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Taurine supplementation at the crossroads of metabolism, inflammation and aging: mechanistic and nutritional perspectives

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Taurine is a non-proteinogenic β-amino acid that plays fundamental roles in cellular homeostasis. Although it is the most abundant free amino acid in many tissues, the full spectrum of its molecular functions has only recently begun to be elucidated. Taurine supplementation has shown promising outcomes in human studies, with emerging relevance in precision nutrition and the prevention of metabolic and age-related diseases. In this review, we summarize the current knowledge on taurine's molecular mechanisms, including its roles in antioxidant defense, anti-inflammatory signaling, calcium regulation, mitochondrial function, and lipid metabolism. We integrate mechanistic insights with evidence from clinical and nutritional studies examining taurine supplementation in the contexts of oxidative stress, inflammation, metabolic syndrome, and physical performance. Increasing data suggest that taurine can modulate key pathways linked to metabolism, inflammation, and healthy aging. Physiological synthesis and dietary intake appear sufficient to maintain basal health; however, human trials indicate that supplementation of 1–6 g day^{-1} may further promote metabolic resilience and mitochondrial function without adverse effects. Collectively, these findings position taurine as a promising dietary compound at the interface of metabolism, inflammation, and aging, highlighting its potential as a modulator of healthspan within precision nutrition strategies.

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1. Introduction

Taurine (2-aminoethanesulfonic acid) is among the most ancient and phylogenetically conserved small molecules present in many animal tissues and has attracted increasing scientific interest for its potential to modulate diverse physiological processes.[1] First isolated from the bile of the ox *Bos taurus*, this unconventional amino sulfonic acid differs from classical amino acids by carrying a sulfonic rather than a carboxylic group and is therefore not incorporated into proteins.[1] Although taurine has no direct role in protein synthesis, it is one of the most abundant free amino acids in the body. In mammals, its tissue concentrations are within the micromole per gram wet weight range, whereas body fluids contain substantially lower levels (10–200 μM).[1] The highest concentrations of taurine are found in the retina, heart, brain, muscles, and kidney, and in platelets and leukocytes, while the majority of the body's total taurine content resides in skeletal muscle.[1–4]

The taurine pool in the body is maintained through the interplay of dietary intake, small endogenous synthesis, and excretion. Seafood (up to ~827 mg/100 g), fish and shrimp (~40–90 mg/100 g), dark poultry (~337 mg/100 g), poultry (~30–40 mg/100 g), and other meats represent the richest dietary sources, whereas dairy contain small quantities (~2–8 mg/100 g), fruits, vegetables, nuts, and legumes contribute only to negligible amounts,[5,6] and the estimated intake is 40–400 mg day^{-1}.[7] Once ingested, taurine is efficiently absorbed in the small intestine *via* multiple apical transport systems, including the Na^+ and Cl^--dependent transporters TauT (taurine transporter, encoded by *SLC6A6*), as well as H^+-coupled PAT1 (proton-coupled amino acid transporter 1). Among these, TauT predominates under physiological conditions.[8] The known taurine analogues or inhibitors that block TauT include β-alanine, γ-aminobutaric acid (GABA) and guanidinoethyl sulfonate (GES).[9,10] After uptake, taurine traverses the basolateral membrane of enterocytes into the lamina propria and enters the portal circulation unmetabolized. In blood, it circulates as a free amino acid, readily distributed to extra-intestinal tissues and cells where it is taken up primarily by TauT.[11] In the liver, GAT2 (GABA transporter) also contrib-

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utes significantly to taurine uptake.[12] In tissues expressing estrogen receptors, taurine uptake may be influenced by estradiol levels. While 17β-estradiol treatment decreased PAT1 activity in Caco-2 cells and reduced *SLC6A6* expression in HepG2 cells and mouse liver,[13,14] it increased *SLC6A6* expression in the breast carcinoma cell line MCF-7.[15] Therefore, tissue taurine distribution may depend on sex and estrogen levels, although the direction of this effect appears to be tissue-specific and remains debated. Because mammals lack the enzymatic machinery required for taurine catabolism, the compound cannot be metabolized further. Instead, taurine is primarily eliminated through renal excretion in urine or utilized in the liver for bile acid conjugation, although modifications such as *N*-acylations or formation of taurine haloamines may occur under specific conditions.[11,16,17]

Taurine is thought to be synthesized primarily in the liver, but also in the kidneys, brain, adipocytes, mammary gland, and testis.[1] It is endogenously synthesized in mammals from the sulfur-containing amino acids, methionine and cysteine (Fig. 1). The main pathway begins with the oxidation of cysteine by cysteine dioxygenase (CDO), a non-heme iron enzyme that converts cysteine to cysteine sulfinic acid.[1] Subsequently, cysteine sulfinic acid can be oxidized non-enzymatically to cysteic acid, which is then decarboxylated by cysteine sulfinic acid decarboxylase (CSAD) to taurine.[18,19] Preferably, however, cysteine sulfinic acid is directly decarboxylated by CSAD to generate hypotaurine.[20] This decarboxylation of cysteine sulfinic acid to hypotaurine can also be catalyzed by glutamic acid decarboxylases and by glutamic acid like decarboxylase 1, though with lower catalytic efficiency.[19,20] The terminal step, the oxidation of hypotaurine to taurine, has since 1962 been assigned to the enzyme hypotaurine dehydrogenase, though it could never be purified and thus remained to be identified.[21] In 2020, the NAD(P)H-dependent flavin-containing monooxygenase 1 (FMO1) has been identified as the catalysing enzyme of this step.[21] While *FMO1* is expressed in the adult liver of other mammals, in human liver it is only expressed in the fetus and strongly downregulated in adults.[22–25] This might account for the higher taurine synthesis capacity reported in rodents.[26] These findings challenge the view that taurine synthesis is the highest in the liver, as CDO and CSAD activities are the highest in this tissue.[27] *FMO1* has been shown to be expressed in many extra-hepatic tissues in humans including the kidney,[23] brain,[28] small intestine,[29] and heart,[30] from where taurine can be transported to other tissues. In addition to the classical route, an alternative pathway contributes to hypotaurine production through coenzyme A (CoA) degradation. During CoA turnover, cysteamine is released and subsequently oxidized by cysteamine dioxygenase to hypotaurine.[31] Taurine synthesis pathways can be influenced by other signaling pathways and cofactors. CSAD as well as enzymes involved in cysteine synthesis are dependent on pyridoxal-5′-phosphate (PLP), the active form of vitamin B6.[32] Both *Csad* and *Cdo1* have been shown to be downregulated by β-estradiol in the liver of female mice,[14] whereas testosterone increased hepatic expression of *Csad* in male mice.[33] Taurine synthesis therefore appears to be differentially regulated by sex hormones. In the liver, taurine synthesis *via Cdo1* and *Csad* is negatively regulated by bile acid-mediated activation of the nuclear farnesoid X receptor (FXR).[34,35]

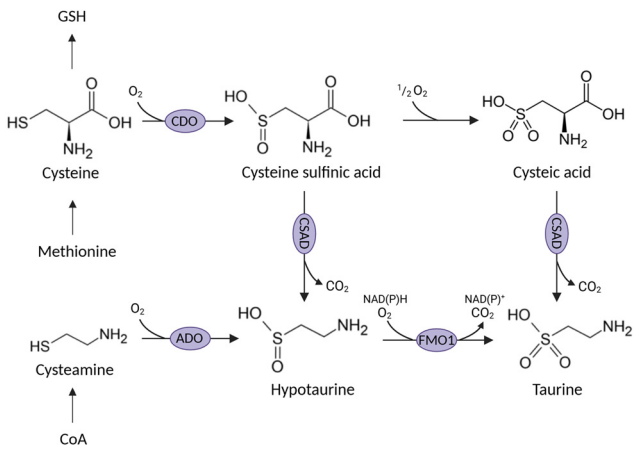

Fig. 1 Synthesis pathways of taurine. Taurine is synthesized from methionine and cysteine, or alternatively from coenzyme A (CoA). Intermediates of the main pathway are cysteine sulfinic acid and hypotaurine. ADO – cysteamine dioxygenase, CDO – cysteine dioxygenase, CSAD – cysteine sulfinic acid decarboxylase, FMO1 – flavin-containing monooxygenase 1.

Since its discovery in 1827,[36] taurine has been extensively studied regarding its diverse roles in cellular physiology. Taurine exerts pleiotropic biological functions and is indispensable for osmoregulation, cellular redox, calcium modulation, mitochondrial activity, retinal function, bile acid conjugation, and neurodevelopment.[11,37] Taurine functions as an endogenous agonist of GABA receptors, thereby acting as a neuromodulator with inhibitory effects in the mature central nervous system. Consistent with these actions, animal studies have demonstrated the anticonvulsive properties of taurine.[38] However, these findings have not been fully reproduced in human studies.

In the context of osmoregulation, taurine is one of the principal organic osmolytes responsible for maintaining the mammalian cell volume, with intracellular levels controlled by the interplay of active uptake, limited synthesis, and passive release. Its accumulation is largely mediated by TauT, whereas efflux occurs through a swelling-activated pathway that remains to be fully understood. Electrophysiological studies consistently implicate anion channels in mediating swelling-induced taurine efflux.[39,40]

In addition to its physiological roles, taurine supplementation has been associated with potential benefits in enhancing physical performance, mitigating oxidative stress, reducing inflammation, and regulating glucose and cholesterol homeostasis. Despite taurine's longstanding presence in scientific research, this molecule has experienced a revival in research interest. Nowadays, taurine is not only considered as a therapeutic agent for several pathologies,[41] but also as an anti-aging agent,[42] and it is marketed as a performance-enhan-

cing ingredient in sports supplements and energy drinks. While recent reviews have addressed the specific aspects of taurine supplementation, such as its roles in sarcopenic obesity,[43] cardiovascular[44] or mitochondrial health,[45] in this review, we provide an overview of taurine's molecular mechanisms, examine how these translate to human studies relevant for overall health and aging, and finally evaluate the use of taurine as a dietary supplement.

2. Molecular mechanisms of taurine

Taurine holds multiple important roles in different tissues. These partially rely on tissue specific structures and pathways, yet there are some molecular mechanisms that seem to be ubiquitously involved in taurine's mediation of homeostasis and health (Fig. 2). We highlight these in the following section.

2.1 Antioxidant and anti-inflammatory properties

One of the most described mechanisms by which taurine is thought to exert beneficial effects on health is by reducing oxidative stress. However, taurine's ability to directly scavenge reactive oxygen and nitrogen species (ROS/RNS) at concentrations present in most tissues is limited. It failed to scavenge the superoxide radical (O_2^-), the hydroxy radical (OH^-), hydrogen peroxide (H_2O_2), and peroxynitrite ($ONOO^-$), whereas its direct metabolic precursors hypotaurine and cysteamine performed much better.[46,47] However, multiple studies have demonstrated a notable activity of taurine in neutralizing several oxidants when taurine was present at higher concentrations, from 15 mM onwards.[48,49] These include superoxide, hydrogen peroxide, and nitric oxide. One study reported scavenging of alkyl and hydroxy radicals at even lower taurine concentrations.[50] Comparability of these results is difficult, as they were obtained using different *in vitro* systems, but they indicate that taurine's direct scavenging activity may be relevant at least in tissues with high physiological taurine content, such as the heart and the retina.[51]

Furthermore, taurine is able to react with hypochlorous acid, a potent oxidant produced in neutrophils by the enzyme myeloperoxidase (MPO), to form taurine chloramine (TauCl).[52] Even though TauCl retains oxidative properties, it is protective against overproduction of the superoxide radical in neutrophils and macrophages during inflammation by interfering with the functional assembly of the superoxide-producing enzyme NADPH oxidase. In addition, TauCl has been reported to facilitate thiol-group oxidation of Kelch-like ECH-associated protein 1 (Keap1).[53] This leads to the release of nuclear factor E2-related factor (Nrf2) into the nucleus, where it induces transcription of many antioxidant enzyme genes.[54,55] One of the antioxidant

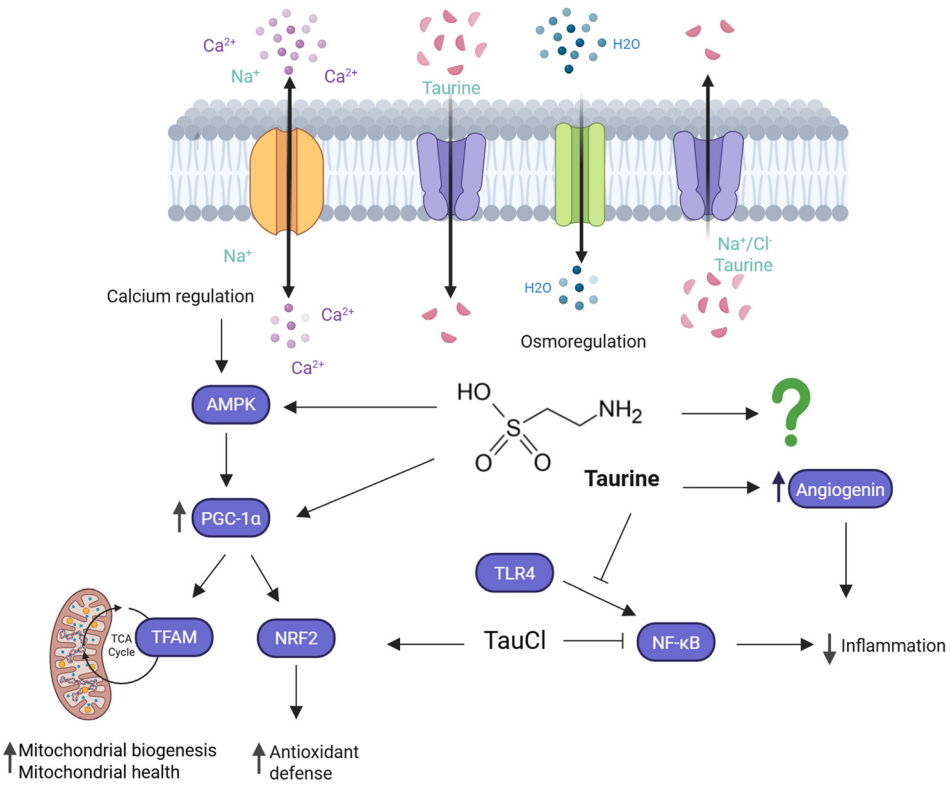

Fig. 2 Molecular targets influenced by taurine. Taurine is involved in calcium and osmoregulation, mitochondrial and antioxidant pathways and inflammation. The exact mechanisms and further potential targets are unknown. AMPK – AMP-activated protein kinase; NFκB – nuclear factor κB; NRF2 – nuclear factor E2-related factor; PGC-1α – peroxisome proliferator-activated receptor gamma coactivator 1-alpha; TauCl – taurine chloramine; TFAM – mitochondrial transcription factor A; TLR4 – Toll-like receptor 4.

enzymes that is upregulated *via* this process is heme oxygenase-1, which exerts protective effects during oxidative stress by degrading free heme to the antioxidant and anti-inflammatory mediators biliverdin and carbon monoxide.[56,57] TauCl also directly interferes with the inflammatory response of immune cells. It is thought to downregulate the activity of the pro-inflammatory transcription factor nuclear factor κB (NFκB) by preventing dissociation from its inhibitor protein IκB and thereby preventing translocation into the nucleus.[54] As a result of this, treatment with TauCl reduces the production of the classical pro-inflammatory mediators interleukin (IL)-1β, IL-6, tumor necrosis factor alpha (TNF-α), and nitric oxide in stimulated immune cells.[58,59] While TauCl production from primary human neutrophils is well characterized *in vitro*, direct *in vivo* evidence from human studies is currently lacking.[52,60] Given its rapid reactivity with proteins and antioxidants, TauCl is best understood as a locally acting paracrine mediator at sites of inflammation, rendering systemic detection in plasma both methodologically and biologically unlikely, which may account for the evidence remaining confined to *in vitro* and *ex vivo* models.[61] The direct role of taurine remains controversial, as some studies reported no direct effect of taurine on inflammatory markers of cultured immune cells,[62,63] whereas others do.[64] In a mechanistic study, taurine upregulated the nuclease angiogenin, which degrades mitochondrial RNA released by activated macrophages, thereby reducing inflammation in inflammatory bowel disease.[64] Furthermore, taurine can promote macrophage polarization towards the anti-inflammatory M2 phenotype.[62] Through these mechanisms, taurine and its derivative TauCl jointly facilitate the resolution of inflammation and cellular stress recovery (Fig. 2).

However, the antioxidant capabilities of taurine seem to extend beyond the direct reduction of oxidants. Numerous studies have demonstrated that taurine treatment strengthened antioxidant defense against stress induced by various models in the liver,[65–67] kidney,[68,69] brain,[70–72] testis,[73,74] and other tissues.[51,75–78] The most consistent outcome across these studies was a rescue in glutathione (GSH) levels, accompanied by restored protein abundance and activity of key antioxidant enzymes: glutathione peroxidase (catalyzing ROS detoxification by oxidizing GSH to glutathione disulfide (GSSG)), glutathione reductase (regenerating GSH from GSSG), glutathione-*S*-transferase (conjugating GSH to electrophilic compounds), as well as superoxide dismutase (SOD) and catalase, which catalyze the stepwise conversion of superoxide into hydrogen peroxide and ultimately water, respectively.[79,80] These effects were accompanied by a reduction in oxidative stress markers, such as malondialdehyde (MDA), a by-product of ROS-induced lipid peroxidation, an effect that has also been observed in human studies.[81] As partial explanations for these effects, activation of the antioxidant machinery *via* the Nrf2 pathway and inhibition of the production of pro-inflammatory mediators *via* Toll-like receptor 4 (TLR4)-NF-κB pathway modulation have been proposed.[65,68,70,72,73,76–78] While taurine treatment consistently upregulates Nrf2 target genes and suppresses NF-κB pathway markers across diverse rodent injury models, the molecular mechanism linking taurine to pathway activation remains poorly defined. Direct binding of taurine to TLR4 has been proposed in one study; however, this putative binding has not been experimentally validated.[77] The downstream effects of these pathways have been replicated in some human studies, supporting their *in vivo* relevance.[81,82] It remains plausible that they represent mutually reinforcing secondary effects downstream of other primary actions of taurine, pending studies that establish direct causal interactions.

These findings partially overlap with the aforementioned actions of TauCl. As most of these data were generated by inducing stress in animals with toxins or diets that in turn also lead to inflammation, it is plausible to assume that at least a part of the effects were mediated by TauCl produced from activated neutrophils. A clear distinction between the effects mediated by TauCl and those mediated by other taurine-dependent mechanisms, with respect to inflammation and antioxidant action, is still lacking. Furthermore, the positive effects of taurine treatment may in part be mediated by the accumulation of sulfur-containing precursors. Hepatic CSAD is downregulated during taurine supplementation,[83–85] and shutting down the main taurine biosynthesis pathway induces accumulation of cysteine and hydrogen sulfide (H_2S).[86] H_2S that is derived from cysteine catabolism has strong antioxidant properties and promotes mitochondrial biogenesis.[87] Accumulation of cysteine and H_2S has been induced by taurine administration in mice and improved carbon tetrachloride-induced liver damage.[85] Moreover, cysteine is the rate-limiting precursor not only for H_2S and taurine synthesis, but also for GSH synthesis. When cysteine availability is limited in the liver, it is preferentially utilized for GSH synthesis, whereas under conditions of abundance it is increasingly directed toward taurine synthesis *via* CSAD and CDO1.[88,89] Some studies have demonstrated that increased taurine production through enhanced cysteine flux toward taurine synthesis, for example *via* CDO1 overexpression, reduces the cell's capacity to synthesize GSH.[90,91] While it has not yet been directly shown that, conversely, taurine supplementation alone can enhance GSH production by sparing cysteine pools, a study published in 2026 showed that taurine combined with B vitamins involved in GSH synthesis can increase GSH levels to physiologically relevant levels in the brain.[92] Another study demonstrated that liver-specific CDO1 knockout in mice resulted in increased resting hepatic cysteine pools and higher GSH regeneration capacity, as well as reduced liver damage in response to acetaminophen-induced liver injury.[93] Whether taurine supplementation can induce comparable GSH production capacity in the liver or in other taurine-synthesizing tissues remains to be established. Collectively, this highlights the necessity of also taking metabolites upstream and downstream of taurine into account when investigating its molecular mechanisms.

2.2 Mitochondrial health and calcium homeostasis

It might not be a coincidence that taurine is most present in tissues with high energy demand. There are several mecha-

nisms by which taurine influences mitochondrial health and energy metabolism. Taurine has been shown to be transported into mitochondria by TauT.[94] The intracellular localization of TauT towards the plasma or mitochondrial membrane appears to depend on its phosphorylation status, which is regulated by protein kinase A.[94] Evidence also suggests that taurine may be synthesized within mitochondria.[95] Hansen *et al.*[96,97] proposed taurine as a pH buffer for the slightly alkaline mitochondrial matrix that is established by the oxidative phosphorylation (OXPHOS). Inspired by the lack of defined low-molecular-weight physiological pH buffers for this milieu they suggested this role for taurine, as the pK_a of its amino group lies in the relevant range and taurine appears to be abundantly present in mitochondria. Even though the calculated proton buffer capacity of taurine seems small in relation to the proton turnover in active mitochondria, taurine could cushion transients in oxygen supply and thereby help stabilize ATP production. Given the differential pH sensitivity of mitochondrial enzymes involved in the urea cycle, the tricarboxylic acid (TCA) cycle, and fatty acid β-oxidation, taurine may contribute to selective regulation of their activation.[98] However, this hypothesis remains largely theoretical and has not been experimentally validated.

A systemic buffering role of taurine has been proposed not only for mitochondrial pH, but also for mitochondrial calcium homeostasis. When neurons suffer from glutamate-induced calcium overload, pretreatment with taurine rapidly promotes intracellular calcium ($[Ca^{2+}]_i$) clearance, presumably by uptake and buffering into mitochondrial calcium stores.[99] This is supported by taurine increasing mitochondrial calcium uptake proposedly by upregulating mitochondrial calcium uniporter activity.[100] Additionally, taurine reduces calcium-induced swelling in isolated mitochondria.[101] This could be due to taurine's role as an osmoregulator or an increase of the mitochodrial calcium-buffering capacities. Taurine also influences whole cell calcium homeostasis. By being co-imported with Na^+ by the TauT, taurine can reduce the rate at which the Na^+–Ca^{2+} exchanger (NCX) usually exports calcium, thereby increasing $[Ca^{2+}]_i$ in myocytes.[102] When intracellular Na^+ is high, the NCX can operate in reverse mode, thus importing Ca^{2+}. During glutamate-induced neuronal excitation, when this is the case, taurine protects against calcium overload either by directly inhibiting NCX reverse-mode activity independently of TauT, or by restricting calcium influx through interactions with other calcium channels.[103,104] As cytosolic calcium acts as a second messenger in many central signaling pathways and mitochondrial calcium content directly influences OXPHOS rates, taurine's regulatory functions in this context warrant further investigation.[105] Taurine-mediated calcium regulation has already been reported to influence the pathways of inflammation,[64] energy metabolism,[106] and lipid metabolism,[107] and additional mechanisms are expected to be identified in the future.

A more direct way in which taurine ensures mitochondrial health is through its conjugation to uridine residues of specific mitochondrial transfer RNAs (mt-tRNAs).[108] These taurine–uridine conjugations (5-taurinomethyluridine (τm^5U) and 5-taurinomethyl-2-thiouridine (τm^5s^2U)) stabilize the codon–anticodon interaction and are critical for translation of mitochondrially encoded proteins and for respiratory function. Knockout of the enzymes responsible for these reactions abolishes the formation of τm^5U and τm^5s^2U in mt-tRNA and causes severe consequences.[109] It has been shown that taurine starvation of cats, which in contrast to other mammals cannot synthesize taurine, leads to a reduction in the levels of taurine-conjugated nucleotides in mt-tRNAs.[110] Inhibiting taurine import into mitochondria in cancer cells by TauT knockdown reduced the formation of τm^5U modifications, blunted mitochondrial translation and diminished tumor growth in xenografts.[94] Another study demonstrated reduced levels of τm^5U mt-tRNA and a dependent electron transport chain complex I subunit protein in the liver of aged mice, which was restored by taurine supplementation.[42] Importantly, studies on patient-derived tissue have demonstrated that mt-tRNAs carrying pathogenic mutations associated with MELAS (mitochondrial myopathy, encephalopathy, lactic acidosis, and stroke-like episodes) are specifically deficient in the τm^5U modification and that this deficiency is the primary molecular cause of the translational defects observed clinically in MELAS.[111,112] Taurine supplementation reduced the stroke-like episode frequency by ≥50% in 8 of 10 MELAS patients in a phase III open-label clinical trial, and 5 of 10 patients showed a significant increase in the τm^5U modification rate of the affected mt-tRNA from peripheral leukocytes.[113] Together with the evidence for taurine serving as a critical substrate to mt-tRNA modifications described above, these findings support the physiological relevance of taurine-dependent mt-tRNA modifications in humans. Nevertheless, it remains to be established whether reductions in taurine-conjugated mt-tRNAs occur in healthy individuals and whether taurine supplementation can actively enhance mitochondrial translation and reduce ROS production *via* this mechanism.

Besides acting within mitochondria, several studies in rodents have identified long-term taurine supplementation to induce increased transcription of mitochondria-related genes including peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PGC-1α) in the brain, skeletal muscle and adipose tissue. PGC-1α acts as a master regulator of energy metabolism, facilitating the expression of genes involved in mitochondrial biogenesis, glucose metabolism and oxidative stress protection.[114] In the brain, long-term taurine supplementation to healthy wild-type mice led to increased expression and protein activity of PGC-1α, proteinkinase B (Akt), cAMP response element-binding protein (CREB) and PTEN-induced kinase 1 (PINK1), regulating mitochondrial biogenesis and quality control.[115] The isolated mitochondria of these mice exhibited elevated ATP levels and reduced calcium-induced swelling. These effects were accompanied by enhanced memory and reduced anxiety/depression-like behaviour in the behavioural tests of the animals. Similar results were obtained for skeletal muscle in a study in which healthy rats received taurine supplementation for a shorter period,

leading to increased expression of PGC-1α and muscle differentiation and growth factor myocyte enhancer factor-2 (MEF2).[106] In a cell culture model, they demonstrated that these changes were the result of AMP-activated protein kinase (AMPK) signaling induced by taurine-stimulated calcium influx. Proposedly *via* the same pathway, regeneration of aged mouse skeletal muscle was improved post injury.[116] Activation of the AMPK-PGC-1α pathway has also been demonstrated in adipose tissue after taurine was administered alongside a high-fat diet to mice.[117] As a consequence, this induced elevated rates of mitochondrial β-oxidation. Phenotypic changes included body weight reduction and an increase in energy expenditure. Taken together, all of these studies imply a decisive role of mitochondrial function for the positive effects of taurine supplementation. Validating these findings in humans is inherently challenging, as the tissue specific expression of these genes cannot be assessed non-invasively *via* the blood. Nevertheless, adipose tissue biopsies from obese subjects have shown that taurine supplementation, when combined with exercise training, increased the expression of key mitochondria-related genes including PGC-1α, suggesting that at least some of these effects translate to humans.[118] Determining how taurine stimulates the pathways that improve mitochondrial function, either directly or indirectly *via* systemic effects such as calcium regulation and osmoregulation, may finally provide the missing link between taurine's health benefits and its molecular mechanisms.

Overall, taurine's molecular mechanisms have been thoroughly reviewed elsewhere, complementing the present discussion.[45,51,54]

3. Exercise, oxidative stress and age-specific human studies

3.1 Exercise studies

Taurine may enhance exercise performance through multiple interconnected molecular mechanisms acting in skeletal muscle and related systems. Experimental evidence indicates that taurine modulates intracellular Ca^{2+} handling by stabilizing sarcoplasmic reticulum Ca^{2+} release and improving excitation–contraction coupling,[1,119] thereby supporting force production and neuromuscular efficiency. In addition, taurine may contribute to membrane stabilization and ion homeostasis, helping to preserve Na^{+}, K^{+}, and Ca^{2+} gradients during muscle contractions.[119] Taurine conjugates with mitochondrial tRNA to facilitate the synthesis of mitochondrial-encoded proteins,[45] which may support efficient electron transport chain activity and ATP production, potentially contributing to improvements in aerobic endurance. Furthermore, taurine exerts indirect antioxidant and anti-inflammatory effects that may protect contractile proteins from exercise-induced oxidative stress, which could contribute to reduced exercise-induced muscle damage.[120] Finally, as a major intracellular osmolyte, taurine contributes to the regulation of the cellular osmotic balance in skeletal muscle.[119] Spriet and Whitfield[7] reviewed the importance of taurine in skeletal muscle highlighting that evidence from rodent models shows that reducing muscle taurine levels impairs contractile function, whereas supplementation increases the muscle taurine content and partly improves the performance.[121–125] In humans, however, although acute taurine ingestion markedly elevates plasma concentrations, no corresponding increase occurs in skeletal muscle, thereby limiting ergogenic effects.[126,127] Studies in isolated human muscle fibers demonstrated that taurine exposure can enhance sarcoplasmic reticulum Ca^{2+} accumulation, yet clinical trials have produced conflicting and inconclusive results regarding supplementation on performance and recovery.[126–129] The same mixed results have been reported in more recent randomized clinical trials (RCTs),[130–135] systematic reviews[136] and meta-analyses (Table 1).

An up-to-date systematic review and meta-analysis of 23 RCTs including 308 healthy adult participants found a small-to-moderate beneficial effect of single-dose taurine ingestion (1–6 g) on exercise performance.[137] Benefits were more evident in males (n = 255) and this effect was mostly pronounced when taurine was supplemented 1 h prior to exercise and was most reliably demonstrated in aerobic endurance and strength/power, while it was not significant in anaerobic performance and muscular endurance. In women (n = 53), no significant benefit was observed. There was no linear dose dependency and no difference between trained and untrained populations. Notably, most studies (n = 15) recruited trained athletes, with only a few (n = 8) including untrained volunteers. Reflecting the heterogeneity of results and risk of bias, the certainty of evidence was judged to be low to very low.[137] The more evident effects observed in males compared to females may reflect the male-dominated nature of the available evidence, as most included studies recruited exclusively male participants (n = 19), three recruited only females, and only one included both sexes.[137] Therefore, the absence of a clear effect in women may be interpreted as reflecting limited evidence rather than definitive ineffectiveness. In addition to sampling-related limitations, biological and physiological factors may contribute to the observed sex-related differences as sexual hormones play a role in endogenous taurine synthesis and tissue taurine uptake.[138] Moreover, the effects of taurine may vary across the menstrual cycle and with oral contraceptive use, as fluctuations in sex hormones can influence body water regulation, exercise capacity, metabolism, cognition, sleep, and thermoregulation.[139] Extrapolating the mechanism of 17β-estradiol dependent taurine uptake regulation to the skeletal muscle, which does express estrogen receptors, fluctuations in estrogen levels across the menstrual cycle or with hormonal contraceptive use may dynamically regulate intracellular taurine availability in women.

Another systematic review identified eight chronic taurine supplementation trials (7 days to 8 weeks), all of which were exclusively performed in healthy adult males.[136] Protocols included aerobic and anaerobic exercise tests, with daily doses (1.66 g up to 10 g) compared to placebo. Taurine improved the antioxidant status, reduced muscle damage markers, and mod-

Table 1 Recent meta-analyses of human RCTs on taurine supplementation in healthy and cardiometabolic diseased subjects. Risk of bias and heterogeneity varied among included RCTs and the same RCT can be included in multiple meta-analyses

Study	Research area	Population	Taurine dosage and duration	Outcomes	Significant findings	Number of participants and studies
Deng *et al.* (2025)[142]	Exercise	Healthy adults (trained and untrained)	1–4 g day^{-1}, acute	HR, lactate, RT, RPE, physical & cognitive exercise performance (various types)	None	185 from 9 RCTs
Deng *et al.* (2025)[137]	Exercise	Healthy adults (trained and untrained)	14–100 mg per kg BW, acute	Exercise performance (various types)	↑Aerobic endurance, ↑strength and power	308 from 23 RCTs
Waldron *et al.* (2018)[143]	Exercise	Healthy and diseased adults	1–6 g day^{-1}, acute, 2 weeks	TTE, exercise performance (strength, time)	↑TTE	116 from 10 RCTs
Faghfouri *et al.* (2022)[81]	Metabolic health	Healthy and diseased adults	1.5–6 g day^{-1}, 3 days–6 months	IL-6, TNF-α, CRP, MDA	↓CRP, ↓MDA	382 from 14 RCTs
Guan & Miao (2020)[144]	Metabolic health	Healthy and diseased adolescents and adults	0.5–6 g day^{-1}, 15 days–6 months	TC, LDL, HDL, TG, BP, FBG, BMI, BW	↓TC, ↓TG, ↓BP	391 from 12 RCTs
Nie *et al.* (2025)[145]	Metabolic health	Healthy and diseased adults	0.5–6 g day^{-1}, 1–16 weeks	IL-1β, IL-6, IL-10, TNF-α, CRP, TBARS, SOD, GSH, CAT, TC, LDL, HDL, TG, LF, BP, HR, FBG, insulin, HbA1c, HOMA-IR, BMI, BW, WC, fat mass	↑IL-1β, ↓TNF-α, ↓CRP, ↓MDA, ↓TBARS, ↓TC, ↓LDL, ↑HDL, ↓TG, ↑LF, ↓BP, ↓FBG, ↓insulin, ↓HbA1c, ↓HOMA-IR, ↓fat mass	1394 from 34 RCTs
Sun *et al.* (2025)[146]	Metabolic health	Adults with overweight/obesity	1–3 g day^{-1}, 2–12 weeks	TC, LDL, HDL, TG, FBG, insulin, BMI	↓TC, ↓LDL (only in obese), ↑HDL (only in overweight), ↓TG, ↓FBG, ↑insulin sensitivity	414 from 9 RCTs
Tao *et al.* (2022)[147]	Metabolic health	Adults with diabetes	1–5 g day^{-1}, 2–16 weeks	TC, LDL, HDL, TG, BP, FBG, insulin, HbA1c, HOMA-IR, BMI, BW, energy intake, protein, fat, WC	↓FBG, ↓HbA1c, ↓HOMA-IR	219 from 5 RCTs
Tzang *et al.* (2024)[148]	Metabolic health	Healthy and diseased children, adolescents, and adults	0.5–6 g day^{-1}, 5 days–12 weeks	TG, HDL, BP, FBG	↓TG, ↓BP, ↓FBG	1024 from 25 RCTs
Tzang *et al.* (2024)[149]	Cardiovascular	Healthy and diseased adults	1.5–6 g day^{-1}, 7 days–12 months	BP, HR, LVEF, NYHA	↓BP, ↓HR, ↑LVEF, ↓NYHA	808 from 20 RCTs
Waldron *et al.* (2018)[150]	Cardiovascular	Healthy and diseased adults	1–6 g day^{-1}, acute, 12 weeks	BP	↓BP	103 from 7 RCTs
Cao *et al.* (2025)[151]	Cognitive health	Diseased adults	Taurine 1–3 g day^{-1}, 2–48 weeks	Cognitive exercise performance (various types)	None	402 from 7 RCTs

RCT – randomized clinical trial, HR – heart rate, RT – reaction time, RPE – rating of perceived exertion, TTE – time to exhaustion, IL-6 – interleukin-6, TNF-α – tumor necrosis factor alpha, CRP – C-reactive protein, MDA – malondialdehyde, IL-1β – interleukin-1β, IL-10 – interleukin-10, TBARS – thiobarbituric acid reactive species, SOD – superoxide dismutase, GSH – glutathione, CAT – catalase, TC – total cholesterol, LDL – low-density lipoprotein, HDL – high density lipoprotein, TG – triacylglyceride, BP – blood pressure, FBG – fasting blood glucose, BMI – body mass index, BW – body weight, HbA1c – glycated hemoglobin, HOMA-IR – homeostatic model assessment for insulin resistance, LF – measurements of liver function, WC – waist circumference, LVEF – left ventricular ejection fraction, NYHA – New York Heart Association functional classification

estly enhanced endurance in some studies. The strongest benefits occurred with multi-week dosing of 2–6 g day^{-1}, particularly for oxidative stress reduction and muscle recovery, though performance results were inconsistent due to variations in sample size, training status, and exercise type.[136] Thus, although taurine is essential for muscle function, further research is required to elucidate the mechanisms regulating its transport into human skeletal muscle and to determine its true potential as an ergogenic nutrient. To date, there are no authorized health claims about taurine as a sports supplement authorised by the European Commission; nevertheless, taurine has been marketed as such since a long time.[140,141]

In general, human trials on taurine supplementation lack methodological consistency. In the context of diabetes and obesity, an 8-week supplementation period with 3 g day^{-1} of taurine has been established by several research groups, thereby enabling improved comparability among studies.[43,152–156] For

other study populations, similarly standardized supplementation protocols are needed to enhance comparability. Consistency across studies is also essential for evaluating dose–response relationships, which require comparable disease contexts, baseline health status, and intervention durations. Although an intervention duration of 8 weeks is often considered long-term, longer intervention periods within comparable populations would provide additional insight into effects that may only emerge after several months of supplementation. Another important variable is diet, which should be controlled or at least carefully monitored, as it can influence plasma taurine concentrations as well as other study outcomes.[82] As highlighted previously, it is important to isolate effects caused by taurine within specific disease and health contexts, as these effects may vary substantially between conditions. Given that taurine appears to serve a homeostatic function, its effects may be more subtle in healthy individuals, which is particularly relevant in the contexts of sports performance and healthy aging. Another important and often neglected aspect concerns sex-dependent differences in response to taurine supplementation. In the existing literature, females are underrepresented in most animal and human studies, despite evidence indicating that taurine synthesis and distribution, as well as bile acid metabolism, which is thought to mediate some of taurine's effects and thereby may influence study outcomes, are differentially regulated by the sex hormones estrogen and testosterone.[138,157] Considering that several human studies have already reported sex-specific differences in response to taurine supplementation,[138] and that many diseases potentially affected by taurine, such as cardiovascular disease and type 2 diabetes, also exhibit pronounced sex differences,[158,159] the inclusion of both sexes in future studies is essential. Meta-analyses such as those presented in Table 1 provide a useful overview of existing human studies but should be interpreted with caution, as they aggregate heterogenous study populations and study designs.

3.2 Oxidative stress and inflammation studies

As discussed previously, taurine and its precursors are linked to cellular redox balance and the modulation of inflammation; therefore, supplementation has been proposed as an antioxidant and anti-inflammatory strategy, given that chronic inflammation is associated with aging and the development of conditions such as cardiovascular disease, obesity, and diabetes.[81,160]

A RCT reports that taurine supplementation (1.5 g day^{-1} for 16 weeks) increased plasma taurine and SOD levels in sedentary postmenopausal women aged 55–70 years, whereas the oxidative stress marker MDA rose only in the placebo group.[82] Some participants in both experimental groups were classified as obese, which might have amplified the effect of taurine in this study, as taurine exerts strong effects on adipose tissue, as will also be discussed later in this review. Food intake was monitored throughout the study and revealed between groups and also within groups before and after the intervention. However, this was not considered to have significantly influenced the study outcomes. Notably, zinc intake in the taurine group declined after the intervention, whereas plasma zinc concentrations decreased in both experimental groups, which may have affected SOD activity, as zinc is an essential cofactor of SOD.[80,82] It has to be noted that the participants were subject to increased basal stress as the study was performed during an intensive period of emotional stress due to the COVID-19 pandemic, which also might have affected individuals differently.[82] The results nevertheless suggest a protective effect of taurine against oxidative damage and chronic inflammation.

Faghfouri *et al.*[81] conducted the first systematic review and dose–response meta-analysis to evaluate the effects of taurine supplementation on inflammatory and oxidative stress biomarkers. Fourteen controlled clinical trials (382 participants, aged 19–85 years) were included, with intervention doses ranging from 1500 to 6000 mg day^{-1} and supplementation periods from 3 to 180 days. The included studies targeted a wide range of different populations, which were diabetic patients, obese participants, severe burn patients, heart failure patients, and patients with chronic alcoholism, hip fracture or acute lymphoblastic leukemia. Furthermore, three studies featured an additional exercise intervention. The pooled analysis revealed that taurine significantly reduced the plasma levels of MDA and the inflammation marker C-reactive protein but showed no significant effect on TNF-α or IL-6. Time–response analysis indicated that supplementation for 56 days exerted the most pronounced benefits on oxidative stress and inflammation. Subgroup analysis suggested greater effects in interventions using ≤3000 mg day^{-1}. The subgroup analysis furthermore suggested greater effects in younger adults (18–50 years) and obese individuals, while heterogeneity across studies was substantial.[81] The pooled and subgroup analyses were heavily influenced by the low number of studies included and heterogeneity of the studied populations. For example, three studies featuring obese or diabetic middle aged-participants demonstrated a reduction in plasma TNF-α after 56 days of taurine supplementation, whereas measurements from a study in elderly female subjects with or without performing physical exercise showed an increase or no change in plasma TNF-α after 98 days of supplementation.[81] Considering this heterogeneity, the available evidence does not support the conclusion that longer durations of taurine supplementation reduce its efficacy in lowering circulating TNF-α levels.

Collectively, these findings suggest that taurine may ameliorate systemic inflammation and oxidative stress, yet the extent and efficacy are highly dependent on the baseline health status of the individuals and potentially also on their age and sex.[138] To reliably assess dose– and time–response relationships for taurine supplementation in oxidative stress and inflammation, more rigorously designed RCTs that focus on said parameters while keeping other cofounding factors as small as possible are needed.

3.3 Age-specific studies

As discussed later in this review, taurine has also been proposed as an anti-aging agent. Even though there are no human

trials on taurine's direct effect on aging yet, there are some studies published that target people of higher age. We would like to refer to a work by Batitucci *et al.*[43] that comprehensively reviews the impact of taurine supplementation and physical exercise, including clinical trials, on sarcopenic obesity, a health condition that is especially prevalent in older adults.

A RCT investigated the effects of 14 weeks of physical exercise, alone or in combination with taurine supplementation (1.5 g day^{-1}), on inflammation, cognition, and peripheral markers of blood–brain barrier integrity in institutionalized elderly women.[161] 48 participants (83.5 ± 6.9 years) were allocated into four groups: physical exercise (n = 13), taurine supplementation (n = 12; 1.5 g day^{-1}), physical exercise combined with taurine supplementation (n = 11), and control (n = 12). Comorbidities such as hypertension (75%), heart failure (58%), and dyslipidemia (35%) were present among the participants; however, the authors did not further specify their distribution across the different experimental groups. These comorbidities, as well as the fact that some participants in all groups were classified as obese, may have influenced the study outcomes. Vitamin and mineral intake were not tracked, although all participants were assessed as being at risk of malnutrition according to the mini nutritional assessment. Exercise sessions were multimodal, chair-based, and performed twice a week under specialist supervision. Outcomes included plasma cytokines (IL-1β, IL-1ra, IL-6, IL-10, IL-17, TNF-α), serum markers of blood–brain barrier permeability, cognitive status, and handgrip strength. Measurements were taken at baseline and post-intervention.[161] The results demonstrated that physical exercise significantly reduced pro-inflammatory markers (TNF-α, IL-6) and improved the cytokine balance (IL-1β/IL-1ra, IL-6/IL-10, TNF-α/IL-10 ratios). Taurine supplementation alone decreased the IL-1β/IL-1ra ratio, while exercise combined with taurine supplementation uniquely improved cognitive performance, as reflected by higher cognitive test scores. Blood–brain barrier integrity was preserved in all intervention groups or even increased moderately in the taurine-only group.[161] Further analysis of samples from this study, reported in a subsequent publication, revealed reductions in plasma myeloperoxidase (MPO) and matrix metalloproteinase-9 (MMP-9) levels.[162] These enzymes have been selected as outcome measures because both play a role in oxidative stress or inflammation propagation in several age-related pathologies.[162,163] Overall, the findings suggest that taurine supplementation represents a viable strategy to promote health in older women, especially when combined with physical exercise. Comparable studies in older men have yet to be conducted. Another RCT, already discussed in detail in chapter 3.2, has shown that taurine supplementation (1.5 g day^{-1} for 16 weeks) increased plasma SOD levels in postmenopausal women, whereas MDA increased only in the placebo group, suggesting that taurine supplementation may be a viable nutritional strategy for controlling oxidative stress during the aging process.[82]

Robust clinical evidence demonstrating the efficacy of taurine supplementation in human aging is lacking. Future research should prioritize mechanistic investigations and even longer RCTs to clarify whether taurine supplementation can exert clinically meaningful effects on human aging.

4. Taurine and metabolic syndrome

Metabolic syndrome is a disease state defined by a combination of characteristics related to altered energy metabolism, leading to an increased risk of cardiovascular diseases, type 2 diabetes and other organ dysfunctions. The pathologies that together constitute metabolic syndrome include obesity, insulin resistance or hyperglycemia, dyslipidemia and elevated blood pressure.[164] They are highly interconnected and reinforce each other. The prevalence of metabolic syndrome is increasing globally, linked to an increasing sedentary lifestyle and availability of energy-dense foods. Depending on the region and ethnicity, metabolic syndrome affects approximately 10–40% of the global population,[164] pointing to the importance of potential beneficial dietary interventions such as taurine supplementation.

In multiple human studies, a link between taurine and the features of metabolic syndrome has been established. The basal plasma taurine content of obese and diabetic participants was lower than that in control groups.[155,165–168] In obese middle-aged women, taurine supplementation (3 g day^{-1} for 8 weeks) significantly increased plasma adiponectin and reduced markers of inflammation and oxidative stress as compared to placebo.[155] Energy and macronutrient intake was tracked and did not differ between groups. In another study, 3 g day^{-1} of taurine for 7 weeks reduced serum triacylglycerol (TG) and improved the total cholesterol to high-density lipoprotein cholesterol (HDL-C) ratio in young adult overweight and obese participants, though dietary intake was not tracked.[169] Participants in both of these studies had no known history of endocrine disease and were instructed not to change their daily activity.[155,169] Healthy young men receiving a controlled high-cholesterol, high-fat diet for 3 weeks exhibited an attenuated rise in total serum cholesterol, low-density lipoprotein cholesterol (LDL-C) and LDL when additionally being supplemented with 6 g taurine per day.[170] Furthermore, supplementation with 3 g taurine for 8 weeks showed promising results across different studies in patients with type 2 diabetes for reducing insulin resistance as assessed by the Homeaostatic Model Assessment for Insulin Resistance,[153,154,156] fasting blood glucose,[153,154] and glycated hemoglobin,[154] which serves as an moderate indicator for hyperglycemia.[171] In a study on resting blood pressure (n = 144), taurine supplementation of 2.4 g day^{-1} for 12 weeks *versus* placebo reduced systolic blood pressure in type 2 diabetic patients with elevated blood pressure at the baseline.[172] In a different study (n = 97), taurine supplementation of 1.6 g day^{-1} for the same duration *versus* placebo reduced both systolic and diastolic blood pressure in non-diabetic prehypertensive middle-aged participants.[173] In both of these studies, taurine supplementation also increased endothelium-dependent and -independent vasodilation.[172,173] Even though indi-

vidual study outcomes are not always consistent and study designs are often heterogeneous, meta-analyses support the beneficial effects of taurine supplementation on the features of metabolic syndrome across multiple studies (Table 1).

Interestingly, analysis of clinical risk factors and blood taurine levels from 11 966 subjects of the EPIC-Norfolk study established a negative correlation between taurine levels and the prevalence of obesity and type 2 diabetes, but surprisingly a positive correlation with total cholesterol, LDL-C, and dyslipidemia.[42] This may be explained by the fact that the major food sources of taurine, meat and seafood,[5] are also rich in cholesterol[174] and are consumed at a large margin in the UK,[175] where this study was conducted. Dietary cholesterol intake is associated with higher circulating total cholesterol and LDL-C levels,[176] whereas on the other hand many foods that reduce LDL-C levels are plant-based and do not contain taurine.[177,178] The inverse correlation between blood taurine levels and obesity and type 2 diabetes could be explained by these diseases presumably reducing taurine levels causatively by reducing TauT activity, renal taurine absorption and taurine synthesis in white adipose tissue (WAT).[179,180] Furthermore, obesity appears to increase the metabolic taurine flux, which can contribute to lower taurine levels in obese individuals.[181]

These human studies are underpinned by a wide range of mechanistic research studies (Fig. 3). Taurine's role in cardiovascular health has already been well summarized in a different review.[44] One mechanism by which taurine is thought to reduce blood pressure and lower the risk of cardiovascular events is by enhancing H_2S synthesis in arteries and platelets,[172,173,182] a mechanism of taurine that has also been described as protective in the liver and kidneys of rodents.[85,183] Sun *et al.*[173] and Li *et al.*[172] demonstrated that the H_2S donor NaHS reduces calcium influx in human arteries and platelets, thereby increasing vascular relaxation and reducing platelet activation, respectively. In addition, they reported increased plasma H_2S concentrations following taurine supplementation in clinical trials, linking this mechanism to the observed clinical effects of taurine in reducing blood pressure.

Regarding hyperlipidemia, taurine can influence lipid metabolism in different ways, as demonstrated in animal studies. The direct effect of taurine on cholesterol synthesis *via* HMG-CoA reductase (HMGCR), the rate-limiting enzyme in cholesterol synthesis, remains debated: taurine supplementation actually increased the HMGCR protein level in hamsters and mice being fed a high-fat diet,[66,184–186] while it was found reduced in rats[187] or in a model of alcoholic liver disease.[188] Besides the use of different animal models, variations in the dietary fat sources may account for the contradicting results, as HMGCR levels and cholesterol metabolism are differentially affected by this.[189] Taurine facilitates the clearance of circulating LDL-C by increasing the expression and binding affinity of the LDL receptor, thereby increasing the uptake into the liver.[185,190] Taurine then promotes the clearance of hepatic cholesterol by upregulating its incorporation into bile acids through upregulation of cholesterol 7α-hydroxylase (CYP7A1), the rate-limiting enzyme in bile acid synthesis, which also results in increased bile acid secretion.[191] It is proposed that this occurs *via* taurine-mediated decreases in the upstream negative-regulators small heterodimer partner (SHP), mitogen-activated protein kinase kinase (MEK1/2) and phosphorylated c-Jun in the liver.[84,107] Taurine also directly binds to and activates liver X receptor-α (LXR-α), which in rodents further increases *Cyp7a1* expression, whereas in humans it inhibits *CYP7A1* expression by inducing *SHP* expression.[192,193] This LXR-α-mediated upregulation of *SHP* appears to be overridden by the taurine-dependent decrease in SHP levels. Thereby taurine increases CYP7A1 levels even in the hepatocytes of humans.[84,107] Furthermore, LXR-α usually induces production of sterol regulatory element-binding protein 1c (SREBP-1c), an important positive regulator of lipid synthesis. During taurine-induced LXR-α activation, however, the induction of SREBP-1c is prevented *via* taurine-activated AMPK[187,194] and through inhibition of its nuclear translocation by taurine-mediated induction of insulin induced gene 2 (INSIG2).[192] This AMPK activation concurrently increases mitochondrial β-oxidation, which further solidifies the anti-hyperlipidemic effects of taurine in the liver.[187] Because AMPK has been shown to be activated by taurine-mediated calcium influx in muscle cells and the clearance of free cholesterol *via* MEK1/2-CYP7A1 in human hepatocytes appears to be under control of taurine-mediated calcium signaling, it can be inferred that the AMPK activation in the liver might follow the same mechanism.[106,107]

Lipid metabolism is also thought to be altered by taurine in adipose tissue during obesity. Several studies attributed reduced weight gain through long-term taurine supplementation in rodent models of obesity to elevated fatty acid degradation *via* β-oxidation and to the increase in lipolysis, whilst fatty acid synthesis and lipogenesis were reduced.[117,195,196] The beneficial effect of taurine on obesity has also been attributed to 'browning' of WAT towards the metabolically more active and energy consuming brown adipose tissue (BAT). This is indicated by an increased protein level of PGC-1α and uncoupling protein 1 (UCP1), the latter of which is responsible for non-shivering thermogenesis.[117,197] However, the occurrence of 'browning' and upregulation of *Pgc-1α* and *Ucp1* in both WAT and BAT is not consistent across all studies.[195,196,198] What seems to be consistent is a reduction in obesity-induced chronic inflammation by long-term taurine supplementation. Lin *et al.*[62] observed reduced infiltration of inflammatory macrophages into WAT of obese mice, while anti-inflammatory M2 macrophage markers were increased. As there are neutrophils present in adipose tissue during obesity, this effect might stem from TauCl being produced.[54,199] Reduced levels of circulating cytokines and adipose tissue cytokines have been confirmed by other animal studies as well.[195,196,200] Reduced cytokine secretion from adipose tissue may improve insulin sensitivity and attenuate damage to other tissues, such as to insulin producing pancreatic β-cells. Moreover, taurine supplementation has been shown to improve cellular insulin signaling and to protect and even stimulate β-cells, leading to increased glucose tolerance in mice.[179,201] A taurine derivative, *N*-acetyltaurine, has recently been demonstrated to reduce

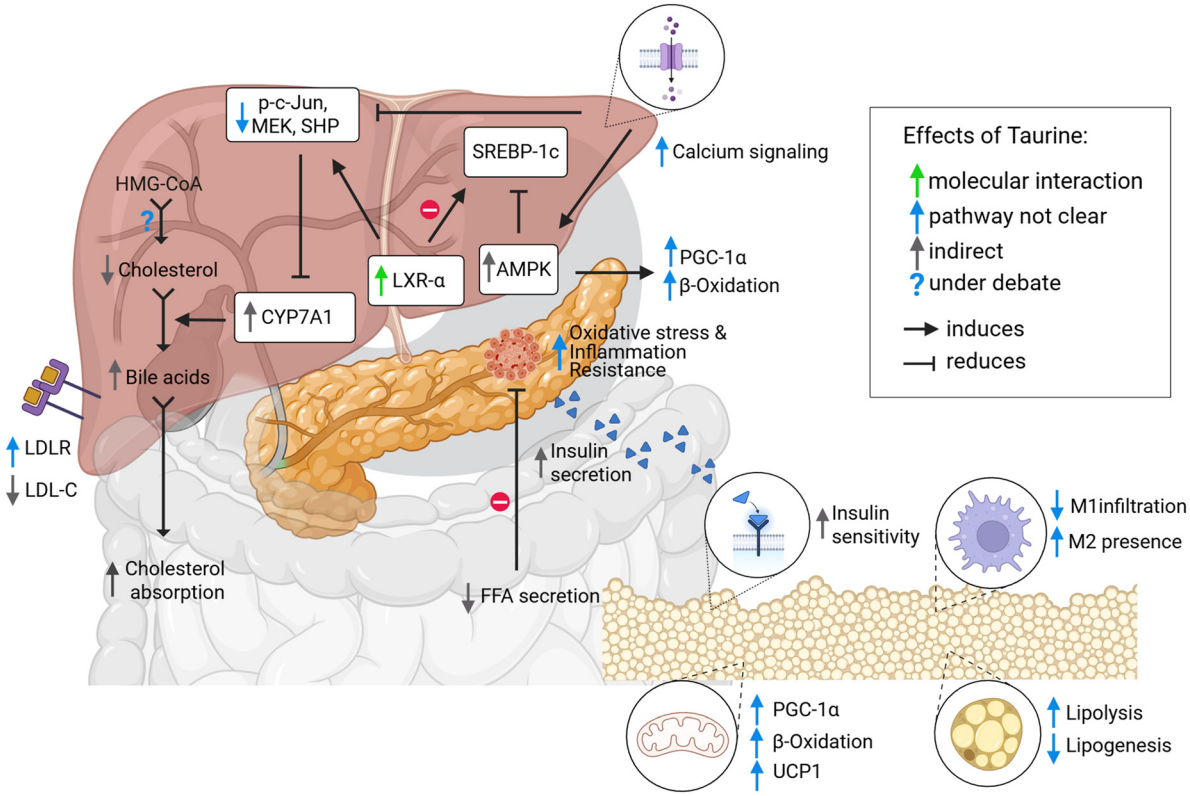

Fig. 3 Taurine's molecular impact on lipid metabolism. Taurine alters systemic lipid metabolism and energy metabolism in adipose tissue and protects pancreatic islets from cell damage. Mechanisms influencing hypertension are not depicted. AMPK – AMP-activated protein kinase; CYP7A1 – cholesterol 7α-hydroxylase; FFA: free fatty acid; HMG-CoA – HMG-Coenzyme A; HMGCR – HMG reductase; LDL-C: low-density lipoprotein cholesterol; LDLR – LDL receptor; p-c-Jun – phosphorylated c-Jun; MEK – mitogen-activated protein kinase kinase; PGC-1α – peroxisome proliferator-activated receptor gamma coactivator 1-alpha; UCP1 – uncoupling protein 1; SHP – small heterodimer binding partner; SREBP-1c – sterol regulatory element-binding protein 1c.

adipose tissue mass in obese mice.[202] Whether *N*-acetyltaurine mediates some of the effects observed for taurine supplementation is not yet clear.

De Carvalho *et al.*[118,203,204] were the first to investigate the direct translation of the here presented mechanisms to humans by taking subcutaneous WAT (scWAT) biopsy samples from obese women before and after an 8-week taurine supplementation intervention (3 g day^{-1}). They demonstrated increased expression of aconitase 2 (*ACO2*) and acyl-CoA oxidase 2 (*ACOX1*) following taurine supplementation, which are important genes involved in the TCA cycle and fatty acid oxidation.[118] However, the taurine intervention lacked a placebo control group for comparison. Other genes related to lipid metabolism such as *CPT1α* and *PPARα*, as well as genes associated with mitochondrial function, including *PGC-1α* and *UCP1*, were significantly upregulated only when taurine supplementation was combined with exercise, in contrast to taurine supplementation or exercise only.[118] Nonetheless, histological analysis revealed a significant reduction in adipocyte size, and cells exhibited multilocular lipid droplets, which are a characteristic of adipocyte "browning" in the scWAT of participants after 8 weeks of taurine supplementation.[203] These findings indicate the beneficial effects of taurine supplementation on adipocyte structure and metabolism. Furthermore, histological analysis showed a reduced presence of mast cells, which are contributors to obesity-induced inflammation. While in the human scWAT samples no reduction of inflammatory cytokines could be observed after 8 weeks of 3 g day^{-1} taurine supplementation, this intervention has been shown to reduce the IL-6 concentration in the plasma of the participants from whom the biopsy samples were taken.[203] The same intervention has also been reported to reduce plasma concentrations of the chronic inflammation marker highly sensitive C-reactive protein and IL-6 in other human obesity studies,[155,205] which highlights taurine also acting in other tissues, contributing to restoration of systemic metabolic health. Effects of taurine on insulin signaling pathways demonstrated in adipocyte cell culture were not mirrored in human scWAT.[204] De Carvalho *et al.* clearly highlighted the challenges associated with translating findings in taurine research from animal and cell culture models to human application. The data they provided indicate that mechanisms identified in rodent models may also apply to humans, yet the supplementation period and dosage may not have been sufficient to elicit these effects in human adipose tissue.[118,203,204] While human trials typically employ 1–6 g

day^{-1} of oral taurine supplementation for 1–16 weeks, mouse studies are commonly conducted using 1–5% taurine administered *ad libitum* in drinking water for 3–6 months, or *via* intraperitoneal injection, which is likely to increase taurine availability in target tissues.

Again, altogether taurine demonstrates a wide range of effects in different tissues, all contributing to the attenuation of metabolic syndrome features, rather than acting on a singular defined target (Fig. 3). The results of the studies presented here clearly support the idea of taurine as a dietary supplement helping to alleviate or prevent the development of metabolic syndrome. This approach is worth pursuing and warrants further validation in human studies.

5. Taurine in aging

Taurine has been implicated in aging. This idea originated from reports suggesting that circulating levels of taurine may decline in humans with age.[42,206,207] In addition, tissue levels and liver synthesis rates of taurine have been observed to decline in aging rats.[83,208] Ito *et al.*[209] further demonstrated that TauT knockout mice, which exhibit markedly reduced tissue taurine levels,[210] have a shortened lifespan and exhibit signs of premature aging and cellular senescence in skeletal muscle. However, this concept of taurine deficiency as a driver of aging does not hold up against recent studies, which convincingly demonstrate stable circulating taurine levels in humans and non-human primates, as well as stable taurine fluxes in mice.[181,211] Fernandez *et al.*[211] conducted an analysis of multiple longitudinal datasets from large humans and non-human primates and mouse cohort studies examining taurine levels, age and health status. They found no correlation – or if at all a positive – between circulating taurine concentrations and age, while there was no consistent correlation among taurine concentration and health status measures such as knee strength, grip strength and body weight. Positive correlations between plasma taurine levels and age were stronger in females than in males. This effect may stem from the alleviation of estrogen-dependent repression of taurine synthesis following the postmenopausal decline in estrogen levels.[14] The authors conclude that inter-individual variability in circulating taurine levels exceeded the intra-individual age-related changes.[211] Notably, many other studies also reported no change or even an increase in circulating taurine concentrations during aging. Fernandez *et al.*[211] summarized these studies in the SI. Despite this, earlier reports suggesting an age-related decrease have been widely cited. The high variability across existing studies may reflect differences in species, sex, diet, health status, and study design, for example reliance on cross-sectional *vs.* longitudinal data or pooling of sexes or other categories.[211] However, this only addresses physiological taurine levels. Active taurine supplementation on the other hand appears promising for supporting healthy aging independently of taurine deficiency, as taurine has been implicated in several processes related to aging.

Some studies have reported findings consistent with taurine attenuating several hallmarks of aging.[212] The strongest evidence, derived from aged mouse and non-human primate models, supports effects on mitochondrial dysfunction and chronic inflammation.[42] Further data from aged mice suggest reduced stem cell exhaustion, cellular senescence, and increased autophagy as a consequence of taurine supplementation.[42] Further associative evidence links taurine to improvements in epigenetic alterations,[42] deregulated nutrient-sensing,[42,213,214] loss of proteostasis,[215] dysbiosis,[157,216] genomic instability,[42,217] telomere shortening[42,218] and stem cell exhaustion,[42,219,220] though these findings are largely confined to TauT KO mouse models or *in vitro* systems. Although the available evidence does not indicate that taurine directly intervenes in each hallmark of aging at the molecular level, taurine supplementation has consistently been shown to beneficially influence multiple aging-associated phenotypes *in vitro* and *in vivo*. Future studies should prioritize taurine supplementation over TauT knockout or TauT inhibition models to yield greater translational relevance, as these models are useful for mechanistic demonstration but do not mirror the aging phenotype. Furthermore, studies comparing the effects of long-term taurine supplementation in aged *versus* young mice – without the use of stress or disease models – are needed to fully elucidate the potential anti-aging effect of taurine.

In this context, Singh *et al.*[42] conducted a large study investigating the effect of long-term taurine supplementation on aging in mice. Remarkably, daily supplementation of 1000 mg per kg body weight to middle-aged mice, which corresponds to ~6 g day^{-1} for a 70 kg adult,[221] increased the median lifespan by 10 to 12%. The authors also examined the health outcome of aged taurine-supplemented mice and presented several beneficial effects. The taurine supplemented group exhibited reduced weight gain over the course of the treatment and a lower fat pad to body weight ratio. Although another report suggested that low-dose taurine impairs the bone microstructure in mice,[222] in this study taurine was found to increase the skeleton strength in addition to the overall bone density in the aged group.[42] Moreover, the mice exhibited greater grip strength and better neuromuscular coordination, as evidenced by motor tests. Glucose tolerance, gastrointestinal transit, anxiety-like behaviour, and blood leukocyte ratios were also improved in the aged taurine-supplemented group compared to the aged control group.[42] As these results were obtained in aged mice solely through taurine supplementation – without applying additional stress or disease models, as done in previous studies – this supports taurine's role in promoting healthy aging. It remains to be elucidated how these effects translate to humans, and which dosages and supplementation strategies can be utilized without causing side effects. Notably, taurine supplementation in aged non-human primates also yielded improvements in bone density and metabolic markers, providing an initial translational bridge to humans.[42] Further addressing this, a double-blinded human RCT using 4 g day^{-1} taurine to assess its effect on metabolic and aging biomarkers

is already running.[223] Such well-designed clinical studies will be essential to further clarify taurine's potential in supporting human healthspan.

To provide an overview of the evidence discussed across the preceding chapters, Table 2 summarizes taurine's proposed molecular mechanisms alongside the corresponding preclinical and human clinical evidence, with an attempt to assess how robustly each mechanism has been translated to humans. It aims to indicate where mechanism-to-outcome links are currently best supported, as well as areas in which supplementation effects are clinically observed but mechanistically less well understood.

6. Taurine intake, supplementation and safety

Taurine supplementation has been reported since 1975 and energy drinks containing taurine were first introduced in Austria in 1987.[6,224] It is considered essential for neonates and is a component of many infant formulas and parenteral nutrition regimens.[225] Because of endogenous synthesis, taurine is considered non-essential in adults. Yet, many publications conclude that adults also rely on dietary taurine intake and its supplementation to foster health benefits should be considered.[1] Particularly individuals with a vegan diet consume almost no taurine, resulting in decreased plasma levels.[5,226] However, there are currently no reports of taurine-deficiency related symptoms in vegans. Studies in rats revealed that animals fed a taurine-deficient diet still maintained normal tissue taurine concentrations. Large human cohort studies correlating basal circulating taurine concentrations with health status show no correlation between low taurine levels and health impairments.[211] Moreover, higher taurine plasma levels have been associated with increased total cholesterol and LDL-C levels.[42] This may be due to taurine-rich foods also containing large amounts of cholesterol.[5,6,174] We therefore conclude that (a) either the amounts of taurine obtained from increasing taurine-rich foods in the diet have no significant effect on health, or (b) the increase in taurine consumption *via* a Western-type diet is overshadowed by more pronounced effects of other dietary components. An excessive focus on taurine-rich nutrients might also reduce the intake of healthy plant-based, taurine-deficient foods. Thus, we do not advise increasing taurine intake *via* diet adaptations and rather recommend a well-balanced diet.

In contrast to taurine obtained from dietary sources, active taurine supplementation at higher doses appears effective in promoting overall health and mitigating disease- and age-related dysfunctions. The studies summarized in this review provide evidence that daily doses of 1–6 g of taurine can support mitochondrial function, improve the metabolic and oxidative balance, and thereby promote general health. In comparison to related metabolites within similar pathways, such as *N*-acetylcysteine (NAC), a precursor of GSH commonly used as an antioxidant supplement, taurine may offer a broader spectrum of biological effects beyond the classical GSH-related antioxidant actions described for NAC and is generally well tolerated.[227–230] We anticipate that taurine supplementation within the given range may yield beneficial outcomes in future human studies and may ultimately qualify as a safe and effective strategy for daily nutritional support.

While there are several studies that investigated the beneficial effects of taurine in humans, information about the adverse effects of taurine is scarce. Most human studies have reported no adverse effects. In 2008, Shao and Hathcock[230] tried to establish a safety level of oral taurine supplementation based on studies conducted up to this timepoint. With the highest dosage being 10 g day^{-1} for 6 months, they did not find significant adverse effects among all studies analyzed and proposed an observed safety level of 3 g day^{-1}. There are some other studies that reported adverse effects, such as mild muscle cramps or fatigue at daily doses of 5–10 g.[127,231] In a study of patients with MELAS, supplementation with high doses of taurine (9–12 g day^{-1}) for one year resulted in 8 mild to moderate adverse events in 6 out of 10 patients, which were considered treatment-related.[113] Older studies using intravenous administration of 150–200 mg per kg body weight taurine in epilepsy patients did not report side effects, at least not for the relatively short treatment duration.[232] However, almost all of these studies feature small sample sizes, examine diseased populations, or lack clinically relevant safety outcome measures. Thus, well-designed studies with focus on safety outcome measures are required to establish reliable safety thresholds for taurine supplementation with respect to dosage and duration. In its 2009 scientific opinion on taurine as a constituent of energy drinks, the European Food Safety Authority (EFSA) established a No Observed Adverse Effect Level (NOAEL) of 1000 mg per kg body weight per day in rats, which corresponds to 161 mg per kg body weight or approximately 11 g day^{-1} in a 70 kg human adult when adjusted for body surface area.[221,233] The Norwegian Scientific Committee for Food Safety (VKM) proposed 21 mg per kg body weight or about 1.5 g for a 70 kg adult as the daily intake that is unlikely to cause adverse health effects in 2015.[234] The actual safe daily intake of taurine may lie between these values, or potentially even above them. It should be noted that although the vast majority of animal studies reported positive effects of taurine, some animal and cell culture experiments have described negative effects. For instance, in contrast to many other studies,[42,235] one study reported a negative impact of taurine supplementation on the bone microstructure in rats.[222] Recent studies have reported that gastric cancer and leukemia cells increase TauT expression to promote tumor growth.[236,237] In gastric cancer, this elicited taurine deficiency in $CD8^+$ T cells, thereby weakening the immune defense.[236] This highlights that information on possible differential effects of taurine in specific disease contexts or when combined with medications is still lacking and that taurine co-administration in addition to some already existing therapies might be of great value.

Table 2 Summary of taurine's proposed molecular mechanisms, preclinical evidence, human clinical findings, and the strength of mechanism-to-outcome translation in humans

Domain	Proposed molecular mechanism	Preclinical evidence	Human/clinical evidence	Mechanism → outcome link in humans	Ref.
Antioxidant & anti-inflammatory action	Indirect action *via* formation of TauCl, activating antioxidant response, dampening pro-inflammatory signaling; restoration of the glutathione system; upregulation of angiogenin	Mechanisms characterized in human immune cells *in vitro* (TauCl) and in mice (angiogenin); consistent reduction of oxidative damage and cytokines in rodent stress models	Meta-analyses of RCTs: reduced plasma MDA and CRP; effects on individual cytokines population-dependent	Inferred: TauCl not detectable *in vivo* (rapid protein reactivity); clinical biomarker responses consistent with the pathway but causal mechanism unresolved	51, 52, 54, 60, 64, 81, 82 and 145
Mitochondrial translation	Substrate role in a specific uridine modification (τm^5U) on mitochondrial tRNAs that is required for accurate translation of OXPHOS subunits	Causally established in genetic and animal models; depletion abolishes the modification and impairs mitochondrial function	Phase III clinical trial in MELAS patients: high-dose supplementation increased τm^5U in peripheral leukocytes and reduced stroke-like episodes	Demonstrated: in mitochondrial disease; direct relevance and the rate-limiting role in healthy individuals remain unknown	108–113
Mitochondrial biogenesis & Ca^{2+} handling	Activation of PGC-1α-driven transcriptional programmes with tissue-dependent upstream signaling; intracellular and mitochondrial Ca^{2+} regulation	Reproducible mitochondrial gene induction in rodent brain, muscle and adipose tissue; Ca^{2+} effects shown in isolated cells. The direct mechanism partly resolved in muscle cells	Expression of mitochondrial biogenesis markers increased in adipose tissue biopsies of supplemented obese women, but only with combined exercise	Inferred: the pathway only partially translated; taurine supplementation alone insufficient at currently tested doses	45, 106, 115, 117 and 118
Lipid metabolism & adipose tissue remodeling	Stimulation of hepatic cholesterol clearance and bile acid synthesis; redirection of energy use toward fatty acid oxidation; anti-inflammatory remodelling of adipose tissue	Hepatic mechanisms partly resolved in human hepatocyte cell lines; adipose tissue effects consistent in rodent obesity models	Meta-analyses of RCTs: improvements in the lipid profile; adipose tissue biopsies confirm reduced adipocyte size and inflammatory remodelling	Partially demonstrated: for adipose tissue remodelling (human biopsy data); inferred for hepatic lipid handling (no human liver data available)	62, 145, 187, 191, 192, 194, 195 and 203
Blood pressure & vascular function	Enhancement of hydrogen sulfide (H_2S) synthesis in vascular tissue, reducing vascular Ca^{2+} influx, promoting vasodilation and decreasing platelet activation	Mechanism validated in human arteries and platelets *ex vivo*	Multiple RCTs and meta-analyses: consistent blood pressure reduction; the same trials show increased plasma H_2S and enhanced vasodilation	Partially demonstrated: taurine increases plasma H_2S and reduces BP within RCTs, strong supporting mechanistic evidence for H_2S-induced vasorelaxation in human arteries *ex vivo*	44, 149, 172 and 173
Glucose homeostasis & insulin sensitivity	Protection of pancreatic β-cells, improvement of cellular insulin signaling, and reduction of inflammatory pressure on insulin action	β-Cell protection and improved glucose tolerance reproducible in rodent diabetes models	RCTs and meta-analyses: improvements in fasting glucose, HbA1c, and insulin resistance in type 2 diabetes	Inferred: cellular insulin-signaling effects not replicated in human adipose biopsies at currently tested doses; the molecular mechanism in human tissue unresolved	145, 153, 154, 156, 179 and 201
Physical performance	Stabilization of skeletal muscle Ca^{2+} handling; ion homeostasis and antioxidant protection of muscle protein homeostasis during exercise	Supported in isolated human muscle fibres and in rodent depletion/supplementation studies	Meta-analyses: small acute benefits on aerobic endurance and strength in males (low certainty); chronic effects inconsistent	Weak: oral supplementation does not raise human skeletal muscle taurine, breaking the mechanistic chain established in rodents	119, 120, 127, 128, 136 and 137
Aging & healthspan	Action on multiple aging hallmarks, with the strongest support for mitochondrial dysfunction and chronic inflammation	Lifespan extension and improved healthspan in middle-aged mice and non-human primates; most hallmark evidence from taurine-deficient models	Observational correlation with cardiometabolic risk markers in a large cohort; first dedicated RCT ongoing	Not established: no human supplementation data directly linking taurine to aging endpoints	42 and 223

Mechanism → outcome link labels: demonstrated = causal link shown in human data; partially demonstrated = human biological evidence exists but incomplete; inferred = consistent with but not directly shown in human data; weak/not established = specific barrier identified or no human mechanistic data. References are intended as representative examples; for a more comprehensive discussion, please refer to the respective chapters and highlighted reviews. BP – blood pressure; Ca^{2+} – calcium; CRP – C-reactive protein; H_2S – hydrogen sulfide; HbA1c – glycated hemoglobin; MDA – malondialdehyde; MELAS – mitochondrial myopathy, encephalopathy, lactic acidosis, and stroke-like episodes; OXPHOS – oxidative phosphorylation; PGC-1α – peroxisome proliferator-activated receptor gamma coactivator 1-alpha; RCT – randomised clinical trial; TauCl – taurine chloramine; tRNA – transfer RNA; τm^5U – 5-taurinomethyluridine.

7. Conclusion

Taurine's importance has been extensively assessed, and the ongoing research interest is well deserved. While acute treatment with taurine holds great potential in co-application with other drugs because of its cytoprotective effects,[51,238] long-term supplementation with taurine may be especially suited for individuals with metabolic syndrome[146,150] and as a facilitator of overall health and healthy aging.[42,81] The effect of supplementation for the purpose of boosting physical performance is limited and holds little value for broad, population-wide use.[136,137] However, the evidence in all of these areas besides obesity and diabetes research[43,201] is still limited and heterogeneous; more well-designed RCTs are needed, especially to assess taurine's promising involvement in healthy aging.

Although many changes in gene expression and pathway activity induced by taurine, particularly those related to mitochondrial function and lipid metabolism, have already been identified *in vitro* and *in vivo*, a clear causative link is often missing. The direct targets and upstream mechanisms underlying these effects have not been elucidated in most cases, and the observations therefore remain largely correlative. For this purpose, more mechanistic research is required. Of similar importance is then the evaluation and contextualization of the results, as the phenotypes of taurine supplementation – or deficiency – are most probably caused by the interplay of many different factors, rather than by taurine targeting a single, still-unknown pathway.

Taurine supplementation is thought to reduce endogenous taurine synthesis.[83] How this influences the abundance of its sulfur-containing precursors and which biological effects this entails remain to be characterized. Furthermore, taurine can form derivatives such as TauCl or *N*-acetyltaurine that are thought to mediate some effects of taurine treatment.[59,202] More of these downstream metabolites may be identified in the future and could shed more light on the actions of this highly abundant amino acid.

Author contributions

BJ. B.: conceptualization, investigation, writing – original draft, and writing – review & editing. M. C.: conceptualization, investigation, and writing – original draft. J. F.: conceptualization and supervision. K. H.: supervision and writing – review & editing.

Conflicts of interest

The authors declare no conflicts of interest.

Abbreviations

AMPK	AMP-activated protein kinase
BAT	Brown adipose tissue
Ca^{2+}_i	Intracellular calcium
CDO	Cysteine dioxygenase
CoA	Coenzyme A
CSAD	Cysteine sulfinic acid decarboxylase
CYP7A1	Cholesterol 7α-hydroxylase
FMO1	Flavin-containing monooxygenase 1
GABA	γ-Aminobutaric acid
GSH	Glutathione
H_2S	Hydrogen sulfide
HDL	High-density lipoprotein
HDL-C	High-density lipoprotein cholesterol
HMGCR	HMG-CoA reductase
IL	Interleukin
LDL	Low-density lipoprotein
LDL-C	Low-density lipoprotein cholesterol
LXR-α	Liver X receptor-α
MDA	Malondialdehyde
MEF2	Myocyte enhancer factor-2
MEK1/2	Mitogen-activated protein kinase kinase
MELAS	Mitochondrial myopathy, encephalopathy, lactic acidosis, and stroke-like episodes
mt-tRNA	Mitochondrial transfer RNAs
NAC	*N*-Acylcysteine
NCX	Natrium calcium exchanger
Nrf2	Nuclear factor E2-related factor
OXPHOS	Oxidative phosphorylation
PGC-1α	Peroxisome proliferatior-activated receptor gamma coactivator 1-alpha
RCT	Randomised clinical trial
ROS	Reactive oxygen species
SHP	Small heterodimer binding partner
SOD	Superoxide dismutase
TauCl	Taurine chloramine
TauT	Taurine transporter SLC6A6
τm^5U	5 taurinomethyluridine
τm5s2U	5 taurinomethyl-2 thiouridine
TCA	Tricarboxylic acid
TG	Triacylglycerol
UCP1	Uncoupling protein 1
WAT	White adipose tissue

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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References

1 R. J. Huxtable, Physiological actions of taurine, *Physiol. Rev.*, 1992, **72**, 101–163.
2 D. W. Sved, J. L. Godsey, S. L. Ledyard, A. P. Mahoney, P. L. Stetson, S. Ho, N. R. Myers, P. Resnis and A. G. Renwick, Absorption, tissue distribution, metabolism and elimination of taurine given orally to rats, *Amino Acids*, 2007, **32**, 459–466.
3 E. Park, S. Y. Park, I. S. Cho, B. S. Kim and G. Schuller-Levis, A novel cysteine sulfinic acid decarboxylase knockout mouse: Taurine distribution in various tissues with and without taurine supplementation, *Adv. Exp. Med. Biol.*, 2017, **975**, 461–474.
4 D. B. Learn, V. A. Fried and E. L. Thomas, Taurine and Hypotaurine Content of Human Leukocytes, *J. Leukocyte Biol.*, 1990, **48**, 174–182.
5 S. A. Laidlaw, M. Grosvenor and J. D. Kopple, The taurine content of common foodstuffs, *J. Parenter. Enteral Nutr.*, 1990, **14**, 183–188.
6 G. Wu, Important roles of dietary taurine, creatine, carnosine, anserine and 4-hydroxyproline in human nutrition and health, *Amino Acids*, 2020, **52**, 329–360.
7 L. L. Spriet and J. Whitfield, Taurine and skeletal muscle function, *Curr. Opin. Clin. Nutr. Metab. Care*, 2015, **18**, 96–101.
8 C. M. H. Anderson, A. Howard, J. R. F. Walters, V. Ganapathy and D. T. Thwaites, Taurine uptake across the human intestinal brush-border membrane is via two transporters: H+-coupled PAT1 (SLC36A1) and Na+- and Cl−-dependent TauT (SLC6A6), *J. Physiol.*, 2009, **587**, 731–744.
9 B. Du, L. Cheng, J. Xie, L. Chen and K. Yan, Molecular basis of human taurine transporter uptake and inhibition, *Nat. Commun.*, 2025, **16**(1), 1–12.
10 M. Richter, S. J. Moroniak and H. Michel, Identification of competitive inhibitors of the human taurine transporter TauT in a human kidney cell line, *Pharmacol. Rep.*, 2019, **71**, 121–127.
11 I. H. Lambert, D. M. Kristensen, J. B. Holm and O. H. Mortensen, Physiological role of taurine – from organism to organelle, *Acta Physiol.*, 2015, **213**, 191–212.
12 Y. Zhou, S. Holmseth, C. Guo, B. Hassel, G. Höfner, H. S. Huitfeldt, K. T. Wanner and N. C. Danbolt, Deletion of the γ-aminobutyric acid transporter 2 (GAT2 and SLC6A13) gene in mice leads to changes in liver and brain taurine contents, *J. Biol. Chem.*, 2012, **287**, 35733–35746.
13 C. U. Nielsen, M. Pedersen, S. Müller, T. Kæstel, M. Bjerg, N. Ulaganathan, S. Nielsen, K. L. Carlsen, M. K. Nøhr and R. Holm, Inhibitory Effects of 17-α-Ethinyl-Estradiol and 17-β-Estradiol on Transport Via the Intestinal Proton-Coupled Amino Acid Transporter (PAT1) Investigated In Vitro and In Vivo, *J. Pharm. Sci.*, 2021, **110**, 354–364.
14 Q. Ma, J. Zhao, W. Cao, J. Liu and S. Cui, Estradiol decreases taurine level by reducing cysteine sulfinic acid decarboxylase via the estrogen receptor-a in female mice liver, *Am. J. Physiol.: Gastrointest. Liver Physiol.*, 2015, **308**, G277–G286.
15 D. B. Shennan and J. Thomson, Estrogen regulation and ion dependence of taurine uptake by MCF-7 human breast cancer cells, *Cell. Mol. Biol. Lett.*, 2007, **12**, 396–406.
16 G. Falascina, L. B. Bindels, V. Di Marzo and A. Cutignano, Validation of a fast and sensitive UPLC-MS/MS quantitative method for N-acyl taurine analysis in biological samples, *J. Pharm. Biomed. Anal.*, 2023, **226**, 115252.
17 J. Marcinkiewicz and E. Kontny, Taurine and inflammatory diseases, *Amino Acids*, 2014, **46**, 7–20.
18 E. Siakkou, S. M. Wilbanks and G. N. L. Jameson, Simplified cysteine dioxygenase activity assay allows simultaneous quantitation of both substrate and product, *Anal. Biochem.*, 2010, **405**, 127–131.
19 M. Tappaz, K. Almarghini, F. Legay and A. Remy, Taurine biosynthesis enzyme cysteine sulfinate decarboxylase (CSD) from brain: The long and tricky trail to identification, *Neurochem. Res.*, 1992, **17**, 849–859.
20 I. Winge, K. Teigen, A. Fossbakk, E. Mahootchi, R. Kleppe, F. Sköldberg, O. Kämpe and J. Haavik, Mammalian CSAD and GADL1 have distinct biochemical properties and patterns of brain expression, *Neurochem. Int.*, 2015, **90**, 173–184.
21 S. Veeravalli, I. R. Phillips, R. T. Freire, D. Varshavi, J. R. Everett and E. A. Shephard, Flavin-Containing Monooxygenase 1 Catalyzes the Production of Taurine from Hypotaurine, *Drug Metab. Dispos.*, 2020, **48**, 378–385.
22 C. Dolphin, E. A. Shephard, S. Povey, C. N. A. Palmer, D. M. Ziegler, R. Ayesh, R. L. Smith and I. R. Phillips, Cloning, primary sequence, and chromosomal mapping of a human flavin-containing monooxygenase (FMO1), *J. Biol. Chem.*, 1991, **266**, 12379–12385.
23 C. T. Dolphin, T. E. Cullingford, E. A. Shephard, R. L. Smith and I. R. Phillips, Differential Developmental and Tissue-Specific Regulation of Expression of the Genes Encoding Three Members of the Flavin-Containing Monooxygenase Family of Man, FMO1, FMO3 and FMO4, *Eur. J. Biochem.*, 1996, **235**, 683–689.
24 S. B. Koukouritaki, P. Simpson, C. K. Yeung, A. E. Rettie and R. N. Hines, Human Hepatic Flavin-Containing Monooxygenases 1 (FMO1) and 3 (FMO3) Developmental Expression, *Pediatr. Res.*, 2002, **51**(2), 236–243.
25 J. Zhang and J. R. Cashman, Quantitative Analysis OF FMO Gene Mrna Levels in Human Tissues, *Drug Metab. Dispos.*, 2006, **34**, 19–26.
26 T. Miyazaki, Identification of a novel enzyme and the regulation of key enzymes in mammalian taurine synthesis, *J. Pharmacol. Sci.*, 2024, **154**, 9–17.
27 M. H. Stipanuk, Role of the Liver in Regulation of Body Cysteine and Taurine Levels: A Brief Review, *Neurochem. Res.*, 2004, **29**, 105–110.
28 D. Hernandez, A. Janmohamed, P. Chandan, I. R. Phillips and E. A. Shephard, Organization and evolution of the flavin-containing monooxygenase genes of human and

mouse: identification of novel gene and pseudogene clusters, *Pharmacogenet. Genomics*, 2004, **14**, 117–130.
29 C. K. Yeung, D. H. Lang, K. E. Thummel and A. E. Rettie, Immunoquantitation of FMO1 in Human Liver, Kidney, and Intestine, *Drug Metab. Dispos.*, 2000, **28**, 1107–1111.
30 Y. H. Kim, J. H. Lee, D. S. Lim, W. J. Shim, Y. M. Ro, G. H. Park, K. G. Becker, Y. S. Cho-Chung and M. K. Kim, Gene expression profiling of oxidative stress on atrial fibrillation in humans, *Exp. Mol. Med.*, 2003, **35**(5), 336–349.
31 J. E. Dominy, C. R. Simmons, L. L. Hirschberger, J. Hwang, R. M. Coloso and M. H. Stipanuk, Discovery and Characterization of a Second Mammalian Thiol Dioxygenase, Cysteamine Dioxygenase, *J. Biol. Chem.*, 2007, **282**, 25189–25198.
32 Z. F. Stephan, J. A. Sturman and K. C. Hayes, Vitamin B6 deficiency decreases lipoprotein 3H-cholesterol incorporation into biliary sterols in cebus monkeys, *Nutr. Res.*, 1984, **4**, 421–435.
33 D. Zhang, J. Fan, H. Liu, G. Qiu and S. Cui, Testosterone enhances taurine synthesis by upregulating androgen receptor and cysteine sulfinic acid decarboxylase expressions in male mouse liver, *Am. J. Physiol.: Gastrointest. Liver Physiol.*, 2023, **324**, G295–G304.
34 T. A. Kerr, Y. Matsumoto, H. Matsumoto, Y. Xie, L. L. Hirschberger, M. H. Stipanuk, S. Anakk, D. D. Moore, M. Watanabe, S. Kennedy and N. O. Davidson, Cysteine sulfinic acid decarboxylase regulation: A role for farnesoid X receptor and small heterodimer partner in murine hepatic taurine metabolism, *Hepatol. Res.*, 2014, **44**, E218–E228.
35 Y. Wang, J. Li, D. Matye, Y. Zhang, K. Dennis, W. X. Ding and T. Li, Bile acids regulate cysteine catabolism and glutathione regeneration to modulate hepatic sensitivity to oxidative injury, *JCI Insight*, 2018, **3**, e99676.
36 F. Tiedemann and L. Gmelin, Einige neue Bestandtheile der Galle des Ochsen, *Ann. Phys.*, 1827, **85**, 326–337.
37 W. Kilb and A. Fukuda, Taurine as an Essential Neuromodulator during Perinatal Cortical Development, *Front. Cell. Neurosci.*, 2017, **11**, 328.
38 S. S. Oja and P. Saransaari, Taurine and epilepsy, *Epilepsy Res.*, 2013, **104**, 187–194.
39 I. H. Lambert and D. B. Hansen, Regulation of Taurine Transport Systems by Protein Kinase CK2 in Mammalian Cells, *Cell. Physiol. Biochem.*, 2011, **28**, 1099–1110.
40 D. B. Shennan, Swelling-Induced Taurine Transport: Relationship with Chloride Channels, Anion-Exchangers and Other Swelling-Activated Transport Pathways, *Cell. Physiol. Biochem.*, 2008, **21**, 15–28.
41 S. Schaffer and H. W. Kim, Effects and Mechanisms of Taurine as a Therapeutic Agent, *Biomol. Ther.*, 2018, **26**, 225.
42 P. Singh, K. Gollapalli, S. Mangiola, D. Schranner, M. A. Yusuf, M. Chamoli, S. L. Shi, B. L. Bastos, T. Nair, A. Riermeier, E. M. Vayndorf, J. Z. Wu, A. Nilakhe, C. Q. Nguyen, M. Muir, M. G. Kiflezghi, A. Foulger, A. Junker, J. Devine, K. Sharan, S. J. Chinta, S. Rajput, A. Rane, P. Baumert, M. Schönfelder, F. Iavarone, G. di Lorenzo, S. Kumari, A. Gupta, R. Sarkar, C. Khyriem, A. S. Chawla, A. Sharma, N. Sarper, N. Chattopadhyay, B. K. Biswal, C. Settembre, P. Nagarajan, K. L. Targoff, M. Picard, S. Gupta, V. Velagapudi, A. T. Papenfuss, A. Kaya, M. G. Ferreira, B. K. Kennedy, J. K. Andersen, G. J. Lithgow, A. M. Ali, A. Mukhopadhyay, A. Palotie, G. Kastenmüller, M. Kaeberlein, H. Wackerhage, B. Pal and V. K. Yadav, Taurine deficiency as a driver of aging, *Science*, 2023, **380**, eabn9257.
43 G. Batitucci, G. F. Abud, G. U. Ortiz, L. F. Belisário, S. G. Travieso, M. C. de Lima Viliod, A. C. R. Venturini and E. C. de Freitas, Sarcobesity: New paradigms for healthy aging related to taurine supplementation, gut microbiota and exercise, *Ageing Res. Rev.*, 2024, **101**, 102460.
44 G. Santulli, U. Kansakar, F. Varzideh, P. Mone, S. S. Jankauskas and A. Lombardi, Functional Role of Taurine in Aging and Cardiovascular Health: An Updated Overview, *Nutrients*, 2023, **15**, 4236.
45 C. J. Jong, P. Sandal and S. W. Schaffer, The Role of Taurine in Mitochondria Health: More Than Just an Antioxidant, *Molecules*, 2021, **26**, 4913.
46 O. I. Aruoma, B. Halliwell, B. M. Hoey and J. Butler, The antioxidant action of taurine, hypotaurine and their metabolic precursors, *Biochem. J.*, 1988, **256**, 251–255.
47 T. R. Mehta and J. Dawson, Taurine is a weak scavenger of peroxynitrite and does not attenuate sodium nitroprusside toxicity to cells in culture, *Amino Acids*, 2001, **20**, 419–433.
48 F. Kilic, R. Bhardwaj, J. Caulfeild and J. R. Trevithick, Modelling Cortical Cataractogenesis 22: Is in vitro Reduction of Damage in Model Diabetic Rat Cataract by Taurine Due to Its Antioxidant Activity?, *Exp. Eye Res.*, 1999, **69**, 291–300.
49 M. W. S. Oliveira, J. B. Minotto, M. R. de Oliveira, A. Zanotto-Filho, G. A. Behr, R. F. Rocha, J. C. F. Moreira and F. Klamt, Scavenging and antioxidant potential of physiological taurine concentrations against different reactive oxygen/nitrogen species, *Pharmacol. Rep.*, 2010, **62**, 185–193.
50 S. H. Cheong, S. H. Moon, S. J. Lee, S. H. Kim and K. J. Chang, Antioxidant and DNA Protection Effects of Taurine by Electron Spin Resonance Spectroscopy, *Adv. Exp. Med. Biol.*, 2013, **776**, 167–177.
51 P. F. Surai, K. Earle-payne and M. T. Kidd, Taurine as a Natural Antioxidant: From Direct Antioxidant Effects to Protective Action in Various Toxicological Models, *Antioxidants*, 2021, **10**, 1876.
52 S. J. Weiss, R. Klein, A. Slivka and M. Wei, Chlorination of taurine by human neutrophils. Evidence for hypochlorous acid generation, *J. Clin. Invest.*, 1982, **70**, 598–607.
53 S. I. Seol, I. S. Kang, J. S. Lee, J. K. Lee and C. Kim, Taurine Chloramine-Mediated Nrf2 Activation and HO-1 Induction Confer Protective Effects in Astrocytes, *Antioxidants*, 2024, **13**, 169.

54 C. Kim and Y. N. Cha, Taurine chloramine produced from taurine under inflammation provides anti-inflammatory and cytoprotective effects, *Amino Acids*, 2014, **46**, 89–100.
55 J. S. Jang, S. Piao, Y.-N. Cha and C. Kim, Taurine Chloramine Activates Nrf2, Increases HO-1 Expression and Protects Cells from Death Caused by Hydrogen Peroxide, *J. Clin. Biochem. Nutr.*, 2009, **45**, 37–43.
56 C. Kim, J. S. Jang, M. R. Cho, S. R. Agarawal and Y. N. Cha, Taurine chloramine induces heme oxygenase-1 expression via Nrf2 activation in murine macrophages, *Int. Immunopharmacol.*, 2010, **10**, 440–446.
57 R. Tenhunen, H. S. Marver and R. Schmid, The enzymatic conversion of heme to bilirubin by microsomal heme oxygenase., *Proc. Natl. Acad. Sci. U. S. A.*, 1968, **61**, 748–755.
58 E. Park, J. Jia, M. R. Quinn and G. Schuller-Levis, Taurine Chloramine Inhibits Lymphocyte Proliferation and Decreases Cytokine Production in Activated Human Leukocytes, *Clin. Immunol.*, 2002, **102**, 179–184.
59 G. B. Schuller-Levis and E. Park, Taurine and Its Chloramine: Modulators of Immunity, *Neurochem. Res.*, 2004, **29**, 117–126.
60 E. Kontny, E. Wojtecka-Łukasik, K. Rell-Bakalarska, W. Dziewczopolski, W. Maśliński and S. Maślinski, Impaired generation of taurine chloramine by synovial fluid neutrophils of rheumatoid arthritis patients, *Amino Acids*, 2002, **23**, 415–418.
61 W. Gottardi and M. Nagl, N-chlorotaurine, a natural antiseptic with outstanding tolerability, *J. Antimicrob. Chemother.*, 2010, **65**, 399–409.
62 S. Lin, S. Hirai, Y. Yamaguchi, T. Goto, N. Takahashi, F. Tani, C. Mutoh, T. Sakurai, S. Murakami, R. Yu and T. Kawada, Taurine improves obesity-induced inflammatory responses and modulates the unbalanced phenotype of adipose tissue macrophages, *Mol. Nutr. Food Res.*, 2013, **57**, 2155–2165.
63 T. Sartori, G. Galvão dos Santos, A. Nogueira-Pedro, E. Makiyama, M. M. Rogero, P. Borelli and R. A. Fock, Effects of glutamine, taurine and their association on inflammatory pathway markers in macrophages, *Inflammopharmacology*, 2018, **26**, 829–838.
64 L. X. Wu, J. H. Xie, J. Y. Li, W. P. Li, X. T. Mao, L. J. Huang, H. T. Chen, J. Y. Zhong, L. M. Lin, S. Su, Y. Y. Li, Q. Cao and J. Jin, Intestinal taurine acts as a novel immunometabolic modulator of IBD by degrading redundant mitochondrial RNA, *Cell. Mol. Immunol.*, 2025, **2025**, 1–16.
65 C. J. Lin, C. C. Chiu, Y. C. Chen, M. L. Chen, T. C. Hsu and B. S. Tzang, Taurine Attenuates Hepatic Inflammation in Chronic Alcohol-Fed Rats Through Inhibition of TLR4/MyD88 Signaling, *J. Med. Food*, 2015, **18**, 1291–1298.
66 Y. Y. Chang, C. H. Chou, C. H. Chiu, K. T. Yang, Y. L. Lin, W. L. Weng and Y. C. Chen, Preventive effects of taurine on development of hepatic steatosis induced by a high-fat/cholesterol dietary habit, *J. Agric. Food Chem.*, 2011, **59**, 450–457.
67 H. Tabassum, H. Rehman, B. D. Banerjee, S. Raisuddin and S. Parvez, Attenuation of tamoxifen-induced hepatotoxicity by taurine in mice, *Clin. Chim. Acta*, 2006, **370**, 129–136.
68 A. M. H. Ghanim, M. R. T. Farag, M. A. Anwar, N. A. M. Ali, M. A. Hawas, H. M. E. Elsallab, W. A. Elhendawy, L. A. Basyouni, O. A. Refaey, K. E. Zaki, N. A. M. Ali and H. A. Metwaly, Taurine alleviates kidney injury in a thioacetamide rat model by mediating Nrf2/HO-1, NQO-1, and MAPK/NF-κB signaling pathways, *Can. J. Physiol. Pharmacol.*, 2022, **100**, 352–360.
69 S. Y. Saad and A. C. Al-Rikabi, Protection Effects of Taurine Supplementation against Cisplatin-Induced Nephrotoxicity in Rats, *Chemotherapy*, 2002, **48**, 42–48.
70 F. Piao, Y. Zhang, L. Yang, C. Zhang, J. Shao, X. Liu, Y. Li and S. Li, Taurine Attenuates As2O3-Induced Autophagy in Cerebrum of Mouse Through Nrf2 Pathway, *Adv. Exp. Med. Biol.*, 2017, **975**(Pt 2), 863–870.
71 M. Qiao, P. Liu, X. Ren, T. Feng and Z. Zhang, Potential protection of taurine on antioxidant system and ATPase in brain and blood of rats exposed to aluminum, *Biotechnol. Lett.*, 2015, **37**, 1579–1584.
72 A. E. Farage, M. Taha, B. A. Khattab, N. E. Al-Hazmi, A. E. A. Mohamed, M. M. Mona, M. M. Abd-Elsalam, A. E. Elsukary, M. A. F. E. Sarhan, A. S. Abdelmonsef, T. A. S. Baokbah, I. El-Shenbaby, R. T. Eldesoky and E. Hussin, Taurine protects against gentamicin-induced neurotoxicity through dual modulation of Nrf2 and NF-κB pathways, *Tissue Cell*, 2026, **100**, 103382.
73 J. Das, J. Ghosh, P. Manna, M. Sinha and P. C. Sil, Taurine protects rat testes against NaAsO2-induced oxidative stress and apoptosis via mitochondrial dependent and independent pathways, *Toxicol. Lett.*, 2009, **187**, 201–210.
74 H. A. A. Aly and R. M. Khafagy, Taurine reverses endosulfan-induced oxidative stress and apoptosis in adult rat testis, *Food Chem. Toxicol.*, 2014, **64**, 1–9.
75 X. Yu, K. Chen, N. Wei, Q. Zhang, J. Liu and M. Mi, Dietary taurine reduces retinal damage produced by photochemical stress via antioxidant and anti-apoptotic mechanisms in Sprague–Dawley rats, *Br. J. Nutr.*, 2007, **98**, 711–719.
76 L. Wang, L. Jiang, Y. Chu, F. Feng, W. Tang, C. Chen, Y. Qiu, Z. Hu, H. Diao and Z. Tang, Dietary Taurine Improves Growth Performance and Intestine Health via the GSH/GSSG Antioxidant System and Nrf2/ARE Signaling Pathway in Weaned Piglets, *Antioxidants*, 2023, **12**, 1852.
77 J. Zheng, J. Zhang, Y. Zhou, D. Zhang, H. Guo, B. Li and S. Cui, Taurine Alleviates Experimental Colitis by Enhancing Intestinal Barrier Function and Inhibiting Inflammatory Response through TLR4/NF-κB Signaling, *J. Agric. Food Chem.*, 2024, **72**, 12119–12129.
78 C. Chen, M. Qi, W. Zhang, F. Chen, Z. Sun, W. Sun, W. Tang, Z. Yang, X. Zhao and Z. Tang, Taurine alleviated paraquat-induced oxidative stress and gut-liver axis damage in weaned piglets by regulating the Nrf2/Keap1 and TLR4/NF-κB signaling pathways, *J. Anim. Sci. Biotechnol.*, 2025, **16**, 1–23.

79 S. M. Deneke and B. L. Fanburg, Regulation of cellular glutathione, *Am. J. Physiol.-Lung Cell. Mol. Physiol.*, 1989, **257**, 63–173.
80 O. M. Ighodaro and O. A. Akinloye, First line defence antioxidants-superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPX): Their fundamental role in the entire antioxidant defence grid, *Alexandria J. Med.*, 2018, **54**, 287–293.
81 A. H. Faghfouri, S. M. Seyyed Shoura, P. Fathollahi, M. A. Shadbad, S. Papi, A. Ostadrahimi and E. Faghfuri, Profiling inflammatory and oxidative stress biomarkers following taurine supplementation: a systematic review and dose-response meta-analysis of controlled trials, *Eur. J. Clin. Nutr.*, 2021, **76**(5), 647–658.
82 G. F. Abud, F. G. De Carvalho, G. Batitucci, S. G. Travieso, C. R. Bueno Junior, F. Barbosa Junior, J. S. Marchini and E. C. de Freitas, Taurine as a possible antiaging therapy: A controlled clinical trial on taurine antioxidant activity in women ages 55 to 70, *Nutrition*, 2022, **101**, 111706.
83 B. Eppler and R. Dawson, Dietary taurine manipulations in aged male Fischer 344 rat tissue: taurine concentration, taurine biosynthesis, and oxidative markers, *Biochem. Pharmacol.*, 2001, **62**, 29–39.
84 Q. Song, S. Kobayashi, Y. Kataoka and H. Oda, Direct Molecular Action of Taurine on Hepatic Gene Expression Associated with the Amelioration of Hypercholesterolemia in Rats, *Antioxidants*, 2024, **13**, 990.
85 A. Tsuboi, H. Khanom, R. Kawabata, T. Matsui, S. Murakami and T. Ito, Taurine ameliorates cellular senescence associated with an increased hydrogen sulfide and a decreased hepatokine, IGFBP-1, in CCl4-induced hepatotoxicity in mice, *Redox Biol.*, 2025, **83**, 103640.
86 I. Ueki, H. B. Roman, A. Valli, K. Fieselmann, J. Lam, R. Peters, L. L. Hirschberger and M. H. Stipanuk, Knockout of the murine cysteine dioxygenase gene results in severe impairment in ability to synthesize taurine and an increased catabolism of cysteine to hydrogen sulfide, *Am. J. Physiol. Endocrinol. Metab.*, 2011, **301**, 668–684.
87 B. Murphy, R. Bhattacharya and P. Mukherjee, Hydrogen sulfide signaling in mitochondria and disease, *FASEB J.*, 2019, **33**, 13098–13125.
88 M. H. Stipanuk, R. M. Coloso, R. A. G. Garcia and M. F. Banks, Cysteine Concentration Regulates Cysteine Metabolism to Glutathione, Sulfate and Taurine in Rat Hepatocytes, *J. Nutr.*, 1992, **122**, 420–427.
89 M. H. Stipanuk and I. Ueki, Dealing with methionine/homocysteine sulfur: Cysteine metabolism to taurine and inorganic sulfur, *J. Inherited Metab. Dis.*, 2011, **34**, 17–32.
90 J. E. Dominy, J. Hwang and M. H. Stipanuk, Overexpression of cysteine dioxygenase reduces intracellular cysteine and glutathione pools in HepG2/C3A cells, *Am. J. Physiol. Endocrinol. Metab.*, 2007, **293**, 62–69.
91 C. W. Ahn, D. Y. Kwon, D. S. Jun, Y. M. Lee and Y. C. Kim, Enhancement of cysteine catabolism into taurine impacts glutathione homeostasis in rats challenged with ethanol, *Amino Acids*, 2015, **47**, 1273–1277.
92 V. M. Anlacan, R. D. G. Jamora, L. F. Krattinger, E. De Longis, M. Hartweg, M. Steinmann and L. Trovò, A nutritional blend of taurine, vitamins B6, B9, and B12 improves motivated behaviors in healthy adults—a double-blinded randomized clinical trial, *Front. Nutr.*, 2026, **13**, 1711478.
93 J. Chen, D. Matye, Y.-D. Clayton, Y. Du, M. N. Hasan, L. Gu and T. Li, Deletion of hepatocyte cysteine dioxygenase type 1, a bile acid repressed gene, enhances glutathione synthesis and ameliorates acetaminophen hepatotoxicity, *Biochem. Pharmacol.*, 2024, **222**, 116103.
94 L. Li, J. You, Z.-Q. Chai, X. Li, X. Cai, L. Wang, F. Yang, L. Zhu, W. Mi, X. Xia, H. Yan, F. Li, J. Wang, T.-J. Zhao, L. Chen, H. Ji, P. Liu, X.-L. Zhou, L. Chen and F. Li, SLC6A6 imports taurine into mitochondria to sustain mitochondrial translation and tumour growth, *Nat. Metab.*, 2026, **8**(3), 704–721.
95 T. Ubuka, A. Okada and H. Nakamura, Production of hypotaurine from L-cysteinesulfinate by rat liver mitochondria, *Amino Acids*, 2008, **35**, 53–58.
96 S. H. Hansen, M. L. Andersen, H. Birkedal, C. Cornett and F. Wibrand, The Important Role of Taurine in Oxidative Metabolism, *Adv. Exp. Med. Biol.*, 2006, **583**, 129–135.
97 S. H. Hansen, M. L. Andersen, C. Cornett, R. Gradinaru and N. Grunnet, A role for taurine in mitochondrial function, *J. Biomed. Sci.*, 2010, **17**, 1–8.
98 S. H. Hansen, H. Birkedal, F. Wibrand and N. Grunnet, Taurine and Regulation of Mitochondrial Metabolism, *Adv. Exp. Med. Biol.*, 2015, **803**, 397–405.
99 A. El Idrissi and E. Trenkner, Taurine Regulates Mitochondrial Calcium Homeostasis, *Adv. Exp. Med. Biol.*, 2003, **526**, 527–536.
100 M. Palmi, G. T. Youmbi, F. Fusi, G. P. Sgaragli, H. B. F. Dixon, M. Frosini and K. F. Tipton, Potentiation of mitochondrial Ca2+ sequestration by taurine, *Biochem. Pharmacol.*, 1999, **58**, 1123–1131.
101 H. Mohammadi, M. M. Ommati, O. Farshad, A. Jamshidzadeh, M. R. Nikbakht, H. Niknahad and R. Heidari, Taurine and isolated mitochondria: A concentration-response study, *Trends Pharm. Sci. Technol.*, 2019, **5**, 197–206.
102 G. Bkaily, D. Jaalouk, S. Sader, H. Shbaklo, P. Pothier, D. Jacques, P. D'Orléans-Juste, E. J. Cragoe and R. Bose, Taurine indirectly increases [Ca](i) by inducing Ca2+ influx through the Na+-Ca2+ exchanger, *Mol. Cell. Biochem.*, 1998, **188**, 187–197.
103 W. Q. Chen, H. Jin, M. Nguyen, J. Carr, Y. J. Lee, C. C. Hsu, M. D. Faiman, J. V. Schloss and J. Y. Wu, Role of taurine in regulation of intracellular calcium level and neuroprotective function in cultured neurons, *J. Neurosci. Res.*, 2001, **66**, 612–619.
104 J. Y. Wu and H. Prentice, Role of taurine in the central nervous system, *J. Biomed. Sci.*, 2010, **17**, 1–6.
105 E. A. Vilas-Boas, J. V. Cabral-Costa, V. M. Ramos, C. C. Caldeira da Silva and A. J. Kowaltowski, Goldilocks calcium concentrations and the regulation of oxidative

phosphorylation: Too much, too little, or just right, *J. Biol. Chem.*, 2023, **299**, 102904.

106 B. Sun, H. Maruta, Y. Ma and H. Yamashita, Taurine Stimulates AMP-Activated Protein Kinase and Modulates the Skeletal Muscle Functions in Rats via the Induction of Intracellular Calcium Influx, *Int. J. Mol. Sci.*, 2023, **24**, 4125.

107 J. Guo, T. Ou, Y. Gao, Y. Zhao, J. Zhang, Y. Zhang and W. Chen, Taurine reduces cholesterol through CYP7A1 in a calcineurin-dependent manner: Efficacy of taurine in hepatic cholesterol, *Indian J. Exp. Biol.*, 2024, **62**, 802–809.

108 T. Suzuki, T. Suzuki, T. Wada, K. Saigo and K. Watanabe, Taurine as a constituent of mitochondrial tRNAs: new insights into the functions of taurine and human mitochondrial diseases, *EMBO J.*, 2002, **21**, 6581–6589.

109 M. Fakruddin, F. Y. Wei, T. Suzuki, K. Asano, T. Kaieda, A. Omori, R. Izumi, A. Fujimura, T. Kaitsuka, K. Miyata, K. Araki, Y. Oike, L. Scorrano, T. Suzuki and K. Tomizawa, Defective Mitochondrial tRNA Taurine Modification Activates Global Proteostress and Leads to Mitochondrial Disease, *Cell Rep.*, 2018, **22**, 482–496.

110 K. Asano, T. Suzuki, A. Saito, F. Y. Wei, Y. Ikeuchi, T. Numata, R. Tanaka, Y. Yamane, T. Yamamoto, T. Goto, Y. Kishita, K. Murayama, A. Ohtake, Y. Okazaki, K. Tomizawa, Y. Sakaguchi and T. Suzuki, Metabolic and chemical regulation of tRNA modification associated with taurine deficiency and human disease, *Nucleic Acids Res.*, 2018, **46**, 1565–1583.

111 Y. Kirino, T. Yasukawa, S. Ohta, S. Akira, K. Ishihara, K. Watanabe and T. Suzuki, Codon-specific translational defect caused by a wobble modification deficiency in mutant tRNA from a human mitochondrial disease, *Proc. Natl. Acad. Sci. U. S. A.*, 2004, **101**, 15070–15075.

112 Y. Kirino, Y. I. Goto, Y. Campos, J. Arenas and T. Suzuki, Specific correlation between the wobble modification deficiency in mutant tRNAs and the clinical features of a human mitochondrial disease, *Proc. Natl. Acad. Sci. U. S. A.*, 2005, **102**, 7127–7132.

113 Y. Ohsawa, H. Hagiwara, S. I. Nishimatsu, A. Hirakawa, N. Kamimura, H. Ohtsubo, Y. Fukai, T. Murakami, Y. Koga, Y. I. Goto, S. Ohta and Y. Sunada, Taurine supplementation for prevention of stroke-like episodes in MELAS: a multicentre, open-label, 52-week phase III trial, *J. Neurol., Neurosurg. Psychiatry*, 2018, **90**, 529.

114 J. F. Halling and H. Pilegaard, PGC-1α-mediated regulation of mitochondrial function and physiological implications, *Appl. Physiol., Nutr., Metab.*, 2020, **45**, 927–936, DOI: 10.1139/apnm-2020-0005.

115 H. Rezaei, H. W. Wang, W. Tian, J. Zhao, A. Najibi, S. Retana-Márquez, E. Rafiei, A. Rowhanirad, S. Sabouri, M. Kiafar, R. Fazlinezhad, A. M. Niknahad, F. Evazzadeh, S. T. Anousheh, M. M. Ommati, H. Niknahad and R. Heidari, Long-term taurine supplementation regulates brain mitochondrial dynamics in mice, *Basic Clin. Pharmacol. Toxicol.*, 2025, **136**, e14101.

116 A. Barbiera, S. Sorrentino, D. Fard, E. Lepore, G. Sica, G. Dobrowolny, L. Tamagnone and B. M. Scicchitano, Taurine Administration Counteracts Aging-Associated Impingement of Skeletal Muscle Regeneration by Reducing Inflammation and Oxidative Stress, *Antioxidants*, 2022, **11**, 1016.

117 Y. Y. Guo, B. Y. Li, W. Q. Peng, L. Guo and Q. Q. Tang, Taurine-mediated browning of white adipose tissue is involved in its anti-obesity effect in mice, *J. Biol. Chem.*, 2019, **294**, 15014–15024.

118 F. G. De Carvalho, C. F. C. Brandao, G. Batitucci, A. D. O. Souza, G. D. Ferrari, L. C. Alberici, V. R. Muñoz, J. R. Pauli, L. P. De Moura, E. R. Ropelle, A. S. R. da Silva, M. V. M. Junqueira-Franco, J. S. Marchini and E. C. de Freitas, Taurine supplementation associated with exercise increases mitochondrial activity and fatty acid oxidation gene expression in the subcutaneous white adipose tissue of obese women, *Clin. Nutr.*, 2021, **40**, 2180–2187.

119 S. W. Schaffer, C. J. Jong, R. Kc and J. Azuma, Physiological roles of taurine in heart and muscle, *J. Biomed. Sci.*, 2010, **17**, 1–8.

120 A. Thirupathi, R. A. Pinho, J. S. Baker, B. István and Y. Gu, Taurine Reverses Oxidative Damages and Restores the Muscle Function in Overuse of Exercised Muscle, *Front. Physiol.*, 2020, **11**, 582449.

121 A. J. Bakker and H. M. Berg, Effect of taurine on sarcoplasmic reticulum function and force in skinned fast–twitch skeletal muscle fibres of the rat, *J. Physiol.*, 2002, **538**, 185–194.

122 E. J. Hamilton, H. M. Berg, C. J. Easton and A. J. Bakker, The effect of taurine depletion on the contractile properties and fatigue in fast-twitch skeletal muscle of the mouse, *Amino Acids*, 2006, **31**, 273–278.

123 J. Tallis, M. F. Higgins, V. M. Cox, M. J. Duncan and R. S. James, Does a physiological concentration of taurine increase acute muscle power output, time to fatigue, and recovery in isolated mouse soleus (slow) muscle with or without the presence of caffeine?, *Can. J. Physiol. Pharmacol.*, 2014, **92**, 42–49.

124 C. A. Goodman, D. Horvath, C. Stathis, T. Mori, K. Croft, R. M. Murphy and A. Hayes, Taurine supplementation increases skeletal muscle force production and protects muscle function during and after high-frequency in vitro stimulation, *J. Appl. Physiol.*, 2009, **107**, 144–154.

125 T. F. Imagawa, I. Hirano, K. Utsuki, M. Horie, A. Naka, K. Matsumoto and S. Imagawa, Caffeine and Taurine Enhance Endurance Performance, *Int. J. Sports Med.*, 2009, **30**, 485–488.

126 R. J. Ward, M. Francaux, C. Cuisinier, X. Sturbois and P. De Witte, Changes in plasma taurine levels after different endurance events, *Amino Acids*, 1999, **16**, 71–77.

127 S. D. R. Galloway, J. L. Talanian, A. K. Shoveller, G. J. F. Heigenhauser and L. L. Spriet, Seven days of oral taurine supplementation does not increase muscle taurine content or alter substrate metabolism during pro-

longed exercise in humans, *J. Appl. Physiol.*, 2008, **105**, 643–651.

128 T. L. Dutka, C. R. Lamboley, R. M. Murphy and G. D. Lamb, Acute effects of taurine on sarcoplasmic reticulum Ca $^{2+}$ accumulation and contractility in human type I and type II skeletal muscle fibers, *J. Appl. Physiol.*, 2014, **117**, 797–805.

129 J. A. Rutherford, L. L. Spriet and T. Stellingwerff, The Effect of Acute Taurine Ingestion on Endurance Performance and Metabolism in Well-Trained Cyclists, *Int. J. Sport Nutr. Exercise Metab.*, 2010, **20**, 322–329.

130 F. Milioni, E. de Souza Malta, L. G. S. do Amaral Rocha, C. A. A. Mesquita, E. C. de Freitas and A. M. Zagatto, Acute administration of high doses of taurine does not substantially improve high-intensity running performance and the effect on maximal accumulated oxygen deficit is unclear, *Appl. Physiol., Nutr., Metab.*, 2016, **41**, 498–503.

131 B. S. Galan, F. G. Carvalho, P. C. Santos, R. B. Gobbi, C. A. Kalva-Filho, M. Papoti, A. S. Da Silva and E. C. Freitas, Effects of taurine on markers of muscle damage, inflammatory response and physical performance in triathletes, *J. Sports Med. Phys. Fitness*, 2018, **58**, 1318–1324.

132 Z. X. Lim, A. Singh, Z. Z. X. Leow, P. G. Arthur and P. A. Fournier, The effect of acute taurine ingestion on human maximal voluntary muscle contraction, *Med. Sci. Sports Exercise*, 2018, **50**, 344–352.

133 Y. Buzdağlı, C. Eyipınar, F. Öget, E. Şıktar, S. Forbes and A. Tekin, Taurine supplementation enhances anaerobic power in elite speed skaters: A double-blind, randomized, placebo-controlled, crossover study, *Biol. Sport*, 2023, **40**, 741–751.

134 K. Akalp, Ş. Vatansever and G. T. Sönmez, Effects of acute taurine consumption on single bout of muscular endurance resistance exercise performance and recovery in resistance trained young male adults, *Biomed. Hum. Kinet.*, 2023, **15**, 74–82.

135 G. Batitucci, S. I. B. M. Terrazas, M. P. Nóbrega, F. G. De Carvalho, M. Papoti, J. S. Marchini, A. S. R. Da Silva and E. C. De Freitas, Effects of taurine supplementation in elite swimmers performance, *Mot., Rev. Educ. Fis.*, 2018, **24**, e1018137.

136 J. A. Kurtz, T. A. VanDusseldorp, J. A. Doyle and J. S. Otis, Taurine in sports and exercise, *J. Int. Soc. Sports Nutr.*, 2021, **18**, 39.

137 H. Deng, T. Song, M. Yin, K. Xu, Y. Zhong, P. Liu, S. Sun, M. N. Bin Naharudin, A. Yusof and X. Fan, Does One Shot Work? The Acute Impact of a Single Taurine Dose on Exercise Performance: A Meta-Analytic Review, *Scand. J. Med. Sci. Sports*, 2025, **35**, e70123.

138 G. Seghieri, I. Campesi, G. Tonolo, F. Bennardini, I. Stendardi, R. Matucci and F. Franconi, Do Sex and Gender Interact with the Biological Actions of Taurine? A Critical Rereading of the Literature, *Int. J. Mol. Sci.*, 2025, **26**, 8097.

139 S. T. Sims and A. K. Heather, Myths and Methodologies: Reducing scientific design ambiguity in studies comparing sexes and/or menstrual cycle phases, *Exp. Physiol.*, 2018, **103**, 1309–1317.

140 EU Register of Health Claims, https://ec.europa.eu/food/food-feed-portal/screen/health-claims/eu-register, (accessed 24 September 2025).

141 D. Bradley, M. Christodoulou and J. Nganga, European Commission Directorate General for Health and Food Safety Study on food intended for Sportspeople Final Report.

142 H. Deng, L. Wang, P. Liu, M. N. Bin Naharudin and X. Fan, Caffeine and taurine: a systematic review and network meta-analysis of their individual and combined effects on physical capacity, cognitive function, and physiological markers, *J. Int. Soc. Sports Nutr.*, 2025, **22**, 2566371.

143 M. Waldron, S. D. Patterson, J. Tallent and O. Jeffries, The Effects of an Oral Taurine Dose and Supplementation Period on Endurance Exercise Performance in Humans: A Meta-Analysis, *Sports Med.*, 2018, **48**, 1247–1253.

144 L. Guan and P. Miao, The effects of taurine supplementation on obesity, blood pressure and lipid profile: A meta-analysis of randomized controlled trials, *Eur. J. Pharmacol.*, 2020, **885**, 173533.

145 Z. Nie, Y. Liu, M. Zhang, C. Wu, Q. Cao, J. Xu, Y. Zheng, Z. Min, W. Zhang and S. Han, Effects of Oral Taurine Supplementation on Cardiometabolic Risk Factors: A Meta-analysis and Systematic Review of Randomized Clinical Trials, *Nutr. Rev.*, 2025, DOI: 10.1093/nutrit/nuaf220.

146 Q. Sun, J. Wang, H. Wang, H. Yu, K. Wan, F. Ma and R. Wang, Effect of Long-Term Taurine Supplementation on the Lipid and Glycaemic Profile in Adults with Overweight or Obesity: A Systematic Review and Meta-Analysis, *Nutrients*, 2024, **17**, 55.

147 X. Tao, Z. Zhang, Z. Yang and B. Rao, The effects of taurine supplementation on diabetes mellitus in humans: A systematic review and meta-analysis, *Food Chem.: Mol. Sci.*, 2022, **4**, 100106.

148 C.-C. Tzang, L.-Y. Chi, L.-H. Lin, T.-Y. Lin, K.-V. Chang, W.-T. Wu and L. Özçakar, Taurine reduces the risk for metabolic syndrome: a systematic review and meta-analysis of randomized controlled trials, *Nutr. Diabetes*, 2024, **14**, 29.

149 C. C. Tzang, W. C. Lin, L. H. Lin, T. Y. Lin, K. V. Chang, W. T. Wu and L. Özçakar, Insights into the cardiovascular benefits of taurine: a systematic review and meta-analysis, *Nutr. J.*, 2024, **23**, 1–12.

150 M. Waldron, S. D. Patterson, J. Tallent and O. Jeffries, The Effects of Oral Taurine on Resting Blood Pressure in Humans: a Meta-Analysis, *Curr. Hypertens. Rep.*, 2018, **20**, 1–8.

151 Q. Cao, Z. Nie, Y. Liu, J. Xu, L. Chen and S. Han, Effects of taurine supplementation on cognitive function: a systema-

tic review and meta-analysis of randomised controlled trials, *Int. J. Food Sci. Nutr.*, 2025, **76**, 370–380.

152 V. Maleki, R. Mahdavi, F. Hajizadeh-Sharafabad and M. Alizadeh, The effects of taurine supplementation on oxidative stress indices and inflammation biomarkers in patients with type 2 diabetes: A randomized, double-blind, placebo-controlled trial, *Diabetol. Metab. Syndr.*, 2020, **12**, 9.

153 V. Maleki, M. Alizadeh, F. Esmaeili and R. Mahdavi, The effects of taurine supplementation on glycemic control and serum lipid profile in patients with type 2 diabetes: a randomized, double-blind, placebo-controlled trial, *Amino Acids*, 2020, **52**, 905–914.

154 F. Esmaeili, V. Maleki, S. Kheirouri and M. Alizadeh, The Effects of Taurine Supplementation on Metabolic Profiles, Pentosidine, Soluble Receptor of Advanced Glycation End Products and Methylglyoxal in Adults With Type 2 Diabetes: A Randomized, Double-Blind, Placebo-Controlled Trial, *Can. J. Diabetes*, 2021, **45**, 39–46.

155 F. T. Rosa, E. C. Freitas, R. Deminice, A. A. Jordão and J. S. Marchini, Oxidative stress and inflammation in obesity after taurine supplementation: A double-blind, placebo-controlled study, *Eur. J. Nutr.*, 2014, **53**, 823–830.

156 J. Moludi, S. A. Qaisar, M. M. Kadhim, Y. Ahmadi and M. Davari, Protective and therapeutic effectiveness of taurine supplementation plus low calorie diet on metabolic parameters and endothelial markers in patients with diabetes mellitus: a randomized, clinical trial, *Nutr. Metab.*, 2022, **19**, 49.

157 K. Duszka, Versatile Triad Alliance: Bile Acid, Taurine and Microbiota, *Cells*, 2022, **11**, 2337.

158 I. Campesi, G. Seghieri and F. Franconi, Type 2 diabetic women are not small type 2 diabetic men: Sex-and-gender differences in antidiabetic drugs, *Curr. Opin. Pharmacol.*, 2021, **60**, 40–45.

159 M. J. Legato, *Principles of gender-specific medicine: gender in the genomic era*, Elsevier, Academic Press, 3rd edn, 2017.

160 D. Furman, J. Campisi, E. Verdin, P. Carrera-Bastos, S. Targ, C. Franceschi, L. Ferrucci, D. W. Gilroy, A. Fasano, G. W. Miller, A. H. Miller, A. Mantovani, C. M. Weyand, N. Barzilai, J. J. Goronzy, T. A. Rando, R. B. Effros, A. Lucia, N. Kleinstreuer and G. M. Slavich, Chronic inflammation in the etiology of disease across the life span, *Nat. Med.*, 2019, **25**, 1822–1832.

161 M. U. Chupel, L. G. Minuzzi, G. Furtado, M. L. Santos, E. Hogervorst, E. Filaire and A. M. Teixeira, Exercise and taurine in inflammation, cognition, and peripheral markers of blood-brain barrier integrity in older women, *Appl. Physiol., Nutr., Metab.*, 2018, **43**, 733–741.

162 M. U. Chupel, L. G. Minuzzi, G. E. Furtado, M. L. Santos, J. P. Ferreira, E. Filaire and A. M. Teixeira, Taurine supplementation reduces myeloperoxidase and matrix-metalloproteinase-9 levels and improves the effects of exercise in cognition and physical fitness in older women, *Amino Acids*, 2021, **53**, 333–345.

163 A. Yabluchanskiy, Y. Ma, R. P. Iyer, M. E. Hall and M. L. Lindsey, Matrix metalloproteinase-9: Many shades of function in cardiovascular disease, *Physiology*, 2013, **28**, 391–403.

164 I. J. Neeland, S. Lim, A. Tchernof, A. Gastaldelli, J. Rangaswami, C. E. Ndumele, T. M. Powell-Wiley and J. P. Després, Metabolic syndrome, *Nat. Rev. Dis. Primers*, 2024, **10**(1), 1–22.

165 M. Y. Lee, S. H. Cheong, K. J. Chang, M. J. Choi and S. K. Kim, Effect of The Obesity Index on Plasma Taurine Levels in Korean Female Adolescents, *Adv. Exp. Med. Biol.*, 2003, **526**, 285–290.

166 F. Franconi, F. Bennardini, A. Mattana, M. Miceli, M. Ciuti, M. Mian, A. Gironi, R. Anichini and G. Seghieri, Plasma and platelet taurine are reduced in subjects with insulin-dependent diabetes mellitus: effects of taurine supplementation, *Am. J. Clin. Nutr.*, 1995, **61**, 1115–1119.

167 G. De Luca, P. R. Calpona, A. Caponetti, G. Romano, A. Di Benedetto, D. Cucinotta and R. M. Di Giorgio, Taurine and osmoregulation: Platelet taurine content, uptake, and release in type 2 diabetic patients, *Metabolism.*, 2001, **50**, 60–64.

168 M. Merheb, R. T. Daher, M. Nasrallah, R. Sabra, F. N. Ziyadeh and K. Barada, Taurine Intestinal Absorption and Renal Excretion Test in Diabetic PatientsA pilot study, *Diabetes Care*, 2007, **30**, 2652–2654.

169 M. Zhang, L. F. Bi, J. H. Fang, X. L. Su, G. L. Da, T. Kuwamori and S. Kagamimori, Beneficial effects of taurine on serum lipids in overweight or obese non-diabetic subjects, *Amino Acids*, 2004, **26**, 267–271.

170 S. Mizushima, Y. Nara, M. Sawamura and Y. Yamori, Effects of oral taurine supplementation on lipids and sympathetic nerve tone, *Adv. Exp. Med. Biol.*, 1996, **403**, 615–622.

171 R. W. Beck, R. M. Bergenstal, P. Cheng, C. Kollman, A. L. Carlson, M. L. Johnson and D. Rodbard, The Relationships Between Time in Range, Hyperglycemia Metrics, and HbA1c, *J. Diabetes Sci. Technol.*, 2019, **13**, 614–626.

172 Y. Li, Q. Wang, Y. Liu, Q. Li, W. Xia, S. Lin, Q. Yang, A. Scholze, Z. Zhao, H. He, H. Zhang, Z. Yan, M. Tepel, H. Mu, Z. Zhu and D. Liu, Taurine ameliorates blood pressure and vascular function in patients with type 2 diabetes: Randomized, double-blind, placebo-controlled trial, *iScience*, 2025, **28**, 112719.

173 Q. Sun, B. Wang, Y. Li, F. Sun, P. Li, W. Xia, X. Zhou, Q. Li, X. Wang, J. Chen, X. Zeng, Z. Zhao, H. He, D. Liu and Z. Zhu, Taurine Supplementation Lowers Blood Pressure and Improves Vascular Function in Prehypertension: Randomized, Double-Blind, Placebo-Controlled Study, *Hypertension*, 2016, **67**, 541–549.

174 T. T. N. Dinh, L. D. Thompson, M. L. Galyean, J. C. Brooks, K. Y. Patterson and L. M. Boylan, Cholesterol Content and Methods for Cholesterol Determination in Meat and Poultry, *Compr. Rev. Food Sci. Food Saf.*, 2011, **10**, 269–289.

175 C. Stewart, C. Piernas, B. Cook and S. A. Jebb, Trends in UK meat consumption: analysis of data from years 1–11 (2008–09 to 2018–19) of the National Diet and Nutrition Survey rolling programme, *Lancet Planet. Health*, 2021, **5**, e699–e708.

176 M. J. Vincent, B. Allen, O. M. Palacios, L. T. Haber and K. C. Maki, Meta-regression analysis of the effects of dietary cholesterol intake on LDL and HDL cholesterol, *Am. J. Clin. Nutr.*, 2019, **109**, 7–16.

177 M. Schoeneck and D. Iggman, The effects of foods on LDL cholesterol levels: A systematic review of the accumulated evidence from systematic reviews and meta-analyses of randomized controlled trials, *Nutr., Metab. Cardiovasc. Dis.*, 2021, **31**, 1325–1338.

178 Y. Hou, W. He, S. Hu and G. Wu, Composition of polyamines and amino acids in plant-source foods for human consumption, *Amino Acids*, 2019, **51**, 1153–1165.

179 K. Ahmed, H. N. Choi and J. E. Yim, The Impact of Taurine on Obesity-Induced Diabetes Mellitus: Mechanisms Underlying Its Effect, *Endocrinol. Metab.*, 2023, **38**, 482–492.

180 N. Tsuboyama-Kasaoka, C. Shozawa, K. Sano, Y. Kamei, S. Kasaoka, Y. Hosokawa and O. Ezaki, Taurine (2-Aminoethanesulfonic Acid) Deficiency Creates a Vicious Circle Promoting Obesity, *Endocrinology*, 2006, **147**, 3276–3284.

181 C. S. R. Jankowski, L. Z. Samarah, M. R. MacArthur, S. J. Mitchell, D. R. Weilandt, C. J. Hunter, X. Zeng, M. R. McReynolds and J. D. Rabinowitz, Aged mice exhibit widespread metabolic changes but preserved major fluxes, *Cell Metab.*, 2025, **37**, 2280–2294.

182 D. M. Guizoni, I. N. Freitas, J. A. Victorio, I. R. Possebom, T. R. Araujo, E. M. Carneiro and A. P. Davel, Taurine treatment reverses protein malnutrition-induced endothelial dysfunction of the pancreatic vasculature: The role of hydrogen sulfide, *Metabolism.*, 2021, **116**, 154701.

183 P. Huang, Y. Huang, B. Lv, H. Zhang, J. Liu, G. Yang, Y. Tao, D. Bu, G. Wang, J. Du and H. Jin, Endogenous Taurine Downregulation Is Required for Renal Injury in Salt-Sensitive Hypertensive Rats via CBS/H_2S Inhibition, *Oxid. Med. Cell. Longevity*, 2021, **2021**, 5530907.

184 S. Murakami, Y. Kondo-Ohta and K. Tomisawa, Improvement in cholesterol metabolism in mice given chronic treatment of taurine and fed a high-fat diet, *Life Sci.*, 1998, **64**, 83–91.

185 S. Murakami, Y. Kondo, Y. Toda, H. Kitajima, K. Kameo, M. Sakono and N. Fukuda, Effect of taurine on cholesterol metabolism in hamsters: Up-regulation of low density lipoprotein (LDL) receptor by taurine, *Life Sci.*, 2002, **70**, 2355–2366.

186 S. F. Yang, B. S. Tzang, K. T. Yang, Y. C. Hsiao, Y. Y. Chang, C. H. Chan, S. G. Fu and Y. C. Chen, Taurine alleviates dyslipidemia and liver damage induced by a high-fat/cholesterol-dietary habit, *Food Chem.*, 2010, **120**, 156–162.

187 M. D. Morsy, M. S. Aboonq, M. A. Alsleem and A. A. Abusham, Taurine prevents high-fat diet-induced-hepatic steatosis in rats by direct inhibition of hepatic sterol regulatory element-binding proteins and activation of AMPK, *Clin. Exp. Pharmacol. Physiol.*, 2021, **48**, 72–85.

188 R. Tang, Q. Yang, S. Lin, Y. Feng, J. Yang, Q. Lv, G. Wu and J. Hu, Preventive or Curative Administration of Taurine Regulates Lipid Metabolism in the Liver of Rats with Alcoholic Liver Disease, *Adv. Exp. Med. Biol.*, 2019, **1155**, 119–131.

189 T. Kishida, S. Miyazato, H. Ogawa and K. Ebihara, Taurine Prevents Hypercholesterolemia in Ovariectomized Rats Fed Corn Oil but Not in Those Fed Coconut Oil, *J. Nutr.*, 2003, **133**, 2616–2621.

190 Z. F. Stephan, S. Lindsey and K. C. Hayes, Taurine enhances low density lipoprotein binding. Internalization and degradation by cultured Hep G2 cells., *J. Biol. Chem.*, 1987, **262**, 6069–6073.

191 Y. Dong, X. Li, Y. Liu, J. Gao and J. Tao, The molecular targets of taurine confer anti-hyperlipidemic effects, *Life Sci.*, 2021, **278**, 119579.

192 M. H. Hoang, Y. Jia, H. J. Jun, J. H. Lee, K. Y. Hwang, D. W. Choi, S. J. Um, B. Y. Lee, S. G. You and S. J. Lee, Taurine is a liver X receptor-α ligand and activates transcription of key genes in the reverse cholesterol transport without inducing hepatic lipogenesis, *Mol. Nutr. Food Res.*, 2012, **56**, 900–911.

193 B. Goodwin, M. A. Watson, H. Kim, J. Miao, J. K. Kemper and S. A. Kliewer, Differential Regulation of Rat and Human CYP7A1 by the Nuclear Oxysterol Receptor Liver X Receptor-α, *Mol. Endocrinol.*, 2003, **17**, 386–394.

194 Y. Li, S. Xu, M. M. Mihaylova, B. Zheng, X. Hou, B. Jiang, O. Park, Z. Luo, E. Lefai, J. Y. J. Shyy, B. Gao, M. Wierzbicki, T. J. Verbeuren, R. J. Shaw, R. A. Cohen and M. Zang, AMPK Phosphorylates and Inhibits SREBP Activity to Attenuate Hepatic Steatosis and Atherosclerosis in Diet-induced Insulin Resistant Mice, *Cell Metab.*, 2011, **13**, 376.

195 K. Ahmed, H. N. Choi, J.-S. Park, Y. G. Kim, M. K. Bae and J. E. Yim, Taurine supplementation alters gene expression profiles in white adipose tissue of obese C57BL/6J mice: Inflammation and lipid synthesis perspectives, *Heliyon*, 2023, **10**, e23288.

196 K. S. Kim, H. M. Doss, H. J. Kim and H. I. Yang, Taurine Stimulates Thermoregulatory Genes in Brown Fat Tissue and Muscle without an Influence on Inguinal White Fat Tissue in a High-Fat Diet-Induced Obese Mouse Model, *Foods*, 2020, **9**, 688.

197 P. Cao, Y. Jin, M. Li, R. Zhou and M. Yang, PGC-1α may associated with the anti-obesity effect of taurine on rats induced by arcuate nucleus lesion, *Nutr. Neurosci.*, 2016, **19**, 86–93.

198 G. Bagci and H. Okten, The effects of taurine supplementation on obesity and browning of white adipose tissue in high-fat diet-fed mice, *Nucleosides. Nucleotides Nucleic Acids*, 2023, **42**, 151–165.

199 T. Kawai, M. V. Autieri and R. Scalia, Adipose tissue inflammation and metabolic dysfunction in obesity, *Am. J. Physiol.: Cell Physiol.*, 2021, **320**, C375–C391.

200 K. S. Kim, M. J. Jang, S. Fang, S. G. Yoon, I. Y. Kim, J. K. Seong, H. I. Yang and D. H. Hahm, Anti-obesity effect of taurine through inhibition of adipogenesis in white fat tissue but not in brown fat tissue in a high-fat diet-induced obese mouse model, *Amino Acids*, 2019, **51**, 245–254.

201 C. Fogagnolo, G. U. Ortiz, S. G. Travieso, A. C. Rossini-Venturini, G. F. Abud, B. M. Silva, A. S. R. da Silva and E. C. de Freitas, Taurine in Type 2 Diabetes: Plasma Concentrations, Metabolic Pathways, and Potential as a Therapeutic Adjuvant, *Curr. Nutr. Rep.*, 2025, **14**, 119.

202 W. Wei, X. Lyu, A. L. Markhard, S. Fu, R. E. Mardjuki, P. E. Cavanagh, X. Zeng, J. Rajniak, N. Lu, S. Xiao, M. Zhao, M. D. Moya-Garzon, S. D. Truong, J. C. Chou, L. W. Wat, S. Chidambaranathan-Reghupaty, L. Coassolo, D. Xu, F. Shen, W. Huang, C. B. Ramirez, C. Jang, L. Li, K. J. Svensson, M. A. Fischbach and J. Z. Long, PTER is a N-acetyltaurine hydrolase that regulates feeding and obesity, *Nature*, 2024, **633**, 182–188.

203 F. G. De Carvalho, C. F. C. Brandao, V. R. Muñoz, G. Batitucci, M. E. D. A. Tavares, G. R. Teixeira, J. R. Pauli, L. P. De Moura, E. R. Ropelle, D. E. Cintra, A. S. R. da Silva, M. V. M. Junqueira-Franco, J. S. Marchini and E. C. De Freitas, Taurine supplementation in conjunction with exercise modulated cytokines and improved subcutaneous white adipose tissue plasticity in obese women, *Amino Acids*, 2021, **53**, 1391–1403.

204 F. G. De Carvalho, V. R. Muñoz, C. F. C. Brandao, F. M. Simabuco, I. C. B. Pavan, S. C. B. R. Nakandakari, J. R. Pauli, L. P. De Moura, E. R. Ropelle, J. S. Marchini, A. S. R. da Silva and E. C. de Freitas, Taurine upregulates insulin signaling and mitochondrial metabolism in vitro but not in adipocytes of obese women, *Nutrition*, 2022, **93**, 111430.

205 F. H. Shari, A. Y. Ibrahim, J. K. Hassan and H. N. K. Al-Salman, Study effect of sulfur containing amino acid supplementation on oxidative stress, inflammatory markers and serum lipid in relation to obese subjects, *Int. J. Pharm. Res.*, 2020, **12**, 362–370.

206 C. Chih-Kuang, L. Shuan-Pei, L. Shyue-Jye and W. Tuan-Jen, Plasma free amino acids in Taiwan Chinese: The effect of age, *Clin. Chem. Lab. Med.*, 2002, **40**, 378–382.

207 M. Jeevanandam, D. H. Young, L. Ramias and W. R. Schiller, Effect of major trauma on plasma free amino acid concentrations in geriatric patients, *Am. J. Clin. Nutr.*, 1990, **51**, 1040–1045.

208 R. Dawson, S. Liu, B. Eppler and T. Patterson, Effects of dietary taurine supplementation or deprivation in aged male Fischer 344 rats, *Mech. Ageing Dev.*, 1999, **107**, 73–91.

209 T. Ito, N. Yoshikawa, T. Inui, N. Miyazaki, S. W. Schaffer and J. Azuma, Tissue Depletion of Taurine Accelerates Skeletal Muscle Senescence and Leads to Early Death in Mice, *PLoS One*, 2014, **9**, e107409.

210 U. Warskulat, B. Heller-Stilb, E. Oermann, K. Zilles, H. Haas, F. Lang and D. Häussinger, Phenotype of the Taurine Transporter Knockout Mouse, *Methods Enzymol.*, 2007, **428**, 439–458.

211 M. E. Fernandez, M. Bernier, N. L. Price, S. Camandola, M. A. Aon, K. Vaughan, J. A. Mattison, J. D. Preston, D. P. Jones, T. Tanaka, Q. Tian, M. González-Freire, L. Ferrucci and R. de Cabo, Is taurine an aging biomarker?, *Science*, 2025, **388**, eadl2116.

212 C. López-Otín, M. A. Blasco, L. Partridge, M. Serrano and G. Kroemer, Hallmarks of aging: An expanding universe, *Cell*, 2023, **186**, 243–278.

213 Q. Zheng, R. Lin, Z. Li, Q. Zheng and W. Xu, Taurine is a potential therapy for rheumatoid arthritis via targeting FOXO3 through cellular senescence and autophagy, *PLoS One*, 2025, **20**, e0318311.

214 H. Kaneko, M. Kobayashi, Y. Mizunoe, M. Yoshida, H. Yasukawa, S. Hoshino, R. Itagawa, T. Furuichi, N. Okita, Y. Sudo, M. Imae and Y. Higami, Taurine is an amino acid with the ability to activate autophagy in adipocytes, *Amino Acids*, 2018, **50**, 527–535.

215 C. J. Jong, T. Ito, J. Azuma and S. Schaffer, Taurine Depletion Decreases GRP78 Expression and Downregulates Perk-Dependent Activation of the Unfolded Protein Response, *Adv. Exp. Med. Biol.*, 2015, **803**, 571–579.

216 W. Qian, M. Li, L. Yu, F. Tian, J. Zhao and Q. Zhai, Effects of Taurine on Gut Microbiota Homeostasis: An Evaluation Based on Two Models of Gut Dysbiosis, *Biomedicines*, 2023, **11**, 1048.

217 N. Husain and R. Mahmood, Taurine attenuates Cr(VI)-induced cellular and DNA damage: an in vitro study using human erythrocytes and lymphocytes, *Amino Acids*, 2019, **52**(1), 35–53.

218 M. Mashyakhy, A. Alkahtani, A. S. Abumelha, R. J. Sharroufna, M. F. Alkahtany, M. Jamal, A. Robaian, S. Binalrimal, H. Chohan, V. R. Patil, A. T. Raj, S. Bhandi, R. Reda, L. Testarelli and S. Patil, Taurine Augments Telomerase Activity and Promotes Chondrogenesis in Dental Pulp Stem Cells, *J. Pers. Med.*, 2021, **11**, 491.

219 H. J. Ji, G. Y. Zhao, J. F. Luo, X. L. Zhao and M. Zhang, Taurine postponed the replicative senescence of rat bone marrow-derived multipotent stromal cells in vitro, *Mol. Cell. Biochem.*, 2012, **366**, 259–267.

220 Y. Li, F. Xie, L. Yang, X. Wang, Y. Zhang, H. Ge, M. Wang, R. Cao, Q. Zhou and Y. Li, SLC6A6-Mediated Taurine Uptake Sustains Corneal Epithelial Stem/Progenitor Cell Function to Counteract Age-Related Dysfunction, *Invest. Ophthalmol. Visual Sci.*, 2025, **66**, 25.

221 U.S. Department of Health and Human Services Food and Drug Administration Center for Drug Evaluation and Research (CDER), Guidance for Industry: Estimating the Maximum Safe Starting Dose in Adult Healthy Volunteer, 2005, preprint, https://www.fda.gov/regulatory-information/search-fda-guidance-documents/estimating-maximum-safe-starting-dose-initial-clinical-trials-therapeutics-adult-healthy-volunteers.

222 M. Martiniakova, A. Sarocka, R. Babosova, D. Galbavy, E. Kapusta, Z. Goc, G. Formicki and R. Omelka, Bone microstructure of mice after prolonged taurine treatment, *Physiol. Res.*, 2019, **68**, 519–523.

223 H. Hauner, Effect of daily taurine supplementation for 6 months on age and metabolic biomarkers as well as physical fitness in 55–75-year-old-women and men: the TauAge Study, 2024, preprint, https://drks.de/search/en/trial/DRKS00035066.

224 F. Ali, H. Rehman, Z. Babayan, D. Stapleton and D. D. Joshi, Energy drinks and their adverse health effects: A systematic review of the current evidence, *Postgrad. Med.*, 2015, **127**, 308–322.

225 J. Rigo and J. Senterre, Is taurine essential for the neonates?, *Biol. Neonate*, 1977, **32**, 73–76.

226 S. K. Rana and T. A. B. Sanders, Taurine concentrations in the diet, plasma, urine and breast milk of vegans compared with omnivores, *Br. J. Nutr.*, 1986, **56**, 17–27.

227 M. Mahmoudinezhad, F. Abbaszadeh, M. Zarezadeh, N. Bahreini, P. Jamilian, P. Jamilian and A. Ostadrahimi, N-acetylecysteine, a powerful agent in the reinforcement of anti-oxidant profile: A systematic review and dose-response meta-analysis of controlled clinical trials, *Clin. Nutr. ESPEN*, 2023, **54**, 227–238.

228 K. Rhodes and A. Braakhuis, Performance and Side Effects of Supplementation with N-Acetylcysteine: A Systematic Review and Meta-Analysis, *Sports Med.*, 2017, **47**, 1619–1636.

229 M. C. D. S. Tenório, N. G. Graciliano, F. A. Moura, A. C. M. de Oliveira and M. O. F. Goulart, N-Acetylcysteine (NAC): Impacts on Human Health, *Antioxidants*, 2021, **10**, 967.

230 A. Shao and J. N. Hathcock, Risk assessment for the amino acids taurine, l-glutamine and l-arginine, *Regul. Toxicol. Pharmacol.*, 2008, **50**, 376–399.

231 P. L. Pearl, J. Schreiber, W. H. Theodore, R. McCarter, E. S. Barrios, J. Yu, E. Wiggs, J. He and K. M. Gibson, Taurine trial in succinic semialdehyde dehydrogenase deficiency and elevated: CNS GABA, *Neurology*, 2014, **82**, 940–944.

232 L. Bergamini, R. Mutani, M. Delsedime and L. Durelli, First Clinical Experience on the Antiepileptic Action of Taurine, *Eur. Neurol.*, 1974, **11**, 261–269.

233 EFSA Panel on Food Additives and Nutrient Sources added to Food (ANS), The use of taurine and D-glucurono-gamma-lactone as constituents of the so-called "energy" drinks, *EFSA J.*, 2009, **7**, 935.

234 Norwegian Scientific Committee for Food Safety (VKM), *Risk assessment of 'other substances' – Taurine*, 2015.

235 E. Pérez-Hernández, J. J. Pastrana-Carballo, F. Gómez-Chávez, R. C. Gupta and N. Pérez-Hernández, A Key Metabolic Regulator of Bone and Cartilage Health, *Endocrinol. Metab.*, 2022, **37**, 559–574.

236 T. Cao, W. Zhang, Q. Wang, C. Wang, W. Ma, C. Zhang, M. Ge, M. Tian, J. Yu, A. Jiao, L. Wang, M. Liu, P. Wang, Z. Guo, Y. Zhou, S. Chen, W. Yin, J. Yi, H. Guo, H. Han, B. Zhang, K. Wu, D. Fan, X. Wang, Y. Nie, Y. Lu and X. Zhao, Cancer SLC6A6-mediated taurine uptake transactivates immune checkpoint genes and induces exhaustion in CD8+ T cells, *Cell*, 2024, **187**, 2288–2304.

237 S. Sharma, B. J. Rodems, C. D. Baker, C. M. Kaszuba, E. I. Franco, B. R. Smith, T. Ito, K. Swovick, K. Welle, Y. Zhang, P. Rock, F. A. Chaves, S. Ghaemmaghami, L. M. Calvi, A. Ganguly, W. R. Burack, M. W. Becker, J. L. Liesveld, P. S. Brookes, J. C. Munger, C. T. Jordan, J. M. Ashton and J. Bajaj, Taurine from tumour niche drives glycolysis to promote leukaemogenesis, *Nature*, 2025, **644**, 263–272.

238 C. Wen, F. Li, L. Zhang, Y. Duan, Q. Guo, W. Wang, S. He, J. Li, Y. Yin, C. Wen, W. Wang, S. He, J. Li, F. Li, L. Zhang, Y. Duan, Q. Guo and Y. Yin, Taurine is Involved in Energy Metabolism in Muscles, Adipose Tissue, and the Liver, *Mol. Nutr. Food Res.*, 2019, **63**, 1800536.