Inorganic nitrate and nitrite supplementation fails to improve skeletal muscle mitochondrial efficiency in mice and humans

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ABSTRACT

Background: Inorganic nitrate, abundant in leafy green vegetables and beetroot, is thought to have protective health benefits. Adherence to a Mediterranean diet reduces the incidence and severity of coronary artery disease, whereas supplementation with nitrate can improve submaximal exercise performance. Once ingested, oral commensal bacteria may reduce nitrate to nitrite, which may subsequently be reduced to nitric oxide during conditions of hypoxia and in the presence of “nitrite reductases” such as heme- and molybdenum-containing enzymes.

Objective: We aimed to explore the putative effects of inorganic nitrate and nitrite on mitochondrial function in skeletal muscle.

Methods: Mice were subjected to a nitrate/nitrite-depleted diet for 2 wk, then supplemented with sodium nitrate, sodium nitrite, or sodium chloride (1 g/L) in drinking water ad libitum for 7 d before killing. Skeletal muscle mitochondrial function and expression of uncoupling protein (UCP) 3, ADP/ATP carrier protein (AAC) 1 and AAC2, and pyruvate dehydrogenase (PDH) were assessed by respirometry and Western blotting. Studies were also undertaken in human skeletal muscle biopsies from a cohort of coronary artery bypass graft patients treated with either sodium nitrite (30-min infusion of 10 μmol/min) or vehicle [0.9% (wt:vol) saline] 24 h before surgery.

Results: Neither sodium nitrate nor sodium nitrite supplementation altered mitochondrial coupling efficiency in murine skeletal muscle, and expression of UCP3, AAC1, or AAC2, and PDH phosphorylation status did not differ between the nitrate and saline groups. Similar results were observed in human samples.

Conclusions: Sodium nitrite failed to improve mitochondrial metabolic efficiency, rendering this mechanism implausible for the purported exercise benefits of dietary nitrate supplementation. This trial was registered at clinicaltrials.gov as NCT04001283.

Keywords: nitrate, nitrite, mitochondria, uncoupling proteins, pyruvate dehydrogenase

Introduction

Recent data suggest that there are considerable health benefits (particularly cardiovascular) from diets high in inorganic nitrate (NO$_3^-$). The nitrate (NO$_3^-$)–nitrite (NO$_2^-$)–nitric oxide (NO) pathway, whereby dietary inorganic nitrate is processed via the entero-salivary circuit to release NO$_2^-$ and NO (1), is attracting considerable interest. Adherence to a Mediterranean-style diet (typically rich in dietary nitrates) is associated with a lower risk of developing coronary artery disease or heart failure (2, 3).

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Supplemental Figures 1–4 are available from the “Supplementary data” link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/ajcn/

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Data described in the manuscript, code book, and analytic code will be made available upon request pending application and approval.

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Abbreviations used: AAC, ADP/ATP carrier protein; CABG, coronary artery bypass graft; FCCP, carbonyl cyanide-p-trifluoromethoxyphenylhydrazone; HFeF, heart failure with preserved ejection fraction; HFeEF, heart failure with reduced ejection fraction; MAS, mitochondrial assay solution; NIRS, near infrared spectroscopy; NO, nitric oxide; OCR, oxygen consumption rate; PDH, pyruvate dehydrogenase; P.O, phosphate:oxygen; PVDF, polyvinylidene difluoride; TBS, Tris-buffered saline; UCP, uncoupling protein.

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In healthy individuals, increased dietary nitrate consumption has been shown to reduce the oxygen cost of skeletal muscle work during submaximal exercise, implying increased metabolic efficiency (4–8); in clinical settings, a regime of dietary nitrate supplementation improved exercise performance in heart failure with preserved ejection fraction (HFpEF) and muscle contractile function in heart failure with reduced ejection fraction (HFrEF) (9, 10). However, each of these studies was limited by their small sample size. The recent, comparatively large, INDIE (Inorganic Nitrate Delivery to Improve Exercise Capacity) trial (utilizing inhaled nitrite) showed no benefit on exercise capacity in HFrEF (11). It is unclear whether the smaller studies were false positives, or whether the shorter plasma half-life of the inhaled nitrite approach failed to work because of the pulsatile rather than sustained nature of elevation of nitrite.

Oral inorganic nitrate ingestion has also been documented to lower blood pressure (5, 12–14), and nitrite has been shown to inhibit platelet aggregation (15, 16), promote vasodilation (17), ameliorate pulmonary hypertension (18–20), and attenuate cardiac ischemia-reperfusion injury in experimental models (21, 22).

The physiological mechanisms underlying these apparent improvements in metabolic efficiency are not well understood. It has been proposed that ingestion of inorganic nitrate can improve mitochondrial coupling efficiency (i.e., the relationship between mitochondrial respiration and ATP generation) via reduced expression of proteins believed to facilitate mitochondrial proton leak (e.g., the ADP/ATP carrier proteins (AACs) and uncoupling proteins (UCPs)) (6). However, recent work has cast doubt on whether the shorter plasma half-life of the inhaled nitrite approach failed to work because of the pulsatile rather than sustained nature of elevation of nitrite.

Methods

Treatment conditions

Male C57/bl6 mice, 3–5 mo old, were obtained from Harlan Laboratory UK Ltd and the University of East Anglia Disease Modelling Unit. After a 2-wk acclimatization period to local vivarium conditions, mice were subjected to a nitrate/nitrite-depleted diet for 2 wk. Mice were then administered either sodium chloride, sodium nitrate, or sodium nitrite at a concentration of 1 g/L in drinking water ad libitum for 7 d. All experimental procedures and protocols used in this study were reviewed and approved by the Animal Welfare and Ethical Review Body and were conducted according to the specifications of the United Kingdom Animals (Scientific Procedures) Act, 1986.

Determination of plasma nitrate/nitrite concentrations

Mice were anaesthetized using 5% isoflurane and 4 L/min oxygen, and blood was collected via intracardiac puncture into EDTA-containing anticoagulant tubes containing 100 μL 10 mM N-ethylmaleimide. Plasma was generated by centrifugation at 2000 × g for 10 min at room temperature, then snap-frozen using liquid nitrogen and stored at −80°C until analysis. Plasma concentrations of nitrate and nitrite were determined by a dedicated HPLC system (ENO-20; Eicom), as previously reported (28).

Mitochondrial isolation

A subsequent cohort of mice (C57/bl6 mice, 3–5 mo old) were killed by cervical dislocation and gastrocnemius muscle samples harvested from both hind limbs were finely dissected in 1 mL cold isolation buffer (100 mM sucrose, 100 mM KCl, 50 mM Tris-HCl, 1 mM KH2PO4, 0.1 mM EDTA, and 0.2% BSA; pH 7.2) and washed, before incubating with 12 U/g protease (Sigma-Aldrich) in 5 mL isolation buffer for 2 min on ice. The tissue was removed from the protease by brief centrifugation (200 × g for 5 min at 4°C) and resuspended in 20 mL fresh isolation buffer. The suspension was then transferred into a Dounce homogenizer and homogenized using 10 up-and-down strokes on ice, before centrifugation at 700 × g for 10 min at 4°C. The supernatants were filtered (70 μm cell strainer) and centrifuged at 8000 × g for 10 min at 4°C. The pellets were resuspended in cold isolation buffer and centrifuged at 7000 × g for 10 min at 4°C. Isolated mitochondria were resuspended in 150 μL suspension buffer (225 mM mannitol, 75 mM sucrose, 10 mM Tris, and 0.1 mM EDTA; pH 7.2), assayed for protein content (Pierce BCA Protein Assay Kit; ThermoFisher Scientific), and kept on ice until further use.

Mitochondrial respiration

Seahorse XF24 analyzer.

The oxygen consumption rate (OCR) of mitochondria isolated from murine skeletal muscle was initially measured using an XF24 analyzer (Seahorse Bioscience). The mitochondrial suspension was deposited onto XF24 cell culture microplates (Seahorse Bioscience) at a concentration of 2.5 μg/50 μL in mitochondrial assay solution (MAS) buffer (70 mM sucrose, 220 mM mannitol, 10 mM KH2PO4, 5 mM MgCl2, 2 mM HEPES, 1.0 mM EGTA, and 0.2% (wt:vol) fatty acid–free BSA; pH 7.2) containing 10 mM pyruvate/5 mM malate (mitochondrial complex I substrate). The plates were centrifuged at 2000 × g for 20 min at 4°C. Prewarmed (37°C) MAS buffer containing complex I substrate was added to the equivalent wells to a final volume of 495 μL. The plate was equilibrated in a carbon dioxide–free incubator for 8 min at 37°C, then placed in the...
analyzer. OCR was measured in triplicate at baseline, and after sequential addition of 4 mM ADP, 2.5 μg/μL oligomycin, 4 μM carbonyl cyanide-p-trifluoromethoxyphenylhydrazone (FCCP), and 4 μM antimycin A (mitochondrial “stress test”) according to the manufacturer’s instructions. The OCRs were used to determine maximal mitochondrial respiration (FCCP-induced OCR minus antimycin A OCR), leak (oligomycin-induced OCR minus antimycin A OCR), and the respiratory control ratios (ADP-induced OCR:oligomycin-induced OCR), accordingly.

**Oxygen electrode.**

For a more detailed analysis of respiratory function, mitochondrial oxygen uptake activity was measured using a Clark-type oxygen electrode (Oxytherm; Hansatech), calibrated following the manufacturer’s instructions. Aliquots (0.75 mg) of isolated muscle mitochondria were suspended in 1.5 mL air-saturated MAS buffer at 37°C with the addition of 10 mM pyruvate/5 mM malate to initiate mitochondrial oxygen uptake activity (at an acquisition rate of 5 Hz, stirring at 27 rpm). For the assessment of key respiratory parameters, OCRs were measured after the sequential addition of 4 mM ADP (to initiate maximal “state 3” respiration), 5 μM oligomycin (to measure the rate associated with proton leak), 7 μM carboxyatractyloside (to determine the contribution of AAC to the proton leak rate), 2 μM FCCP (to give the maximal uncoupled activity), and 2 μg/mL antimycin A (to fully inhibit mitochondrial respiration). Alternatively, 2 sequential additions of 400 nmol ADP (ε₂₅₀ = 15,400 M⁻¹/cm) were used to induce transient state 3 rates for phosphate:oxygen (P:O) ratio determination. The corresponding amount of oxygen consumed during each state 3 burst was estimated as described in Brown and Cooper (29). Importantly, the order in which “treated” and “control” samples were measured in the electrode was alternated each day to avoid any time-dependent effects (e.g., uncoupling) inadvertently being ascribed to one mitochondrial sample type over the other.

**Immunoblotting**

**Mouse tissue.**

Mice were killed by cervical dislocation. Gastrocnemius muscle was harvested, snap-frozen in liquid nitrogen, then stored at −80°C. Tissue samples were homogenized in lysis buffer (100 mM Tris-Cl, 2 mM Na₃VO₄, and 5 mM NaF; pH 7.4) using a mortar and pestle. Homogenate was subject to 3 freeze–thaw cycles using liquid nitrogen, then centrifuged at 14,000 × g for 15 min at 4°C. Supernatants were retained and stored at −20°C. Total extracted protein was determined by Bradford assay.

SDS-PAGE was conducted under reducing conditions. Samples were loaded in Laemmli buffer containing β-mercaptoethanol, at 20 μg total protein per lane in 10% acrylamide gels. Electrophoresis was conducted at 60 V for 20 min, then 120 V for 80 min. Separated proteins were transferred onto 0.2 μm polyvinylidene difluoride (PVDF) membrane (Bio-Rad) at 100 V for 75 min. Membranes were blocked in 5% (wt:vol) commercially available fat-free milk in 0.1% (vol:vol) Tris-buffered saline (TBS)-Tween for 1 h at room temperature. All antibodies were diluted using 5% (wt:vol) fat-free milk in 0.1% (vol:vol) TBS-Tween. Primary antibodies (Uncoupling Protein 3, 1:500 dilution, Abcam; Pan-Adenine Nucleotide Translocase, 1:500 dilution, Santa-Cruz) were incubated overnight at 4°C, followed by
incubation with anti-rabbit or anti-goat horseradish peroxidase–
conjugated secondary antibodies at 1:5000 dilution (Cell
Signaling Technology) for 1 h at room temperature. Proteins
were visualized using chemiluminescent substrate (ECL:
2.5 mM luminol, 0.4 mM coumaric acid, hydrogen peroxide)
and imaged in a Fusion SL imager (Peqlab). After visualization,
membranes were stained with 0.2% (wt:vol) Coomassie blue for
normalization to the amount of protein per lane (30). Images
were analyzed using ImageJ (NIH).

Human tissue.

Participants were recruited into the “Effect of Nitrite on
Cardiac Muscle and Blood Vessels in Patients Undergoing Coro-
nary Artery Bypass Grafting Surgery” study (NCT04001283),
a randomized, placebo-controlled, double-blind clinical study
investigating the potential mechanisms underlying sodium nitrite
as a medical therapy (Figure 1). Eligible participants were
patients undergoing coronary artery bypass graft (CABG)
surgery, with reasons for exclusion being inability to provide
informed consent, pregnancy or of child-bearing potential, type
1 diabetes mellitus, New York Heart Association class III–IV
heart failure with left ventricular ejection fraction <40%, renal
impairment requiring dialysis, and unstable coronary syndrome
(occurring within the preceding 2 wk). Study participants were
randomly assigned into either the treatment (sodium nitrite
10 μmol/min infused over a period of 30 min) or control [0.9%
(wt:vol) saline–infused equivolume over a period of 30 min]
arms, with blood samples collected immediately before and
after infusion, then 6 h and 24 h postinfusion, and at time of
biopsy. Infusion occurred 24 h before scheduled surgery. Skeletal muscle (pectoral muscle), right atrial appendage, and
left ventricular biopsies were collected immediately before aortic
cross-clamping, snap-frozen using liquid nitrogen, and stored at
−80°C until analysis. The study was approved by the institutional
Ethics of Human Research Committee and complied with the
Declaration of Helsinki. Written informed consent was obtained
in all cases.

Samples were snap-frozen in liquid nitrogen, after which
100–150 μL NP40 cell lysis buffer (ThermoFisher Scientific)
containing a Halt protease and phosphatase inhibitor cocktail
(ThermoFisher Scientific) was added. Samples were manually
crushed, then homogenized on ice using a Pellet Pestle (Sigma-
Aldrich). Samples were then snap-frozen using liquid nitrogen
and allowed to thaw on ice, after which they were homogenized
for a second time. Samples then underwent a further 2 freeze–
thaw cycles using liquid nitrogen, mixing on a vortex after
thawing each time. Samples then underwent centrifugation
at 16,700 × g for 10 min at 4°C; the supernatants were
collected and stored at −80°C. Protein determination was
performed using the Bio-Rad DC Assay (Bio-Rad). Sam-
ples were loaded into Laemmli buffer at a concentration of
1.5 mg/mL and underwent SDS-PAGE using 10% acrylamide
gels under reducing conditions for ∼1 h at 0.08 A, after which
they were transferred onto PVDF membrane (GE Healthcare)
for ∼1.5 h at 0.38 A. Membranes were subsequently blocked
for a minimum of 2 h in either 5% (wt:vol) BSA or skim milk
in TBS-Tween, as appropriate. Primary antibody targets were
Uncoupling Protein-3 (1:1000, Abcam), Adenine Nucleotide
Translocase 1 (1:1000, Abcam), Adenine Nucleotide Translocase
Pyruvate dehydrogenase activity

The activity of the active form (i.e., dephosphorylated) of pyruvate dehydrogenase (PDH) was determined through acetyl-CoA formation, measured after condensation with radioactive oxaloacetate to form citrate, as previously reported (31, 32).

Statistics

All data are expressed as mean ± SD unless stated otherwise. Differences between groups were analyzed by independent t test or ANOVA (as appropriate) for parametric data or Mann–Whitney U test for nonparametric data. Frequency distributions across treatment groups were assessed by χ² test. The human studies were powered in order to detect a treatment difference of 20% in expression and phosphorylation status of metabolic proteins (i.e., PDH, UCP3, AAC1, and AAC2), as determined by immunoblotting. Based on an assumed CV of 20%, n = 14 patients per group would be required for 80% confidence at a 2-sided α of 0.05. Similarly, in murine experiments a treatment difference of 15% in leak respiration (oligomycin respiration minus antimycin A respiration) would require n = 8 per group for 80% confidence at a 2-sided α of 0.05. Analyses were performed using GraphPad Prism version 7.01 or IBM SPSS Statistics version 25.0.0.1.

Results

Murine uptake of supplemented sodium nitrate or nitrite

Plasma concentrations of NO₃⁻ and NO₂⁻ after 7 d supplementation with sodium nitrate or sodium nitrite are depicted in Figure 2. Supplementation with sodium nitrate resulted in an ~7-fold increase in plasma NO₃⁻ concentrations (227 ± 103 μM compared with 33 ± 10 μM, P < 0.0001), with a nonsignificant trend toward increased plasma NO₂⁻ concentrations (4 ± 3 μM compared with 2 ± 1 μM, P = 0.09). This result may be indicative of a limited entero-salivary circuit for reduction of NO₃⁻ to NO₂⁻ (33), because supplementation with sodium nitrite achieved robust increases in both plasma NO₃⁻ (117 ± 62 μM compared with 41 ± 15 μM, P < 0.05) and plasma NO₂⁻ (10.7 ± 10.5 μM compared with 1.7 ± 0.8 μM, P < 0.05) concentrations. These results are comparable with what has been reported previously in mice (28), rats (24), and humans (6) in response to sodium nitrate incorporation into the diet.

The effect of sodium nitrate or nitrite supplementation on murine mitochondrial protein expression and phosphorylation status

The mitochondrial proteins AAC (also known as the adenine nucleotide translocases) and UCP have been implicated in the dissipation of mitochondrial membrane potential by facilitating futile proton leak (34, 35). Sodium nitrate supplementation has been reported to improve mitochondrial energetic efficiency through decreased expression of AAC and UCP3, in particular (6). However, when investigated we observed no alterations in expression of these proteins in skeletal muscle in response to supplementation with either sodium nitrate or sodium nitrite (Figure 3).

Sodium nitrite supplementation has also been reported to attenuate fatty acid utilization by mitochondria (27). By extension and according to the Randle cycle (25), a reciprocal boost in glucose utilization and PDH complex activity may be expected to occur. Activity through the PDH complex is regulated through phosphorylation of 3 distinct serine residues (serines 232, 293,
FIGURE 5  Respiratory activity of skeletal muscle mitochondria isolated from mice supplemented with sodium nitrate ($n = 9$ per group) for 7 d, as assessed by Seahorse XF24 analyzer. (A) Skeletal muscle mitochondrial respiration in response to dietary supplementation with sodium nitrate. (B) RCRs were unchanged in response to supplementation with sodium nitrate. (C) Mitochondrial leak was unchanged in response to sodium nitrate. No significant differences were found between treatment and control groups (at $P < 0.05$; independent $t$ test). See the Methods section for further details. White bars, NaCl; black bars, NaNO$_3$. AA, antimycin A; AU, arbitrary units; FCCP, carbonyl cyanide-p-trifluoromethoxyphenylhydrazone; OCR, oxygen consumption rate; Oligo, oligomycin; RCR, respiratory control ratio; St2, state 2; St3$^*$, state 3 (ADP at saturated concentrations).

FIGURE 6  Respiratory activity of skeletal muscle mitochondria isolated from mice supplemented with sodium nitrite ($n = 5–6$ per group) for 7 d, as assessed by Seahorse XF24 analyzer. (A) Skeletal muscle mitochondrial respiration in response to dietary supplementation with sodium nitrite. Nitrite supplementation resulted in decreased oligomycin-induced respiration when compared with control. *Significant differences: $^*P < 0.05$. (B) RCRs were unchanged in response to supplementation with sodium nitrite. (C) Mitochondrial leak was unchanged in response to sodium nitrite. No significant differences were found between treatment and control groups (at $P < 0.05$; independent $t$ test). See the Methods section for further details. White bars, NaCl; gray bars, NaNO$_2$. AA, antimycin A; AU, arbitrary units; FCCP, carbonyl cyanide-p-trifluoromethoxyphenylhydrazone; OCR, oxygen consumption rate; Oligo, oligomycin; RCR, respiratory control ratio; St2, state 2; St3$^*$, state 3 (ADP at saturated concentrations).

and 300), with decreased phosphorylation of these sites corresponding to increased PDH activity. The effects of sodium nitrate or nitrite supplementation in mice on PDH phosphorylation status in skeletal muscle are summarized in Figure 4. No change in phosphorylation was detected with sodium nitrite supplementation, whereas only a small change was observed with sodium nitrate (Figure 4). These findings correlate with no observable difference in PDH activity in response to nitrite (Supplemental Figure 1; please see Supplemental Figure 2 for example blots).

The effect of sodium nitrate or nitrite supplementation on murine mitochondrial energetics

After observing limited change in protein expression levels, we investigated the impact of both nitrite and nitrate
supplementation on mitochondrial efficiency directly by respiratory analysis of isolated mitochondria. As summarized in Figure 5, sodium nitrate supplementation had no effect on mitochondrial respiration associated with proton leak activity (OCRs in the presence of oligomycin; Figure 5A, C), coupling efficiency (e.g., the respiratory control ratio; Figure 5B), or respiratory activity in any of the conditions tested. In contrast, sodium nitrite supplementation appeared to decrease mitochondrial activity in the presence of oligomycin (Figure 6). However, the respiratory control ratio (Figure 6B) remained unchanged, suggesting that the apparent decrease was due to a general
The clinical characteristics of this cohort are summarized in Table 1, whereas pharmacokinetics of plasma NO$_3^-$ and NO$_2^-$ in response to infusion are depicted in Figure 9. Infusion of sodium nitrite resulted in an immediate increase in plasma NO$_3^-$ concentrations, whereas plasma NO$_2^-$ concentrations had increased by 6 h postinfusion.

Infusion of sodium nitrite before surgery did not alter the expression of UCP3, AAC1, or AAC2 in human skeletal muscle. Similarly, PDH expression and phosphorylation status remained unchanged. These findings in humans are consistent with our findings in mice, where little or no change in these proteins was observed.

### Effects of sodium nitrite supplementation on human mitochondrial protein expression

Given our observations with mice, we took the opportunity to investigate the impact of sodium nitrite infusion on expression of mitochondrial UCPS in human skeletal muscle of patients scheduled for CABG surgery (Figure 8). For data on the effect of sodium nitrite infusion on cardiac expression of mitochondrial proteins, please see Supplemental Figures 3 and 4.

Table 1

|                  | Placebo (n = 15) | Nitrite (n = 20) | P  |
|------------------|-----------------|-----------------|----|
| Age, y           | 67 ± 10         | 62 ± 9          | 0.199 |
| Sex, male        | 11 (73.3)       | 19 (95.0)       | 0.070 |
| Height, cm       | 167 ± 10        | 172 ± 10        | 0.130 |
| Weight, kg       | 89 ± 15         | 88 ± 16         | 0.959 |
| Body surface area, m$^2$ | 2.02 ± 0.22 | 2.04 ± 0.23    | 0.714 |
| SBP baseline, mm Hg | 131 ± 17  | 125 ± 19        | 0.356 |
| SBP postinfusion, mm Hg | 123 ± 22 | 117 ± 21        | 0.467 |
| DBP baseline, mm Hg | 76 ± 9    | 73 ± 10         | 0.383 |
| DBP postinfusion, mm Hg | 70 ± 9    | 68 ± 12         | 0.592 |
| HR baseline, bpm | 61 (56, 68)     | 64 (57, 72)     | 0.227 |
| HR postinfusion, bpm | 58 (55, 63) | 64 (55, 74)    | 0.178 |
| Diabetes mellitus | 4 (26.7)       | 7 (35.0)        | 0.599 |
| Myocardial infarction | 7 (46.7)  | 7 (35.0)        | 0.486 |
| Hypertension     | 11 (73.3)       | 10 (50.0)       | 0.163 |
| Smoking status   |                 |                 | 0.325 |
| Never            | 5 (33.3)        | 10 (50.0)       |     |
| Ex-smoker        | 9 (60.0)        | 7 (35.0)        |     |
| Current          | 1 (6.7)         | 3 (15.0)        |     |
| Aspirin          | 12 (80.0)       | 13 (65.0)       | 0.331 |
| β-blockers       | 14 (93.3)       | 16 (80.0)       | 0.265 |
| Oral nitrates    | 2 (13.3)        | 4 (20.0)        | 0.605 |
| Calcium channel blockers | 4 (26.7) | 4 (20.0)       | 0.642 |
| ACEi/ARB         | 8 (53.3)        | 12 (60.0)       | 0.693 |
| Statins          | 15 (100.0)      | 19 (95.0)       | 0.380 |

1Values are n (%), mean ± SD, or median (IQR). ACEi, angiotensin-converting enzyme inhibitors; ARB, angiotensin receptor type 2 blockers; DBP, diastolic blood pressure; HR, heart rate; SBP, systolic blood pressure.

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Discussion

Numerous studies have reported on improved exercise performance in healthy participants in response to ingestion of inorganic nitrate (4, 5, 7, 13, 14, 36). The inclusion of inorganic nitrate into the diet, whether through dietary sources (e.g., beetroot, spinach) or through other therapeutic avenues (e.g., supplements), has been consistently reported to improve muscle performance (8, 13, 37) and to decrease the oxygen cost of submaximal exercise (4, 5, 7, 14), with no detectable changes in plasma substrate concentrations (7, 14, 36). These improvements in exercise performance have also been observed in cardiovascular diseases such as stable angina (38), and heart failure with either preserved (9) or reduced (10) ejection fraction.

Based in part on data obtained via near infrared spectroscopy (NIRS), as well as unchanged plasma substrate concentrations, it was postulated that the exercise benefits of inorganic nitrate could be attributed to improvements in mitochondrial efficiency, specifically increased coupling of mitochondrial respiration to ATP generation, through decreased expression of AAC and UCP3 and reduced proton leak activity (6). Given the canonical understanding of the entero-salivary circuit for absorption of exogenous nitrates (39, 40), together with the observations regarding NO and mitochondrial respiration (41), these findings provide an attractive mechanism to account for the apparent exercise benefits of inorganic nitrates.

It should be noted that studies using the NIRS technique have shown reduced muscle oxygen consumption after ingestion of...
inorganic nitrate (4), but this is directly related to alterations in regional blood flow (42, 43). This is particularly relevant when considering the known vasodilator properties of nitrite, the putative active component of inorganic nitrate (1, 15, 44–46). Using quantitative fMRI, reductions in muscle oxygen consumption at submaximal exercise with inorganic nitrate were shown to be more prominent in muscles with higher proportions of type 1 fibers, suggesting a mitochondrial, rather than vascular, effect (47). However, previous human studies have observed that oral inorganic nitrate does not alter glucose uptake nor insulin sensitivity (36).

Importantly, our investigation failed to find any alterations in mitochondrial respiration in response to inorganic nitrate, nor were any changes in expression of the proteins AAC1, AAC2, or UCP3 observed in either human or murine skeletal muscle tissue. Indeed, recent work by others has also cast doubt on the idea that inorganic nitrate improves mitochondrial respiratory efficiency: whereas there was a slight reduction in whole body oxygen consumption, Whitfield et al. (23) observed no changes in mitochondrial respiration or UCP content in response to inorganic nitrate (ingested as beetroot juice) (23). Furthermore, we found no substantive changes in the phosphorylation status of the PDH complex, nor any increase in PDH activity. As such, there is now a growing body of evidence to indicate that previously observed exercise benefits in response to inorganic nitrate/nitrite are unlikely due to improvements in mitochondrial oxygen efficiency.

There are some limitations to the present study which need to be acknowledged. Although broadly similar, plasma NO$_2^-$ and NO$_3^-$ concentrations in our murine cohorts were slightly higher than what has been reported previously (28). In addition, we collected no functional data to complement our physiological data. With regards to our human data, plasma NO$_2^-$ and NO$_3^-$ concentrations at the time of biopsy were similar to those at baseline, although this does not preclude the possibility of long-lasting effects: indeed, we have recently reported on a persulfide-signaling-based mechanism whereby sodium nitrite may induce long-lasting effects in vascular tissue (48). Lastly, this investigation does not address the possibility of divergent effects between dietary nitrate and dietary nitrate supplementation: dietary nitrate supplementation was observed to reduce whole body oxygen consumption (while leaving the respiratory exchange ratio and indexes of glucose handling unchanged), yet infusion with sodium nitrite failed to demonstrate the same effects (36). These results were replicated to an extent in mice and humans (23, 24), where supplementation with nitrate-rich beetroot juice or sodium nitrate solution also reduced whole body oxygen consumption. These latter studies reported similar results to our own in that they did not observe any reductions in mitochondrial leak nor improvements in mitochondrial coupling efficiency.

The evidence underlying the vascular effects of inorganic nitrate/nitrite remains convincing, however. Hypoxic potentiation of inorganic nitrite as a vasodilator, and its augmentation in the presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin. Hypoxic potentiation of inorganic nitrite as a vasodilator, and its augmentation in the presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previously (15), and similar work has reported a seeming dependence on myoglobin presence of hemoglobin, have been reported previous...
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