>
<td>Beetroot gel</td>
<td>391 mg (6.3 mmol)</td>
<td>3 h</td>
<td>27±2 y (4 M; 1 F)</td>
<td>Optimal</td>
<td>da Silva 2016 (73)</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------</td>
<td>--------------</td>
<td>-------------------</td>
<td>-----</td>
<td>-----------------</td>
<td>---------</td>
<td>-------------------</td>
</tr>
<tr>
<td>No effect on clinic BP</td>
<td>Beetroot juice</td>
<td>341 mg (5.5 mmol)</td>
<td>2.5 h</td>
<td>Nitrate: 21±1 y (5 M; 15 F)</td>
<td>Placebo: 21±1 y (7 M; 13 F)</td>
<td>Healthy</td>
<td>Optimal Wightman 2015 (74)</td>
</tr>
<tr>
<td>No effect on clinic BP</td>
<td>Sodium nitrate</td>
<td>0.1-10 mg/kg body weight</td>
<td>4 h</td>
<td>25±1 y (15 M)</td>
<td>Healthy</td>
<td>Optimal</td>
<td>Rodriguez-Mateos 2015 (75)</td>
</tr>
<tr>
<td>No effect on clinic BP</td>
<td>Beetroot juice</td>
<td>694 mg (11.2 mmol)</td>
<td>2 h</td>
<td>57±10 y (5 M; 4 F)</td>
<td>Healthy</td>
<td>Optimal</td>
<td>Coggan 2015 (63)</td>
</tr>
<tr>
<td>No effect on clinic BP</td>
<td>Beetroot juice</td>
<td>310 mg (5 mmol)</td>
<td>3 h</td>
<td>25±5 y (7 M; 4 F)</td>
<td>Healthy</td>
<td>Optimal</td>
<td>Bakker 2015 (76)</td>
</tr>
<tr>
<td>No effect on clinic BP</td>
<td>Beetroot juice</td>
<td>738 mg (11.9 mmol)</td>
<td>3 h</td>
<td>Young: 27±6 y (11 M; 5 F)</td>
<td>Old: 59±6 y (8 M; 7 F)</td>
<td>Healthy</td>
<td>Normal/high-normal Shepherd 2016 (69)</td>
</tr>
<tr>
<td>No effect on clinic BP</td>
<td>Beetroot juice</td>
<td>403-434 mg (6.5-7.0 mmol)</td>
<td>2 h</td>
<td>23±3 y (20 M)</td>
<td>Healthy</td>
<td>Optimal</td>
<td>Lefferts 2016 (70)</td>
</tr>
</tbody>
</table>

Screening/baseline blood pressure was based on criteria in the Australian guidelines for the diagnosis and management of hypertension in adults (150). BP, blood pressure; DBP, diastolic blood pressure; SBP, systolic blood pressure.
### Table 2. Intervention studies investigating the chronic effects of inorganic nitrate on blood pressure in humans.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Blood pressure effect</th>
<th>Nitrate source</th>
<th>Nitrate dose</th>
<th>Duration</th>
<th>Subjects</th>
<th>Screening/baseline blood pressure</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>↓ Clinic DBP</td>
<td>Beetroot juice</td>
<td>450 mg/d (7.3 mmol/d)</td>
<td>3 d</td>
<td>24±1 y (6 M) Healthy</td>
<td>Normal</td>
<td>Keen 2015 (86)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic, home and ambulatory SBP</td>
<td>Beetroot juice</td>
<td>398 mg/d (6.4 mmol/d)</td>
<td>28 d</td>
<td>n=64 (26 M; 38 F) Nitrate: 58±14 y Placebo: 56±16 y Drug-naïve and treated hypertensive</td>
<td>Grade 1 hypertension</td>
<td>Kapil 2015 (87)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic SBP</td>
<td>High nitrate vegetables</td>
<td>339±133 mg/d (5.5±2.1 mmol/d)</td>
<td>7 d</td>
<td>20±2 y (19 F) Healthy</td>
<td>Optimal</td>
<td>Ashworth 2015 (88)</td>
<td></td>
</tr>
<tr>
<td>↓ Home SBP</td>
<td>Beetroot juice</td>
<td>300-400 mg/d (4.8-6.4 mmol/d)</td>
<td>21 d</td>
<td>n=21 (12 M; 9 F) Beetroot: 63±2 y Placebo: 61±1 y Older overweight</td>
<td>Normal/high-normal</td>
<td>Jajja 2014 (90)</td>
<td></td>
</tr>
<tr>
<td>↓ Clinic SBP</td>
<td>Sodium nitrate</td>
<td>9.3 mg/kg body weight/d</td>
<td>28 d</td>
<td>63±6 y (4 M; 7 F) Moderate cardiovascular risk</td>
<td>High-normal</td>
<td>Rammos 2014 (89)</td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>DBP/Na intake</td>
<td>Duration</td>
<td>Age/Gender</td>
<td>BP Status</td>
<td>Study/Reference</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------------------</td>
<td>----------</td>
<td>--------------</td>
<td>---------------------</td>
<td>-----------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japanese traditional diet</td>
<td>18.8 mg/kg/body weight/d</td>
<td>10 d</td>
<td>36±10 y (10 M; 15 F)</td>
<td>Healthy</td>
<td>Optimal Sobko 2010 (92)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium nitrate</td>
<td>6.2 mg/kg body weight/d</td>
<td>3 d</td>
<td>24 y (15 M; 2 F)</td>
<td>Healthy</td>
<td>Optimal Larsen 2006 (93)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**No effect**

- **No effect on clinic BP**
  - Beetroot juice: 375 mg/d (6 mmol/d) over 42 d: Nitrate: 53±10 y (12 M; 21 F) Placebo: 53±12 y (12 M; 22 F) Hypercholesterolaemic 62±5 y (14 M; 16 F) Overweight and obese
  - Beetroot juice: 600 mg/d (9.7 mmol/d) over 7 d: High-normal
  - Beetroot juice: 434 mg/d (7 mmol/d) over 7 d: Treated hypertensive
  - Green leafy vegetables: 300 mg/d (4.8 mmol/d) over 7 d: High-normal
  - Beetroot juice: 465 mg/d (7.5 mmol/d) over 14 d: Grade 1 hypertension T2DM
  - High nitrate diet: 155 mg/d (2.5 mmol/d) over 3 d: High-normal
  - Beetroot juice: 527 mg/d (8.5 mmol/d) over 3 d: Older
  - Combination: 682 mg/d (11 mmol/d) over 3 d: Normal

- **Combination:** 682 mg/d (11 mmol/d) over 3 d: High-normal
Screening/baseline blood pressure was based on criteria in the Australian guidelines for the diagnosis and management of hypertension in adults (150). BP, blood pressure; DBP, diastolic blood pressure; SBP, systolic blood pressure; T2DM, type 2 diabetes mellitus.
Table 3. Intervention studies investigating the acute effects of inorganic nitrate on endothelial function in humans.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Nitrate source</th>
<th>Nitrate dose</th>
<th>Duration</th>
<th>Subjects</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑ FMD</td>
<td>Beetroot juice</td>
<td>375 mg (6 mmol)</td>
<td>3 h</td>
<td>Nitrate: 53±10 y (12 M; 21 F)</td>
<td>Velmurugan 2016 (50)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Placebo: 53±12 y (12 M; 22 F)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hypercholesterolaemic</td>
<td></td>
</tr>
<tr>
<td>↑ FMD</td>
<td>Beetroot juice</td>
<td>310 mg (5 mmol)</td>
<td>3 h</td>
<td>25±5 y (7 M; 4 F)</td>
<td>Bakker 2015 (76)</td>
</tr>
<tr>
<td></td>
<td>Sodium nitrate</td>
<td>0.1-10 mg/kg body weight</td>
<td>4 h</td>
<td>24±1 y (15 M)</td>
<td>Rodriguez-Mateos 2015 (75)</td>
</tr>
<tr>
<td>↑ FMD</td>
<td>Beetroot juice</td>
<td>500 mg (8.1 mmol)</td>
<td>2 h</td>
<td>61±7 y (20 M)</td>
<td>Joris 2013 (79)</td>
</tr>
<tr>
<td>↑ FMD</td>
<td>Sodium nitrate</td>
<td>9.3 mg/kg body weight</td>
<td>1.5 h</td>
<td>26±1 y (5 M; 5 F)</td>
<td>Heiss 2012 (112)</td>
</tr>
<tr>
<td>↑ FMD</td>
<td>Spinach</td>
<td>182 mg (2.9 mmol)</td>
<td>4 h</td>
<td>47±14 y (6 M; 24 F)</td>
<td>Bondonno 2012 (83)</td>
</tr>
<tr>
<td>↑ FMD</td>
<td>Sodium nitrate</td>
<td>9.3 mg/kg body weight</td>
<td>1.5 h</td>
<td>26±1 y (5 M; 5 F)</td>
<td>Heiss 2012 (112)</td>
</tr>
<tr>
<td>↑ FMD</td>
<td>Spinach</td>
<td>182 mg (2.9 mmol)</td>
<td>4 h</td>
<td>47±14 y (6 M; 24 F)</td>
<td>Bondonno 2012 (83)</td>
</tr>
<tr>
<td>No effect</td>
<td>No effect</td>
<td>Potassium nitrate</td>
<td>3 h</td>
<td>28±2 y (14)</td>
<td>Bahra 2012 (84)</td>
</tr>
</tbody>
</table>

FMD, flow-mediated dilatation.
Table 4. Intervention studies investigating the chronic effects of inorganic nitrate on endothelial function in humans.

<table>
<thead>
<tr>
<th>FMD effect</th>
<th>Nitrate source</th>
<th>Nitrate dose</th>
<th>Duration</th>
<th>Subjects</th>
<th>Reference</th>
</tr>
</thead>
</table>
| Effect     | ↑ FMD          | Beetroot juice | 375 mg/d (6 mmol/d) | 42 d | Nitrate: 53±10 y (12 M; 21 F)  
Placebo: 53±12 y (12 M; 22 F)  
Hypercholesterolaemic  
n=64 (26 M; 38 F) | Velmurugan 2016 (50) |
|            | ↑ FMD          | Beetroot juice | 398 mg/d (6.4 mmol) | 28 d | Nitrate: 58±14 y  
Placebo: 56±16 y  
Drug-naïve and treated hypertensive  
n=64 (26 M; 38 F) | Kapil 2015 (87) |
|            | ↑ FMD          | Sodium nitrate | 9.3 mg/kg body weight/d | 28 d | Nitrate: 63±6 y (4 M; 7 F)  
Male: 65±6 y  
Moderate cardiovascular risk  
Drug-naïve and treated hypertensive  
n=70 (38 M; 32 F) | Rammoss 2014 (89) |
| No effect  | No effect      | Beetroot juice | 465 mg/d (7.5 mmol/d) | 14 d | Nitrate: 67±5 y (18 M; 9 F)  
T2DM  
T2DM  
Drug-naïve and treated hypertensive  
n=50 (29 M; 21 F) | Gilchrist 2013 (68) |

FMD, flow-mediated dilatation; T2DM, type 2 diabetes mellitus.
<table>
<thead>
<tr>
<th>Effect</th>
<th>Nitrate source</th>
<th>Nitrate dose</th>
<th>Duration</th>
<th>Subjects</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuated IR-induced endothelial dysfunction</td>
<td>Potassium nitrate</td>
<td>1488 mg (24 mmol)</td>
<td>3 h</td>
<td>25±1 y (12) Healthy</td>
<td>Kapil 2010 (85)</td>
</tr>
<tr>
<td></td>
<td>Beetroot juice</td>
<td>341 mg (5.5 mmol)</td>
<td>3 h</td>
<td>27±7 y (4 M; 6 F) Healthy</td>
<td>Webb 2008 (40)</td>
</tr>
</tbody>
</table>

IR, ischemic reperfusion.
<table>
<thead>
<tr>
<th>Effect</th>
<th>Arterial stiffness effect</th>
<th>Nitrate source</th>
<th>Nitrate dose</th>
<th>Duration</th>
<th>Subjects</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>↓ Alx</td>
<td>↓ Alx (young only)</td>
<td>Beetroot juice</td>
<td>583 mg (9.4 mmol)</td>
<td>Acute (3 h)</td>
<td>Young: 25±4 y (10 M; 3 F) Old: 64±5 y (9 M; 3 F) Healthy</td>
<td>Hughes 2016 (72)</td>
</tr>
<tr>
<td>↓ PWV</td>
<td></td>
<td>Potassium nitrate</td>
<td>496 mg (8 mmol)</td>
<td>Acute (3 h)</td>
<td>Healthy 28±2 y (14)</td>
<td>Bahra 2012 (84)</td>
</tr>
<tr>
<td>↓ Alx</td>
<td></td>
<td>Beetroot juice</td>
<td>375 mg/d (6 mmol)</td>
<td>Acute (3 h)</td>
<td>Nitrate: 53±10 y (12 M; 21 F) Placebo: 53±12 y (12 M; 22 F) Hypercholesterolaemic</td>
<td>Velmurugan 2016 (50)</td>
</tr>
<tr>
<td>↓ PWV</td>
<td>↓ PWV</td>
<td>Beetroot juice</td>
<td>398 mg/d (6.4 mmol/d)</td>
<td>Chronic (42 d)</td>
<td>n=64 (26 M; 38 F) Nitrate: 58±14 y Placebo: 56±16 y Drug-naïve and treated hypertensive</td>
<td>Kapil 2015 (87)</td>
</tr>
<tr>
<td>↓ PWV</td>
<td>↓ Alx</td>
<td>Sodium nitrate</td>
<td>9.3 mg/kg body weight/d</td>
<td>Chronic (28 d)</td>
<td>63±6 y (4 M; 7 F) Moderate cardiovascular risk</td>
<td>Rammos 2014 (89)</td>
</tr>
<tr>
<td>No effect</td>
<td>No effect on PWV and Alx</td>
<td>Beetroot juice</td>
<td>403-434 mg (6.5-7.0 mmol)</td>
<td>Acute (2 h)</td>
<td>23±3 y (20 M) Healthy</td>
<td>Lefferts 2016 (70)</td>
</tr>
<tr>
<td>No effect</td>
<td>No effect on PWV and Alx</td>
<td>Beetroot bread</td>
<td>68 mg (1.1 mmol)</td>
<td>Acute (6 h)</td>
<td>31±2 y (23 M) Healthy</td>
<td>Hobbs 2013 (80)</td>
</tr>
<tr>
<td>No effect</td>
<td>No effect on PWV and Alx</td>
<td>Beetroot juice</td>
<td>500 mg (8.1 mmol)</td>
<td>Acute (2 h)</td>
<td>61±7 y (20 M) Overweight</td>
<td>Joris 2013 (79)</td>
</tr>
<tr>
<td>No effect</td>
<td>No effect on PWV and Alx</td>
<td>Spinach</td>
<td>220 mg (3.5 mmol)</td>
<td>Acute (3.5 h)</td>
<td>59±8 y (6 M; 20 F) Healthy</td>
<td>Liu 2013 (78)</td>
</tr>
<tr>
<td>No effect</td>
<td>No effect on PWV</td>
<td>Beetroot juice</td>
<td>600 mg/d (9.7 mmol/d)</td>
<td>Chronic (7 d)</td>
<td>62±5 y (14 M; 16 F) Overweight and obese</td>
<td>Lara 2015 (65)</td>
</tr>
<tr>
<td>No effect on PWV and AIx</td>
<td>Green leafy vegetables</td>
<td>300 mg/d (4.8 mmol/d)</td>
<td>Chronic (7 d)</td>
<td>61±7 y (12 M; 26 F)</td>
<td>Pre-hypertensive</td>
<td>Bondonno 2014 (67)</td>
</tr>
</tbody>
</table>

AIx, augmentation index; PWV, pulse wave velocity.
Table 7. Intervention studies investigating the effects of inorganic nitrate on platelet function in humans.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Platelet effect</th>
<th>Nitrate source</th>
<th>Nitrate dose</th>
<th>Duration</th>
<th>Subjects</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>↓ in platelet reactivity in males but not females</td>
<td>Beetroot juice</td>
<td>192 mg (3.1 mmol)</td>
<td>Acute (3 h)</td>
<td>M: 26±1 y (12) F: 24±2 y (12) Healthy</td>
<td>Velmurugan 2013 (125)</td>
<td></td>
</tr>
<tr>
<td>↓ in platelet reactivity in males but not females</td>
<td>Potassium nitrate</td>
<td>496 mg (8 mmol)</td>
<td>Acute (3 h)</td>
<td>M: 27±1 y (12) F: 29±2 y (12) Healthy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ in platelet aggregation</td>
<td>Beetroot juice</td>
<td>1054 mg (17 mmol)</td>
<td>Acute (2.5 h)</td>
<td>31±2 y (5 M; 1 F) Healthy</td>
<td>Webb 2008 (40)</td>
<td></td>
</tr>
<tr>
<td>↓ in platelet aggregation</td>
<td>Potassium nitrate</td>
<td>124 mg (2 mmol)</td>
<td>Acute (2.5 h)</td>
<td>18-44 y (4 M; 3 F)</td>
<td>Richardson 2002 (126)</td>
<td></td>
</tr>
<tr>
<td>↓ in platelet aggregation</td>
<td>Potassium nitrate</td>
<td>31 mg, 124 mg (0.5 mmol, 2 mmol)</td>
<td>Acute (2.5 h)</td>
<td>18-44 y (3 M; 3 F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ in platelet-monocyte aggregates</td>
<td>Beetroot juice</td>
<td>375 mg/d (6 mmol/d)</td>
<td>Chronic (42 d)</td>
<td>Nitrate: 53±10 y (12 M; 21 F) Placebo: 53±12 y (12 M; 22 F) Hypercholesterolaemic</td>
<td>Velmurugan 2016 (50)</td>
<td></td>
</tr>
</tbody>
</table>
Table 8. Intervention studies investigating the effects of inorganic nitrate in animals.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Nitrate source</th>
<th>Background diet</th>
<th>Nitrate dose</th>
<th>Duration</th>
<th>Animals</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood pressure</td>
<td>↓ MAP (6.7 mmol dose only)</td>
<td>KNO₃ in drinking water</td>
<td>Not described</td>
<td>2.5 or 6.7 mmol/kg/d</td>
<td>3 w</td>
<td>Hypoxia WT male mice (n≥8)</td>
</tr>
<tr>
<td></td>
<td>No change in MAP</td>
<td></td>
<td></td>
<td></td>
<td>Hypoxia eNOS KO male mice (n≥8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↓ MAP</td>
<td>NaNO₃ in drinking water</td>
<td>Not described</td>
<td>0.1 mmol/kg/d</td>
<td>8 w</td>
<td>Rats (5≤n≥15)</td>
</tr>
<tr>
<td></td>
<td>↓ MAP (1mM dose only)</td>
<td>Supplemented with NaNO₃</td>
<td>High-salt diet</td>
<td>0.1 or 1 mmol/kg/d</td>
<td>8-11 w</td>
<td>UNX Male Sprague–Dawley rats</td>
</tr>
<tr>
<td></td>
<td>Prevented ↑ in MAP</td>
<td>NaNO₃ in drinking water</td>
<td>Not described</td>
<td>1 mmol/kg/d</td>
<td>8 w</td>
<td>Male SH rats (n=6)</td>
</tr>
<tr>
<td></td>
<td>No change in MAP</td>
<td></td>
<td></td>
<td></td>
<td>Normotensive Wistar Kyoto rats (n=6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↓ MAP</td>
<td>Supplemented with NaNO₃</td>
<td>High-fructose diet</td>
<td>1.8 mmol/kg/d</td>
<td>6 w</td>
<td>Male Sprague–Dawley rats (n=8)</td>
</tr>
<tr>
<td></td>
<td>Prevented ↑ in MAP</td>
<td></td>
<td></td>
<td></td>
<td>Male Sprague–Dawley rats (n=8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↓ MAP</td>
<td>NaNO₃ in drinking water</td>
<td>Standard chow</td>
<td>0.2 mmol/kg/d</td>
<td>1 w</td>
<td>Male Sprague-Dawley rats (n=7)</td>
</tr>
<tr>
<td></td>
<td>↓ MAP and ↓ DBP</td>
<td></td>
<td></td>
<td></td>
<td>Male Sprague-Dawley rats</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No change in MAP</td>
<td>NaNO₃ in drinking water</td>
<td>Standard chow</td>
<td>0.8 mmol/kg/d</td>
<td>2 w</td>
<td>Young male Sprague–Dawley rats (n=8)</td>
</tr>
<tr>
<td></td>
<td>↓ MAP and ↓ SBP</td>
<td></td>
<td></td>
<td></td>
<td>Old male Sprague–Dawley rats (n=5)</td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Effect on SBP/MP</td>
<td>Treatment</td>
<td>Diet/Kal &amp; Concentration</td>
<td>Duration</td>
<td>Species</td>
<td>Number</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------</td>
<td>-----------</td>
<td>--------------------------</td>
<td>----------</td>
<td>---------</td>
<td>--------</td>
</tr>
<tr>
<td>Khalifi 2015 (102)</td>
<td>No change in SBP</td>
<td>NaNO₃ in drinking water</td>
<td>Standard chow</td>
<td>0.1 g/L</td>
<td>8 w</td>
<td>Male Wistar rats (n=8)</td>
</tr>
<tr>
<td>Marsch 2016 (154)</td>
<td>No change in BP</td>
<td>NaNO₃ in drinking water</td>
<td>Western-type diet</td>
<td>0.2 mmol/d</td>
<td>14 w</td>
<td>LDL receptor KO mice (n=15)</td>
</tr>
<tr>
<td>Vilskersts 2014 (99)</td>
<td>Smaller rise in SBP</td>
<td>Mg(NO₃)₂ in drinking water</td>
<td>Not described</td>
<td>0.3 mmol/kg/d</td>
<td>4 w</td>
<td>Male Sprague–Dawley rats (n=5-12)</td>
</tr>
<tr>
<td>Carlstrom 2015 (97)</td>
<td>↓ MAP (0.1mM dose only)</td>
<td>NaNO₃ in drinking water</td>
<td>Standard chow</td>
<td>0.1 or 1 mmol/kg/d</td>
<td>8-10 w</td>
<td>Male Sprague–Dawley rats (n=5-12)</td>
</tr>
<tr>
<td>Bakker 2016 (115)</td>
<td>↑ MAP (1mM dose only)</td>
<td>NaNO₃ in drinking water</td>
<td>High-fat diet</td>
<td>0.1, 1 or 10 mmol/kg/d</td>
<td>10 w</td>
<td>Male ApoE KO mice (n=8-12)</td>
</tr>
<tr>
<td>Hendgen-Cotta 2012 (117)</td>
<td>↑ Perfusion recovery</td>
<td>NaNO₃ in drinking water</td>
<td>Not described</td>
<td>5.0 mmol/kg/d</td>
<td>2 w</td>
<td>Male NMRI mice or C57BL/6 mice (n=21-23)</td>
</tr>
<tr>
<td>Park 2013 (127)</td>
<td>↓ collagen induced platelet aggregation</td>
<td>NaNO₃ in drinking water</td>
<td>Standard chow</td>
<td>1 g/L</td>
<td>1 w</td>
<td>WT C57BL/6 mice (n≥5)</td>
</tr>
</tbody>
</table>

**Vascular function**

- ↓ Ach-mediated vasorelaxation (1mM dose only)
- No vasorelaxation
- ↑ Ach-mediated vessel relaxation (0.1 and 1 mmol dose only)

**Ischaemic reperfusion**

- ↑ Perfusion recovery

**Platelet function**

- ↓ collagen induced platelet aggregation
Ach, acetylcholine; ApoE, apolipoprotein e; eNOS, endothelial nitric oxide synthase; KO, knock-out; LDL, low density lipoprotein; MAP, mean arterial pressure; NMRI, Naval Medical Research Institute; NO, nitric oxide; NOS, nitric oxide synthase; SBP, systolic blood pressure; SH, spontaneously hypertensive; UNX, uninephrectomized; WT, wild-type.
**Table 9.** Intervention studies investigating the effects of inorganic nitrate on cerebral blood flow in humans.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Cerebral blood flow effect</th>
<th>Nitrate source</th>
<th>Nitrate dose</th>
<th>Duration</th>
<th>Subjects</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect</td>
<td>↑ regional cerebral perfusion in frontal lobe white matter but no effect on global cerebral perfusion</td>
<td>High nitrate diet</td>
<td>769 mg (12.4 mmol)</td>
<td>Acute (24 h)</td>
<td>75±7 y (14) Older</td>
<td>Presley 2011 (129)</td>
</tr>
<tr>
<td>No effect</td>
<td>No effect on cerebral blood flow</td>
<td>Sodium nitrate</td>
<td>6.2 mg/kg body weight/d</td>
<td>Chronic (3 d)</td>
<td>25±1 y (20 M) Healthy</td>
<td>Aamand 2014 (130)</td>
</tr>
</tbody>
</table>

NOS, nitric oxide synthase.
<table>
<thead>
<tr>
<th>Study design and population</th>
<th>Nitrate intake assessment</th>
<th>Primary outcome</th>
<th>Adjusted variables</th>
<th>Results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 y follow-up study</td>
<td>FFQ</td>
<td>ASVD mortality</td>
<td>Model 1: Unadjusted. Model 2: Age and energy. Model 3: Age, BMI, physical activity, alcohol intake, history of smoking, socioeconomic status, calcium supplementation group, organic nitrate medication, antihypertensive medication, statin medication, low-dose aspirin, renal function, and energy intake.</td>
<td>↓ ASVD mortality</td>
<td>Blekkenhorst 2017 (53)</td>
</tr>
<tr>
<td>n=1226</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australian female older adults Diabetes and ASVD-free 75.1±2.7 y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 y follow-up study</td>
<td>FFQ</td>
<td>Ischaemic cerebrovascular disease hospitalisation and death</td>
<td>Model 1: Unadjusted. Model 2: Age and energy. Model 3: Age, BMI, energy intake, alcohol intake, energy expended in physical activity, antihypertensive medication, statin medication, low-dose aspirin medication, organic nitrate medication, history of smoking, and treatment.</td>
<td>↓ ischaemic cerebrovascular disease hospitalisation and death</td>
<td>Bondonno 2017 (54)</td>
</tr>
<tr>
<td>n=1226</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australian female older adults Diabetes and ASVD-free 75±3 y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-sectional and 3 y follow-up study</td>
<td>FFQ</td>
<td>eGFR and CKD</td>
<td>Model 1: age, sex, and BMI. Model 2: Additional adjustment for smoking, education, physical activity, diabetes, and hypertension.</td>
<td>↓ eGFR, ↑ CKD (cross-sectional)</td>
<td>Mirmiran 2016 (146)</td>
</tr>
<tr>
<td>n=1538 cross-sectional</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n=1229 follow-up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iranian male and female adults (57% female)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Model 3: Additional adjustment for dietary intake of energy, fibre, and potassium. No association

Bahadoran 2017 (147)

Follow-up of CKD

Model 1: Diabetes risk score.
Model 2: Additional adjustment for dietary total fat, fibre, and vitamin C.

5.8 y follow-up study
n=2139
Iranian male and female adults (54.6% male)
T2DM-free
38.9±12.6 y

FFQ
T2DM

3 y follow-up study
Iranian male and female adults (57% female)
38±12 y

FFQ
Hypertension

Model 1: Adjusted for age and sex.
Model 2: Additional adjustment for weight, 3-year weight change, smoking, education, physical activity, baseline SBP and DBP.
Model 3: Additional adjustment for dietary intake of energy, fibre, sodium, potassium and processed meat.

No association

Golzarand 2016 (145)

ASVD, atherosclerotic vascular disease; BMI, body mass index; CKD, chronic kidney disease; DBP, diastolic blood pressure; eGFR, estimated glomerular filtration rate; FFQ, food frequency questionnaire; SBP, systolic blood pressure; T2DM, type 2 diabetes mellitus.
Figure legends:

**Figure 1.** Observed beneficial effects of nitrate ingestion on cardiovascular-related health outcomes in human and animal studies. ASVD, atherosclerotic vascular disease; CVD, cardiovascular disease.