

## REVIEW

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# Taurine, energy drinks, and neuroendocrine effects

## ABSTRACT

Taurine is an amino acid found abundantly in brain, retina, heart, and reproductive organ cells, as well as in meat and seafood. But it is also a major ingredient in popular “energy drinks,” which thus constitute a major source of taurine supplementation. Unfortunately, little is known about taurine’s neuroendocrine effects. The authors review the sparse data and provide a basic background on the structure, synthesis, distribution, metabolism, mechanisms, effects, safety, and currently proposed therapeutic targets of taurine.

## KEY POINTS

Energy drinks are widely consumed in the United States, with an estimated 354 million gallons sold in 2009, or approximately 5.25 L/year per person over age 10.

Taurine has been reported to have anti-inflammatory action. Supplementation has been proposed to have beneficial effects in epilepsy, heart failure, cystic fibrosis, and diabetes, and has been shown in animal studies to protect against neurotoxic insults from alcohol, ammonia, lead, and other substances.

Taurine is an inhibitory neurotransmitter and neuromodulator. It is structurally analogous to gamma-aminobutyric acid, the main inhibitory neurotransmitter in the brain.

**T**AURINE—AN AMINO ACID found in abundance in the human brain, retina, heart, and reproductive organs, as well as in meat and seafood—is also a major ingredient in “energy drinks” (Table 1).<sup>1,2</sup> Given the tremendous popularity of these drinks in the United States, it would seem important to know and to recognize taurine’s neuroendocrine effects. Unfortunately, little is known about the effects of taurine supplementation in humans.

This paper reviews the sparse data to provide clinicians some background on the structure, synthesis, distribution, metabolism, mechanisms, effects, safety, and proposed therapeutic targets of taurine.

## ■ TAURINE’S THERAPEUTIC POTENTIAL

Taurine has been reported to have widespread anti-inflammatory actions.<sup>3,4</sup> Taurine supplementation has been proposed to have beneficial effects in the treatment of epilepsy,<sup>5</sup> heart failure,<sup>6,7</sup> cystic fibrosis,<sup>8</sup> and diabetes<sup>9</sup> and has been shown in animal studies to protect against neurotoxic insults from alcohol, ammonia, lead, and other substances.<sup>10–16</sup>

In addition, taurine analogues such as homotaurine and *N*-acetyl-homotaurine (acamprostate) have been probed for possible therapeutic applications. Homotaurine has been shown to have antiamyloid activity that could in theory protect against the progression of Alzheimer disease,<sup>17</sup> and acamprostate is approved by the US Food and Drug Administration (FDA) for the treatment of alcohol use disorders.<sup>18</sup>

## ■ TAURINE CONSUMPTION

Energy drinks are widely consumed in the United States, with an estimated 354 million

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**TABLE 1**

**Taurine content of common energy drinks**

<b>Brand (can size)</b>	<b>Taurine per can (mg)</b>	<b>Taurine per 8 oz</b>
Cocaine (8.4 oz)	788	750
Go Girl Sugar-Free (12 oz)	1,200	800
Monster (16 oz)	2,000	1,000
Red Bull (8.3 oz)	1,038	1,000
Rockstar (16 oz)	2,000	1,000
Tab Energy (12 oz)	1,178	785

Based on information from reference 91.

**Vegans take in much less taurine and have lower circulating levels**

gallons sold in 2009, or approximately 5.25 L/year per person over age 10.<sup>1</sup> In 2012, US sales of energy drinks exceeded \$12 billion,<sup>19</sup> with young men, particularly those in the military deployed in war zones, being the biggest consumers.<sup>20–22</sup> Analyses have found that of 49 nonalcoholic energy drinks tested, the average concentration of taurine was 3,180 mg/L, or approximately 750 mg per 8-oz serving.<sup>23,24</sup> Popular brands include Red Bull, Monster, Rockstar (Table 1), NOS, Amp, and Full Throttle.

Taurine is plentiful in the human body, which contains up to 1 g of taurine per kg.<sup>25</sup> Foods such as poultry, beef, pork, seafood, and processed meats have a high taurine content (Table 2).<sup>26–29</sup> People who eat meat and seafood have plentiful taurine intake, whereas vegetarians and vegans consume much less and have significantly lower circulating levels<sup>30</sup> because plants do not contain taurine in appreciable amounts.<sup>26,29</sup>

The typical American diet provides between 123 and 178 mg of taurine daily.<sup>26</sup> Consumption of one 8-oz energy drink can increase the average intake 6 to 16 times. A lacto-ovo vegetarian diet provides only about 17 mg of taurine daily, and an 8-oz energy drink can increase the average intake by 44 to 117 mg.<sup>26</sup> And since a vegan diet provides essentially no taurine,<sup>30</sup> energy drink intake in any amount would constitute a major relative increase in taurine consumption.

**ATTEMPTS TO STUDY TAURINE’S EFFECTS**

Since most clinical trials to date have looked at the effects of taurine in combination with other ingredients such as caffeine, creatine, and glucose<sup>31–35</sup> in drinks such as Red Bull, these studies cannot be used to determine the effects of taurine alone. In the few clinical trials that have tested isolated taurine consumption, data are not sufficient to make a conclusion on direct effects on energy metabolism.

Rutherford et al<sup>36</sup> tested the effect of oral taurine supplementation (1,660 mg) on endurance in trained male cyclists 1 hour before exercise, but observed no effect on fluid intake, heart rate, subjective exertion, or time-trial performance. A small increase (16%) in total fat oxidation was observed during the 90-minute exercise period. Since mitochondria are the main location of fatty acid degradation, this effect may be attributed to taurine supplementation, with subsequent improvement in mitochondrial function.

Zhang et al<sup>37</sup> found a 30-second increase in cycling energy capacity after 7 days of 6 g oral taurine supplementation, but the study was neither blinded nor placebo-controlled.

Kammerer et al<sup>38</sup> tested the effect of 1 g of taurine supplementation on physical and mental performance in young adult soldiers 45 minutes before physical fitness and cognitive testing. This double-blind, placebo-controlled randomized trial found no effect of taurine on cardiorespiratory fitness indices, concentration, or immediate memory, nor did it find any effect of an 80-mg dose of caffeine.

In sum, the available data are far from sufficient to determine the direct effect of taurine consumption on energy metabolism in healthy people.

**PHARMACOLOGY OF TAURINE**

**Chemical structure**

Taurine, or 2-aminoethane sulfonic acid, is a conditionally essential amino acid, ie, we can usually make enough in our own bodies. It was first prepared on a large scale for physiologic investigation almost 90 years ago, through the purification of ox bile.<sup>39</sup> It can be obtained either exogenously through dietary sources or endogenously through biosynthesis from methionine and cysteine precursors, both essential sulfur-

containing alpha-amino acids.<sup>40</sup> Both sources are important to maintain physiologic levels of taurine, and either can help compensate for the other in cases of deficiency.<sup>41</sup>

The structure of taurine has two main differences from the essential amino acids. First, taurine's amino group is attached to the beta-carbon rather than the alpha-carbon, making it a beta-amino acid instead of an alpha-amino acid.<sup>42</sup> Second, the acid group in taurine is sulfonic acid, whereas the essential amino acids have a carboxylic acid.<sup>43</sup> Because of its distinctive structure, taurine is not used as a structural unit in proteins,<sup>43</sup> existing mostly as a free amino acid within cells, readily positioned to perform several unique functions.

### Synthesis

De novo synthesis of taurine involves several enzymes and at least five pathways,<sup>44</sup> mostly differing by the order in which sulfur is oxidized and decarboxylated.<sup>45</sup>

The rate-limiting enzyme of the predominant pathway is thought to be cysteine sulfinate decarboxylase (CSD), and its presence within an organ indicates involvement in taurine production.<sup>44</sup> CSD has been found in the liver,<sup>46</sup> the primary site of taurine biosynthesis, as well as in the retina,<sup>47</sup> brain,<sup>48</sup> kidney,<sup>49</sup> mammary glands,<sup>50,51</sup> and reproductive organs.<sup>52</sup>

### Distribution

Taurine levels are highest in electrically excitable tissues such as the central nervous system, retina, and heart; in secretory structures such as the pineal gland and the pituitary gland (including the posterior lobe or neurohypophysis); and in platelets<sup>25</sup> and neutrophils.<sup>53</sup>

In the fetal brain, the taurine concentration is higher than that of any other amino acid,<sup>54</sup> but the concentration in the brain decreases with advancing age, whereas glutamate levels increase over time to make it the predominant amino acid in the adult brain.<sup>54</sup> Regardless, taurine is still the second most prevalent amino acid in the adult brain, its levels comparable to those of gamma-aminobutyric acid (GABA).<sup>55</sup>

Taurine has also been found in variable amounts in the liver, muscle, kidney, pancreas, spleen, small intestine, and lungs,<sup>56</sup> as well as in several other locations.<sup>45,57</sup>

TABLE 2

### Taurine content of meats, seafood, and dairy products

Food	Preparation	Taurine content (mg per 100 g)
<b>Poultry</b>		
Chicken, dark meat	Broiled	132.9–265.1
Chicken, light meat	Broiled	5.20–24.80
Turkey, dark meat	Roasted	161.4–436.6
Turkey, light meat	Roasted	8.4–13.7
<b>Beef</b>		
Veal	Broiled	8.0–68.0
<b>Pork</b>		
Ham	Baked	34.1–65.9
Pork	Roasted	30.2–83.8
<b>Processed meats</b>		
Bologna, pork/beef	Cured	21.2–40.8
Bologna, turkey	Cured	110.8–135.3
Salami	Cured	39.4–78.6
<b>Seafood</b>		
Blue mussels	Cultured	480.6–539.4
Caviar	Raw	63.6–108.4
Clams	Raw	352.0–688.0
Cod, fillet	Wild	64.4–175.6
Mussels	Raw	530.3–779.7
Oysters	Raw	345.8–446.2
Salmon, fillet	Cultured	54.8–133.2
Scallops	Raw	801.0–853.0
Shrimp, medium	Raw	16.5–61.5
Shrimp, peeled	Wild	215.1–224.9
Shrimp, small	Cooked	8.2–13.8
Squid	Raw	191.5–520.5
Tuna, albacore	Canned	10.2–73.8
Tuna, chunk light	Canned	16.5–61.5
Tuna, in water	Canned	20.5–87.5
White fish	Cooked	10.0–334.0
<b>Dairy products</b>		
Cow's milk, whole	Pasteurized	1.4–3.4
Cow's milk, low-fat	Pasteurized	1.6–3.0
Cow's milk, nonfat	Pasteurized	1.6–3.4
Cow's milk yogurt	Pasteurized	0.7–0.9
Goat's milk	Pasteurized	5.3–8.3
Goat's milk yogurt	Pasteurized	5.0–5.5

Taurine is also present in the male and female reproductive organs. In male rats, taurine and taurine biosynthesis have been localized to Leydig cells of the testes, the cellular source of testosterone in males, as well as the cremaster muscle, efferent ducts, and peritubular myoid

cells surrounding seminiferous tubules.<sup>58</sup> More recently, taurine has been detected in the testes of humans<sup>59</sup> and is also found in sperm and seminal fluid.<sup>60</sup> Levels of taurine in spermatozoa are correlated with sperm quality, presumably by protecting against lipid peroxidation through taurine's antioxidant effects,<sup>61,62</sup> as well as through contribution to the spermatozoa maturation process by facilitating the capacitation, motility, and acrosomal reaction of sperm.<sup>63</sup>

In female rats, taurine has been found in uterine tissue,<sup>64</sup> oviducts,<sup>65</sup> uterine fluid (where it is the predominant amino acid),<sup>66</sup> and thecal cells of developing follicles of ovaries, cells responsible for the synthesis of androgens such as testosterone and androstenedione.<sup>65</sup> Taurine is also a major component of human breast milk<sup>67</sup> and is important for proper neonatal nutrition.<sup>68</sup>

### Metabolism and excretion

Ninety-five percent of taurine is excreted in urine, about 70% as taurine itself, and the rest as sulfate. Most of the sulfate derived from taurine is produced by bacterial metabolism in the gut and then absorbed.<sup>69</sup> However, taurine can also be conjugated with bile acids to act as a detergent in lipid emulsification.<sup>70</sup> In this form, it may be subjected to the enterohepatic circulation, which gives bacteria another chance to convert it into inorganic sulfate for excretion in urine.<sup>69</sup>

### MECHANISMS AND NEUROENDOCRINE EFFECTS

As a free amino acid, taurine has widespread distribution and unique biochemical and physiologic properties and exhibits several organ-specific functions; however, indisputable evidence of a taurine-specific receptor is lacking, and its putative existence<sup>71</sup> is controversial.<sup>72</sup> Nonetheless, taurine is a neuromodulator with a variety of actions.

### Neurotransmission

Taurine is known to be an inhibitory neurotransmitter and neuromodulator.<sup>73</sup> It is structurally analogous to GABA, the main inhibitory neurotransmitter in the brain.<sup>45</sup> Accordingly, it binds to GABA receptors to serve as an agonist,<sup>74,75</sup> causing neuronal hy-

perpolarization and inhibition. Taurine has an even higher affinity for glycine receptors<sup>75</sup> where it has long been known to act as an agonist.<sup>76</sup> GABA and glycine receptors both belong to the Cys-loop receptor superfamily,<sup>77</sup> with conservation of subunits that allows taurine to bind each receptor, albeit at different affinities. The binding effects of taurine on GABA and glycine receptors have not been well documented quantitatively; however, it is known that taurine has a substantially lower affinity than GABA and glycine for their respective receptors.<sup>76</sup>

### Catecholamines and the sympathetic nervous system

Surprisingly little is known about the effects of taurine on norepinephrine, dopamine, and the human sympathetic nervous system.<sup>78</sup> Humans with borderline hypertension given 6 g of taurine orally for 7 days<sup>79</sup> experienced decreases in epinephrine secretion and blood pressure, but normotensive study participants did not experience similar results, possibly because of a better ability to regulate sympathetic tone. Mizushima et al<sup>80</sup> showed that a longer period of taurine intake (6 g orally for 3 weeks) could elicit a decrease in norepinephrine in healthy men with normal blood pressure. Other similar studies<sup>81-83</sup> also suggested interplay between taurine and catecholamines, but the extent is still undetermined.

### Growth hormone, prolactin, sex hormones, and cortisol

Taurine appears to have a complex relationship with several hormones, although its direct effects on hormone secretion remain obscure. Clinical studies of the acute and chronic neuroendocrine effects of taurine loading in humans are needed.

In female rats, secretion of prolactin is increased by the intraventricular injection of 5  $\mu$ L of 2.0  $\mu$ mol taurine over a 10-minute period.<sup>84</sup> Ikuyama et al<sup>85</sup> found an increase in prolactin and growth hormone secretion in adult male rats given 10  $\mu$ L of 0.25  $\mu$ mol and 1.0  $\mu$ mol taurine intraventricularly, yet a higher dose of 4.0  $\mu$ mol had no effect on either hormone. Furthermore, prolactin receptor deficiency is seen in CSD knockout mice, but the receptor is restored with taurine supplementation.<sup>86</sup>

**Most studies have focused not on taurine alone, but combined with caffeine and glucose**

Mantovani and DeVivo<sup>87</sup> reported that 375 to 8,000 mg/day of taurine given orally for 4 to 6 months to epileptic patients stimulated the secretion of growth hormone. However, in another study, a single 75-mg/kg dose of oral taurine did not trigger an acute increase in levels of growth hormone or prolactin in humans.<sup>88</sup> Energy drinks may contain up to 1,000 mg of taurine per 8-oz serving, but the effects of larger doses on growth hormone, which is banned as a supplement by major athletic organizations because of its anabolic and possible performance-enhancing effects, remain to be determined.

Taurine may have effects on human sex hormones, based on the limited observations in rodents.<sup>89–94</sup>

Although human salivary cortisol concentrations were purportedly assessed in response to 2,000 mg of oral taurine,<sup>95</sup> the methods and reported data are not adequate to draw any conclusions.

### Energy metabolism

Mammals are unable to directly use taurine in energy production because they cannot directly reduce it.<sup>25</sup> Instead, bacteria in the gut use it as a source of energy, carbon, nitrogen, and sulfur.<sup>96</sup> However, taurine deficiency appears to impair the cellular respiratory chain, resulting in diminished production of adenosine triphosphate and diminished uptake of long-chain fatty acids by mitochondria, at least in the heart.<sup>97</sup>

Taurine is present in human mitochondria and regulates mitochondrial function. For example, taurine in mitochondria assists in conjugation of transfer RNA for leucine, lysine, glutamate, and glutamine.<sup>98</sup> In *TauT* knockout mice, deficiency of taurine causes mitochondrial dysfunction, triggering a greater than 80% decrease in exercise capacity.<sup>99</sup> Several studies in rodents have shown increased exercise capacity after taurine supplementation.<sup>100–102</sup> In addition, taurine is critical for the growth of blastocytes, skeletal muscle, and myocardium; it is necessary for mitochondrial development and is also important for muscular endurance.<sup>103,104</sup>

### Antioxidation, anti-inflammation, and other functions

Taurine is a major antioxidant, scavenging reactive oxygen and protecting against oxida-

tive stress to organs including the brain,<sup>97,105,106</sup> where it increasingly appears to have neuroprotective effects.<sup>107,108</sup>

Cellular taurine also has anti-inflammatory actions.<sup>3</sup> One of the proposed mechanisms is taurine inhibition of NF-kappa B, an important transcription factor for the synthesis of pro-inflammatory cytokines.<sup>4</sup> This function may be important in protecting polyunsaturated fatty acids from oxidative stress—helping to maintain and stabilize the structure and function of plasma membranes within the lungs,<sup>109</sup> heart,<sup>110</sup> brain,<sup>111</sup> liver,<sup>112</sup> and spermatozoa.<sup>61,62</sup>

Taurine is also conjugated to bile acids synthesized in the liver, forming bile salts<sup>70</sup> that act as detergents to help emulsify and digest lipids in the body. In addition, taurine facilitates xenobiotic detoxification in the liver by conjugating with several drugs to aid in their excretion.<sup>25</sup> Taurine is also implicated in calcium modulation<sup>113</sup> and homeostasis.<sup>114</sup> Through inhibition of several types of calcium channels, taurine has been shown to decrease calcium influx into cells, effectively serving a cytoprotective role against calcium overload.<sup>115,116</sup>

## ■ TAURINE DEFICIENCY

### Fetal and neonatal deficiency

Though taurine is considered nonessential in adults because it can be readily synthesized endogenously, it is thought to be conditionally essential in neonatal nutrition.<sup>68</sup> It is the second most abundant free amino acid in human breast milk<sup>117</sup> and the most abundant free amino acid in fetal brain.<sup>118</sup> In cases of long-term parenteral nutrition, neonates can become drastically taurine deficient<sup>119</sup> due to suboptimal CSD activity,<sup>118</sup> leading to retinal dysfunction.<sup>41</sup> Taurine deficiencies can lead to functional and structural brain damage.<sup>118</sup> Moreover, maternal taurine deficiency results in neurologic abnormalities in offspring<sup>120</sup> and may lead to oxidative stress throughout life.<sup>121</sup>

In 1984, the FDA approved the inclusion of taurine in infant formulas based on research showing that taurine-deficient infants had impaired fat absorption, bile acid secretion, retinal function, and hepatic function.<sup>122</sup> But still under debate are the amount and duration of taurine supplementation required by preterm and low-birth-weight infants, as several

**Taurine levels are highest in nerve tissue, retina, heart, pineal gland, and pituitary gland**

randomized controlled trials failed to show statistically significant effects on growth.<sup>123</sup> Nonetheless, given the alleged detrimental ramifications of a lack of taurine supplementation, as well as the ethical dilemma of performing additional research trials on infants, it is presumed that infant formulas and parenteral nutrition for preterm and low-birth-weight infants will continue to contain taurine.

### Age- and disease-related deficiency

Although taurine deficiency is rare in neonates, it is perhaps inevitable with advancing age. Healthy elderly patients ages 61 to 81 have up to a 49% decrease in plasma taurine concentration compared with healthy individuals ages 27 to 57.<sup>124</sup> While reduced renal retention<sup>125</sup> and taurine intake<sup>126</sup> can account for depressed taurine levels, Eppler and Dawson<sup>127</sup> found that tissue and circulating taurine concentrations decrease over the human life span primarily due to an age-dependent depletion of CSD activity in the liver. This effectively impairs the biosynthesis of endogenous taurine from cysteine or methionine or both, forcing a greater reliance on exogenous sources.

While specific mechanisms have not been fully elucidated, taurine deficiency has also been identified in patients suffering from diseases including but not limited to disorders of bone (osteogenesis imperfecta, osteoporosis),<sup>128</sup> blood (acute myelogenous leukemia),<sup>129</sup> central nervous system (schizophrenia, Friedreich ataxia-spinocerebellar degeneration),<sup>130,131</sup> retina (retinitis pigmentosa),<sup>132</sup> circulatory system and heart (essential hypertension, atherosclerosis),<sup>133</sup> digestion (Gaucher disease),<sup>134</sup> absorption (short-bowel syndrome),<sup>135</sup> cellular proliferation (cancer),<sup>136</sup> and membrane channels (cystic fibrosis),<sup>137</sup> as well as in patients restricted to long-term parenteral nutrition.<sup>138</sup> However, the apparent correlation between taurine deficiency and these conditions does not necessarily mean causation; more study is needed to elucidate a direct connection.

### ■ SAFETY AND TOXICITY OF TAURINE SUPPLEMENTATION

An upper safe level of intake for taurine has not been established. To date, several studies

have involved heavy taurine supplementation without serious adverse effects. While the largest dosage of taurine tested in humans appears to be 10 g/day for 6 months,<sup>139</sup> a number of studies have used 1 to 6 g/day for periods of 1 week to 1 year.<sup>140</sup> However, the assessment of potential acute, subacute, and chronic adverse effects has not been comprehensive. The Scientific Committee on Food of the European Commission<sup>141</sup> reviewed several toxicologic studies on taurine through 2003 and were unable to expose any carcinogenic or teratogenic potential. Nevertheless, based on the available data from trials in humans and lower animals, Shao and Hathcock<sup>140</sup> suggested an observed safe level of taurine of 3 g/day, a conservatively smaller dose that carries a higher level of confidence. Because there is no “observed adverse effect level” for daily taurine intake,<sup>141</sup> more research must be done to ensure safety of higher amounts of taurine administration and to define a tolerable upper limit of intake.

### Interactions with medications

To date, the literature is scarce regarding potential interactions between taurine and commonly used medications.

Although no evidence specifically links taurine with adverse effects when used concurrently with other medications, there may be a link between taurine supplementation and various cytochrome P450 systems responsible for hepatic drug metabolism. Specifically, taurine inhibits cytochrome P450 2E1, a highly conserved xenobiotic-metabolizing P450 responsible for the breakdown of more than 70 substrates, including several commonly used anesthetics, analgesics, antidepressants, antibacterials, and antiepileptics.<sup>142</sup> Of note, taurine may contribute to the attenuation of oxidative stress in the liver in the presence of alcohol<sup>143</sup> and acetaminophen,<sup>144</sup> two substances frequently used and abused. Since the P450 2E1 system catalyzes comparable reactions in rodents and humans,<sup>142</sup> rodents should plausibly serve as a model for further testing of the effects of taurine on various substrates.

### ■ POTENTIAL THERAPEUTIC APPLICATIONS

More analysis is needed to fully unlock and understand taurine’s potential value in healthcare.

**Taurine has a variety of neuromodulatory actions**

Correction of late-life taurine decline in humans could be beneficial for cognitive performance, energy metabolism, sexual function, and vision, but clinical studies remain to be performed. While a decline in taurine with age may intensify the stress caused by reactive oxygen species, taurine supplementation has been shown to decrease the presence of oxidative markers<sup>127</sup> and to serve a neuroprotective role in rodents.<sup>145,146</sup> Taurine levels increase in the hippocampus after experimentally induced gliosis<sup>147</sup> and are neuroprotective against glutamate excitotoxicity.<sup>148,149</sup> Furthermore, data in Alzheimer disease, Huntington disease, and brain ischemia experimental models show that taurine inhibits neuronal death (apoptosis).<sup>13,150,151</sup> Taurine has even been proposed as a potential preventive treatment for Alzheimer dementia, as it stabilizes protein conformations to prevent their aggregation and subsequent dysfunction.<sup>152</sup> Although improvement in memory and cognitive performance has been linked to taurine supplementation in old mice,<sup>145,153</sup> similar results have not been found in adult mice whose taurine levels are within normal limits. Taurine also has transient anticonvulsant effects in some epileptic humans.<sup>154</sup>

Within the male reproductive organs, the age-related decline in taurine may or may not have implications regarding sexuality, as only

very limited rat data are available.<sup>89-91</sup>

In cats, taurine supplementation has been found to prevent the progressive degeneration of retinal photoreceptors seen in retinitis pigmentosa, a genetic disease that causes the loss of vision.<sup>155</sup>

While several energy drink companies have advertised that taurine plays a role in improving cognitive and physical performance, there are few human studies that examine this contention in the absence of confounding factors such as caffeine or glucose.<sup>36,37,95</sup> Taurine supplementation in patients with heart failure has been shown to increase exercise capacity vs placebo.<sup>156</sup> This supports the idea that in cases of taurine deficiency, such as those seen in cardiomyopathy,<sup>157</sup> taurine supplementation could have restorative effects. However, we are not aware of any double-blind, placebo-controlled clinical trial of taurine alone in healthy patients that measured energy parameters as clinical outcomes.

Although it remains possible that acute supraphysiologic taurine levels achieved by supplementation could transiently trigger various psychoneuroendocrine responses in healthy people, clinical research is needed in which taurine is the sole intervention. At present, the most compelling clinical reason to prescribe or recommend taurine supplementation is taurine deficiency. ■

## REFERENCES

1. **US Food and Drug Administration (FDA).** Caffeine intake by the US population. [www.fda.gov/downloads/AboutFDA/CentersOffices/OfficeofFoods/CFSAN/CFSANFOIAElectronicReadingRoom/UCM333191.pdf](http://www.fda.gov/downloads/AboutFDA/CentersOffices/OfficeofFoods/CFSAN/CFSANFOIAElectronicReadingRoom/UCM333191.pdf). Accessed October 4, 2016.
2. **McLellan TM, Lieberman HR.** Do energy drinks contain active components other than caffeine? *Nutr Rev* 2012; 70:730-744.
3. **Park E, Quinn MR, Wright CE, Schuller-Levis G.** Taurine chloramine inhibits the synthesis of nitric oxide and the release of tumor necrosis factor in activated RAW 264.7 cells. *J Leukoc Biol* 1993; 54:119-124.
4. **Kontny E, Szczepanska K, Kowalczewski J, et al.** The mechanism of taurine chloramine inhibition of cytokine (interleukin-6, interleukin-8) production by rheumatoid arthritis fibroblast-like synoviocytes. *Arthritis Rheum* 2000; 43:2169-2177.
5. **Barbeau A, Inoue N, Tsukada Y, Butterworth RF.** The neuropharmacology of taurine. *Life Sci* 1975; 17:669-677.
6. **Kramer JH, Chovan JP, Schaffer SW.** Effect of taurine on calcium paradox and ischemic heart failure. *Am J Physiol* 1981; 240:H238-H246.
7. **Azuma J, Sawamura A, Awata N, et al.** Therapeutic effect of taurine in congestive heart failure: a double-blind crossover trial. *Clin Cardiol* 1985; 8:276-282.
8. **Darling PB, Lepage G, Leroy C, Masson P, Roy CC.** Effect of taurine supplements on fat absorption in cystic fibrosis. *Pediatr Res* 1985; 19:578-582.
9. **Franconi F, Di Leo MA, Bennardini F, Ghirlanda G.** Is taurine beneficial in reducing risk factors for diabetes mellitus? *Neurochem Res* 2004; 29:143-150.
10. **Malcangio M, Bartolini A, Ghelardini C, et al.** Effect of ICV taurine on the impairment of learning, convulsions and death caused by hypoxia. *Psychopharmacology (Berl)* 1989; 98:316-320.
11. **Rivas-Arancibia S, Dorado-Martinez C, Borgonio-Pérez G, et al.** Effects of taurine on ozone-induced memory deficits and lipid peroxidation levels in brains of young, mature, and old rats. *Environ Res* 2000; 82:7-17.
12. **Vohra BP, Hui X.** Improvement of impaired memory in mice by taurine. *Neural Plast* 2000; 7:245-259.
13. **Tadros MG, Khalifa AE, Abdel-Naim AB, Arafa HM.** Neuroprotective effect of taurine in 3-nitropropionic acid-induced experimental animal model of Huntington's disease phenotype. *Pharmacol Biochem Behav* 2005; 82:574-582.
14. **Zhu DM, Wang M, She JQ, Yu K, Ruan DY.** Protection by a taurine supplemented diet from lead-induced deficits of long-term potentiation/depotentialization in dentate gyrus of rats in vivo. *Neuroscience* 2005; 134:215-224.
15. **Chepkova AN, Sergeeva OA, Haas HL.** Taurine rescues hippocampal long-term potentiation from ammonia-induced impairment. *Neurobiol Dis* 2006; 23:512-521.
16. **Wang GH, Jiang ZL, Fan XJ, Zhang L, Li X, Ke KF.** Neuroprotective effect of taurine against focal cerebral ischemia in rats possibly mediated by activation of both GABAA and glycine receptors. *Neuropharmacology* 2007; 52:1199-1209.

17. **Caltagirone C, Ferrannini L, Marchionni N, Nappi G, Scapagnini G, Trabucchi M.** The potential protective effect of tramiprosate (homotaurine) against Alzheimer's disease: a review. *Aging Clin Exp Res* 2012; 24:580–587.
18. **Jonas DE, Amick HR, Feltner C, et al.** Pharmacotherapy for adults with alcohol use disorders in outpatient settings: a systematic review and meta-analysis. *JAMA* 2014; 311:1889–1900.
19. **Sorkin BC, Camp KM, Haggans CJ, et al.** Executive summary of NIH workshop on the use and biology of energy drinks: current knowledge and critical gaps. *Nutr Rev* 2014; 72(suppl 1):1–8.
20. **Centers for Disease Control and Prevention (CDC).** Energy drink consumption and its association with sleep problems among US service members on a combat deployment—Afghanistan, 2010. *MMWR Morb Mortal Wkly Rep* 2012; 61:895–898.
21. **Bailey RL, Saldanha LG, Dwyer JT.** Estimating caffeine intake from energy drinks and dietary supplements in the United States. *Nutr Rev* 2014; 72(suppl 1):9–13.
22. **Stephens MB, Attipoe S, Jones D, Ledford CJ, Deuster PA.** Energy drink and energy shot use in the military. *Nutr Rev* 2014; 72(suppl 1):72–77.
23. **Triebel S, Sproll C, Reusch H, Godelmann R, Lachenmeier DW.** Rapid analysis of taurine in energy drinks using amino acid analyzer and Fourier transform infrared (FTIR) spectroscopy as basis for toxicological evaluation. *Amino Acids* 2007; 33:451–457.
24. **Beverage Industry.** 2013 state of the industry: energy drinks & shots. [www.bevindustry.com/articles/86552-state-of-the-industry-energy-drinks-shots](http://www.bevindustry.com/articles/86552-state-of-the-industry-energy-drinks-shots). Accessed October 4, 2016.
25. **Huxtable RJ.** Physiological actions of taurine. *Physiol Rev* 1992; 72:101–163.
26. **Laidlaw SA, Grosvenor M, Kopple JD.** The taurine content of common foodstuffs. *JPEN J Parenter Enteral Nutr* 1990; 14:183–188.
27. **Manzi P, Pizzoferrato L.** Taurine in milk and yoghurt marketed in Italy. *Int J Food Sci Nutr* 2013; 64:112–116.
28. **Dragnes BT, Larsen R, Ernstsen MH, Mæhre H, Elvevoll EO.** Impact of processing on the taurine content in processed seafood and their corresponding unprocessed raw materials. *Int J Food Sci Nutr* 2009; 60:143–152.
29. **Laidlaw SA, Shultz TD, Cecchino JT, Kopple JD.** Plasma and urine taurine levels in vegans. *Am J Clin Nutr* 1988; 47:660–663.
30. **Rana SK, Sanders TA.** Taurine concentrations in the diet, plasma, urine and breast milk of vegans compared with omnivores. *Br J Nutr* 1986; 56:17–27.
31. **Alford C, Cox H, Wescott R.** The effects of Red Bull energy drink on human performance and mood. *Amino Acids* 2001; 21:139–150.
32. **Hoffman JR, Ratamess NA, Ross R, Shanklin M, Kang J, Faigenbaum AD.** Effect of a pre-exercise energy supplement on the acute hormonal response to resistance exercise. *J Strength Cond Res* 2008; 22:874–882.
33. **Ivy JL, Kammer L, Ding Z, et al.** Improved cycling time-trial performance after ingestion of a caffeine energy drink. *Int J Sport Nutr Exerc Metab* 2009; 19:61–78.
34. **Gonzalez AM, Walsh AL, Ratamess NA, Kang J, Hoffman JR.** Effect of a pre-workout energy supplement on acute multi-joint resistance exercise. *J Sports Sci Med* 2011; 10:261–266.
35. **Yeh TS, Chan KH, Hsu MC, Liu JF.** Supplementation with soybean peptides, taurine, pueraria isoflavone, and ginseng saponin complex improves endurance exercise capacity in humans. *J Med Food* 2011; 14:219–225.
36. **Rutherford JA, Spriet LL, Stellingwerff T.** The effect of acute taurine ingestion on endurance performance and metabolism in well-trained cyclists. *Int J Sport Nutr Exerc Metab* 2010; 20:322–329.
37. **Zhang M, Izumi I, Kagamimori S, et al.** Role of taurine supplementation to prevent exercise-induced oxidative stress in healthy young men. *Amino Acids* 2004; 26:203–207.
38. **Kammerer M, Jaramillo JA, García A, Calderón JC, Valbuena LH.** Effects of energy drink major bioactive compounds on the performance of young adults in fitness and cognitive tests: a randomized controlled trial. *J Int Soc Sports Nutr* 2014; 11:44.
39. **Kermack WO, Slater RH.** The preparation of taurine in considerable quantity. *Biochem J* 1927; 21:1065–1067.
40. **Huxtable RJ, Lippincott SE.** Diet and biosynthesis as sources of taurine in the mouse. *J Nutr* 1982; 112:1003–1010.
41. **Ohkuma S, Tamura J, Kuriyama K.** Roles of endogenous and exogenous taurine and glycine in the formation of conjugated bile acids: analyses using freshly isolated and primary cultured rat hepatocytes. *Jpn J Pharmacol* 1984; 35:347–358.
42. **Chapman GE, Greenwood CE.** Taurine in nutrition and brain development. *Nutrition Research* 1988; 8:955–968.
43. **Andrews S, Schmidt CLA.** Titration curves of taurine and cysteine acid. *J Biol Chem* 1927; 73:651–654.
44. **Huxtable RJ.** Taurine in the central nervous system and the mammalian actions of taurine. *Prog Neurobiol* 1989; 32:471–533.
45. **Jacobsen JG, Smith LH.** Biochemistry and physiology of taurine and taurine derivatives. *Physiol Rev* 1968; 48:424–511.
46. **Hope DB.** Pyridoxal phosphate as the coenzyme of the mammalian decarboxylase for L-cysteine sulphinic and L-cysteine acids. *Biochem J* 1955; 59:497–500.
47. **Pasantes-Morales H, Lopez-Colome AM, Salceda R, Mandel P.** Cysteine sulphinate decarboxylase in chick and rat retina during development. *J Neurochem* 1976; 27:1103–1106.
48. **Oertel WH, Schmechel DE, Weise VK, et al.** Comparison of cysteine sulphinic acid decarboxylase isoenzymes and glutamic acid decarboxylase in rat liver and brain. *Neuroscience* 1981; 6:2701–2714.
49. **Reymond I, Bitoun M, Levillain O, Tappaz M.** Regional expression and histological localization of cysteine sulfinate decarboxylase mRNA in the rat kidney. *J Histochem Cytochem* 2000; 48:1461–1468.
50. **Hu JM, Ikemura R, Chang KT, Suzuki M, Nishihara M, Takahashi M.** Expression of cysteine sulfinate decarboxylase mRNA in rat mammary gland. *J Vet Med Sci* 2000; 62:829–834.
51. **Ueki I, Stipanuk MH.** Enzymes of the taurine biosynthetic pathway are expressed in rat mammary gland. *J Nutr* 2007; 137:1887–1894.
52. **Li JH, Ling YQ, Fan JJ, Zhang XP, Cui S.** Expression of cysteine sulfinate decarboxylase (CSD) in male reproductive organs of mice. *Histochem Cell Biol* 2006; 125:607–613.
53. **Green TR, Fellman JH, Eicher AL, Pratt KL.** Antioxidant role and subcellular location of hypotaurine and taurine in human neutrophils. *Biochim Biophys Acta* 1991; 1073:91–97.
54. **Lefauconnier JM, Portemer C, Chatagner F.** Free amino acids and related substances in human glial tumours and in fetal brain: comparison with normal adult brain. *Brain Res* 1976; 117:105–113.
55. **Sturman JA, Rassin DK, Gaul GE.** Taurine in development. *Life Sci* 1977; 21:1–22.
56. **Sturman JA.** Taurine pool sizes in the rat: effects of vitamin B-6 deficiency and high taurine diet. *J Nutr* 1973; 103:1566–1580.
57. **Terauchi A, Nakazawa A, Johkura K, Yan L, Usuda N.** Immunohistochemical localization of taurine in various tissues of the mouse. *Amino Acids* 1998; 15:151–160.
58. **Lobo MV, Alonso FJ, del Río RM.** Immunohistochemical localization of taurine in the male reproductive organs of the rat. *J Histochem Cytochem* 2000; 48:313–320.
59. **Aaronson DS, Iman R, Walsh TJ, Kurhanewicz J, Turek PJ.** A novel application of 1H magnetic resonance spectroscopy: non-invasive identification of spermatogenesis in men with non-obstructive azoospermia. *Hum Reprod* 2010; 25:847–852.
60. **Holmes RP, Goodman HO, Shihabi ZK, Jarow JP.** The taurine and hypotaurine content of human semen. *J Androl* 1992; 13:289–292.
61. **Alvarez JG, Storey BT.** Taurine, hypotaurine, epinephrine and albumin inhibit lipid peroxidation in rabbit spermatozoa and protect against loss of motility. *Biol Reprod* 1983; 29:548–555.
62. **Das J, Ghosh J, Manna P, Sinha M, Sil PC.** Taurine protects rat testes against NaAsO(2)-induced oxidative stress and apoptosis via mitochondrial dependent and independent pathways. *Toxicol Lett* 2009; 187:201–210.
63. **Mrsny RJ, Meizel S.** Inhibition of hamster sperm Na<sup>+</sup>, K<sup>+</sup>-ATPase activity by taurine and hypotaurine. *Life Sci* 1985; 36:271–275.
64. **Phoenix J, Wray S.** Changes in human and rat uterine phosphoethanolamine and taurine with pregnancy and parturition. *Exp Physiol* 1994; 79:601–604.

65. Lobo MV, Alonso FJ, Latorre A, del Río RM. Immunohistochemical localization of taurine in the rat ovary, oviduct, and uterus. *J Histochem Cytochem* 2001; 49:1133–1142.
66. Casslén BG. Free amino acids in human uterine fluid. Possible role of high taurine concentration. *J Reprod Med* 1987; 32:181–184.
67. Pamblanco M, Portolés M, Paredes C, Ten A, Comín J. Free amino acids in preterm and term milk from mothers delivering appropriate- or small-for-gestational-age infants. *Am J Clin Nutr* 1989; 50:778–781.
68. Rigo J, Senterre J. Is taurine essential for the neonates? *Biol Neonate* 1977; 32:73–76.
69. Sturman JA, Hepner GW, Hofmann AF, Thomas PJ. Metabolism of [35S]taurine in man. *J Nutr* 1975; 105:1206–1214.
70. Bremer J. Species differences in the conjugation of free bile acids with taurine and glycine. *Biochem J* 1956; 63:507–513.
71. Wu JY, Tang XW, Tsai WH. Taurine receptor: kinetic analysis and pharmacological studies. *Adv Exp Med Biol* 1992; 315:263–268.
72. Ripps H, Shen W. Review: taurine: a “very essential” amino acid. *Mol Vis* 2012; 18:2673–2686.
73. Haas HL, Hösl L. The depression of brain stem neurones by taurine and its interaction with strychnine and bicuculline. *Brain Res* 1973; 52:399–402.
74. Bureau MH, Olsen RW. Taurine acts on a subclass of GABAA receptors in mammalian brain in vitro. *Eur J Pharmacol* 1991; 207:9–16.
75. Bhattarai JP, Park SJ, Chun SW, Cho DH, Han SK. Activation of synaptic and extrasynaptic glycine receptors by taurine in preoptic hypothalamic neurons. *Neurosci Lett* 2015; 608:51–56.
76. Horikoshi T, Asanuma A, Yanagisawa K, Anzai K, Goto S. Taurine and beta-alanine act on both GABA and glycine receptors in *Xenopus* oocyte injected with mouse brain messenger RNA. *Brain Res* 1988; 464:97–105.
77. Miller PS, Smart TG. Binding, activation and modulation of Cys-loop receptors. *Trends Pharmacol Sci* 2010; 31:161–174.
78. Fujita T, Sato Y. Hypotensive effect of taurine. Possible involvement of the sympathetic nervous system and endogenous opiates. *J Clin Invest* 1988; 82:993–997.
79. Fujita T, Ando K, Noda H, Ito Y, Sato Y. Effects of increased adrenomedullary activity and taurine in young patients with borderline hypertension. *Circulation* 1987; 75:525–532.
80. Mizushima S, Nara Y, Sawamura M, Yamori Y. Effects of oral taurine supplementation on lipids and sympathetic nerve tone. *Adv Exp Med Biol* 1996; 403:615–622.
81. Fujita T, Sato Y. The antihypertensive effect of taurine in DOCA-salt rats. *J Hypertens Suppl* 1984; 2:S563–S565.
82. Fujita T, Sato Y, Ando K. Changes in cardiac and hypothalamic noradrenergic activity with taurine in DOCA-salt rats. *Am J Physiol* 1986; 251:H926–H933.
83. Sato Y, Ando K, Fujita T. Role of sympathetic nervous system in hypotensive action of taurine in DOCA-salt rats. *Hypertension* 1987; 9:81–87.
84. Scheibel J, Elsasser T, Ondo JG. A neuromodulatory role for taurine in controlling prolactin secretion in female rats. *Psychoneuroendocrinology* 1981; 6:139–144.
85. Ikuyama S, Okajima T, Kato K, Ibayashi H. Effect of taurine on growth hormone and prolactin secretion in rats: possible interaction with opioid peptidergic system. *Life Sci* 1988; 43:807–812.
86. Park E, Park SY, Dobkin C, Schuller-Levis G. Development of a novel cysteine sulfinic acid decarboxylase knockout mouse: dietary taurine reduces neonatal mortality. *J Amino Acids* 2014; 2014:346809.
87. Mantovani J, DeVivo DC. Effects of taurine on seizures and growth hormone release in epileptic patients. *Arch Neurol* 1979; 36:672–674.
88. Carlson HE, Miglietta JT, Roginsky MS, Stegink LD. Stimulation of pituitary hormone secretion by neurotransmitter amino acids in humans. *Metabolism* 1989; 38:1179–1182.
89. Yang J, Wu G, Feng Y, Lv Q, Lin S, Hu J. Effects of taurine on male reproduction in rats of different ages. *J Biomed Sci* 2010; 17(suppl 1):S9.
90. Yang J, Lin S, Feng Y, Wu G, Hu J. Taurine enhances the sexual response and mating ability in aged male rats. *Adv Exp Med Biol* 2013; 776:347–355.
91. Yang J, Zong X, Wu G, Lin S, Feng Y, Hu J. Taurine increases testicular function in aged rats by inhibiting oxidative stress and apoptosis. *Amino Acids* 2015; 47:1549–1558.
92. Scheibel J, Elsasser T, Ondo JG. Stimulation of LH and FSH secretion following intraventricular injection of cysteine acid but not taurine. *Brain Res* 1980; 201:99–106.
93. Price MT, Olney JW, Mitchell MV, Fuller T, Cicero TJ. Luteinizing hormone releasing action of N-methyl aspartate is blocked by GABA or taurine but not by dopamine antagonists. *Brain Res* 1978; 158:461–465.
94. Ma Q, Zhao J, Cao W, Liu J, Cui S. Estradiol decreases taurine level by reducing cysteine sulfinic acid decarboxylase via the estrogen receptor- $\alpha$  in female mice liver. *Am J Physiol Gastrointest Liver Physiol* 2015; 308:G277–G286.
95. Giles GE, Mahoney CR, Brunyé TT, Gardony AL, Taylor HA, Kanarek RB. Differential cognitive effects of energy drink ingredients: caffeine, taurine, and glucose. *Pharmacol Biochem Behav* 2012; 102:569–577.
96. Giehl TJ, Qoronfle MW, Wilkinson BJ. Transport, nutritional and metabolic studies of taurine in staphylococci. *J Gen Microbiol* 1987; 133:849–856.
97. Schaffer SW, Shimada-Takaura K, Jong CJ, Ito T, Takahashi K. Impaired energy metabolism of the taurine-deficient heart. *Amino Acids* 2015 Oct 16. Epub ahead of print.
98. Schaffer SW, Jong CJ, Ito T, Azuma J. Role of taurine in the pathologies of MELAS and MERRF. *Amino Acids* 2014; 46:47–56.
99. Warskulat U, Heller-Stilb B, Oermann E, et al. Phenotype of the taurine transporter knockout mouse. *Methods Enzymol* 2007; 428:439–458.
100. Yatabe Y, Miyakawa S, Miyazaki T, Matsuzaki Y, Ochiai N. Effects of taurine administration in rat skeletal muscles on exercise. *J Orthop Sci* 2003; 8:415–419.
101. Miyazaki T, Matsuzaki Y, Ikegami T, et al. Optimal and effective oral dose of taurine to prolong exercise performance in rat. *Amino Acids* 2004; 27:291–298.
102. Goodman CA, Horvath D, Stathis C, et al. Taurine supplementation increases skeletal muscle force production and protects muscle function during and after high-frequency in vitro stimulation. *J Appl Physiol* (1985) 2009; 107:144–154.
103. Van Winkle LJ, Patel M, Wasserlauf HG, Dickinson HR, Campione AL. Osmotic regulation of taurine transport via system beta and novel processes in mouse preimplantation conceptuses. *Biochim Biophys Acta* 1994; 1191:244–255.
104. Ito T, Kimura Y, Uozumi Y, et al. Taurine depletion caused by knocking out the taurine transporter gene leads to cardiomyopathy with cardiac atrophy. *J Mol Cell Cardiol* 2008; 44:927–937.
105. Aydın AF, Çoban J, Dogan-Ekici I, Betül-Kalaz E, Dogru-Abbasoglu S, Uysal M. Carnosine and taurine treatments diminished brain oxidative stress and apoptosis in D-galactose aging model. *Metab Brain Dis* 2016; 31:337–345.
106. Nagai K, Fukuno S, Oda A, Konishi H. Protective effects of taurine on doxorubicin-induced acute hepatotoxicity through suppression of oxidative stress and apoptotic responses. *Anticancer Drugs* 2016; 27:17–23.
107. Caletti G, Almeida FB, Agnes G, Nin MS, Barros HM, Gomez R. Antidepressant dose of taurine increases mRNA expression of GABAA receptor  $\alpha 2$  subunit and BDNF in the hippocampus of diabetic rats. *Behav Brain Res* 2015; 283:11–55.
108. Gu Y, Zhao Y, Qian K, Sun M. Taurine attenuates hippocampal and corpus callosum damage, and enhances neurological recovery after closed head injury in rats. *Neuroscience* 2015; 291:331–340.
109. Banks MA, Porter DW, Pailles WH, Schwegler-Berry D, Martin WG, Castranova V. Taurine content of isolated rat alveolar type I cells. *Comp Biochem Physiol B* 1991; 100:795–799.
110. Raschke P, Massoudy P, Becker BF. Taurine protects the heart from neutrophil-induced reperfusion injury. *Free Radic Biol Med* 1995; 19:461–471.

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111. Pushpakiran G, Mahalakshmi K, Anuradha CV. Taurine restores ethanol-induced depletion of antioxidants and attenuates oxidative stress in rat tissues. *Amino Acids* 2004; 27:91–96.
112. Refik Mas M, Comert B, Oncu K, et al. The effect of taurine treatment on oxidative stress in experimental liver fibrosis. *Hepatol Res* 2004; 28:207–215.
113. Sebring LA, Huxtable RJ. Taurine modulation of calcium binding to cardiac sarcolemma. *J Pharmacol Exp Ther* 1985; 232:445–451.
114. Schaffer SW, Kramer J, Chovan JP. Regulation of calcium homeostasis in the heart by taurine. *Fed Proc* 1980; 39:2691–2694.
115. Foos TM, Wu JY. The role of taurine in the central nervous system and the modulation of intracellular calcium homeostasis. *Neurochem Res* 2002; 27:21–26.
116. Ito T, Schaffer S, Azuma J. The effect of taurine on chronic heart failure: actions of taurine against catecholamine and angiotensin II. *Amino Acids* 2014; 46:111–119.
117. Gaull GE. Taurine in pediatric nutrition: review and update. *Pediatrics* 1989; 83:433–442.
118. Sturman JA, Rassin DK, Gaull GE. Taurine in developing rat brain: transfer of [35S] taurine to pups via the milk. *Pediatr Res* 1977; 11:28–33.
119. Geggel HS, Ament ME, Heckenlively JR, Martin DA, Kopple JD. Nutritional requirement for taurine in patients receiving long-term parenteral nutrition. *N Engl J Med* 1985; 312:142–146.
120. Sturman JA, Gargano AD, Messing JM, Imaki H. Feline maternal taurine deficiency: effect on mother and offspring. *J Nutr* 1986; 116:655–667.
121. Lerdweeraphon W, Wyss JM, Boonmars T, Roysommuti S. Perinatal taurine exposure affects adult oxidative stress. *Am J Physiol Regul Integr Comp Physiol* 2013; 305:R95–R97.
122. Chesney RW, Helms RA, Christensen M, Budreau AM, Han X, Sturman JA. The role of taurine in infant nutrition. *Adv Exp Med Biol* 1998; 442:463–476.
123. Verner A, Craig S, McGuire W. Effect of taurine supplementation on growth and development in preterm or low birth weight infants. *Cochrane Database Syst Rev* 2007; 4:CD006072.
124. Jeevanandam M, Young DH, Ramias L, Schiller WR. Effect of major trauma on plasma free amino acid concentrations in geriatric patients. *Am J Clin Nutr* 1990; 51:1040–1045.
125. Dawson R Jr, Eppler B, Patterson TA, Shih D, Liu S. The effects of taurine in a rodent model of aging. *Adv Exp Med Biol* 1996; 403:37–50.
126. Han X, Budreau AM, Chesney RW. Molecular cloning and functional expression of an LLC-PK1 cell taurine transporter that is adaptively regulated by taurine. *Adv Exp Med Biol* 1998; 442:261–268.
127. Eppler B, Dawson R Jr. Dietary taurine manipulations in aged male Fischer 344 rat tissue: taurine concentration, taurine biosynthesis, and oxidative markers. *Biochem Pharmacol* 2001; 62:29–39.
128. D'Eufemia P, Finocchiaro R, Celli M, et al. Taurine deficiency in thalassemia major-induced osteoporosis treated with neridronate. *Biomed Pharmacother* 2010; 64:271–274.
129. Muscaritoli M, Conversano L, Petti MC, et al. Plasma amino acid concentrations in patients with acute myelogenous leukemia. *Nutrition* 1999; 15:195–199.
130. Do KQ, Lauer CJ, Schreiber W, et al. Gamma-glutamylglutamine and taurine concentrations are decreased in the cerebrospinal fluid of drug-naive patients with schizophrenic disorders. *J Neurochem* 1995; 65:2652–2662.
131. Lemieux B, Giguère R, Shapcott D. Studies on the role of taurine in Friedreich's ataxia. *Can J Neurol Sci* 1984; 11(suppl 4):610–615.
132. Airaksinen EM, Oja SS, Marnela KM, Sihvola P. Taurine and other amino acids of platelets and plasma in retinitis pigmentosa. *Ann Clin Res* 1980; 12:52–54.
133. Kohashi N, Katori R. Decrease of urinary taurine in essential hypertension. *Jpn Heart J* 1983; 24:91–102.
134. vom Dahl S, Mönnighoff I, Häussinger D. Decrease of plasma taurine in Gaucher disease and its sustained correction during enzyme replacement therapy. *Amino Acids* 2000; 19:585–592.
135. Schneider SM, Joly F, Gehrardt MF, et al. Taurine status and response to intravenous taurine supplementation in adults with short-bowel syndrome undergoing long-term parenteral nutrition: a pilot study. *Br J Nutr* 2006; 96:365–370.
136. Gray GE, Landel AM, Meguid MM. Taurine-supplemented total parenteral nutrition and taurine status of malnourished cancer patients. *Nutrition* 1994; 10:11–15.
137. Thompson GN. Assessment of taurine deficiency in cystic fibrosis. *Clin Chim Acta* 1988; 171:233–237.
138. Cho KH, Kim ES, Chen JD. Taurine intake and excretion in patients undergoing long term enteral nutrition. *Adv Exp Med Biol* 2000; 483:605–612.
139. Durelli L, Mutani R, Fassio F. The treatment of myotonia: evaluation of chronic oral taurine therapy. *Neurology* 1983; 33:599–603.
140. Shao A, Hathcock JN. Risk assessment for the amino acids taurine, L-glutamine and L-arginine. *Regul Toxicol Pharmacol* 2008; 50:376–399.
141. European Commission; Scientific Committee on Food. Opinion on additional information on energy drinks. [http://ec.europa.eu/food/fs/sc/scf/out169\\_en.pdf](http://ec.europa.eu/food/fs/sc/scf/out169_en.pdf). Accessed October 4, 2016.
142. Tanaka E, Terada M, Misawa S. Cytochrome P450 2E1: its clinical and toxicological role. *J Clin Pharm Ther* 2000; 25:165–175.
143. Kerai MD, Waterfield CJ, Kenyon SH, Asker DS, Timbrell JA. Reversal of ethanol-induced hepatic steatosis and lipid peroxidation by taurine: a study in rats. *Alcohol Alcohol* 1999; 34:529–541.
144. Das J, Ghosh J, Manna P, Sil PC. Acetaminophen induced acute liver failure via oxidative stress and JNK activation: protective role of taurine by the suppression of cytochrome P450 2E1. *Free Radic Res* 2010; 44:340–355.
145. El Idrissi A, Shen CH, L'Amoreaux WJ. Neuroprotective role of taurine during aging. *Amino Acids* 2013; 45:735–750.
146. Gharibani P, Modi J, Menzie J, et al. Comparison between single and combined post-treatment with S-methyl-N,N-diethylthiolcarbamate sulfoxide and taurine following transient focal cerebral ischemia in rat brain. *Neuroscience* 2015; 300:460–473.
147. Junyent F, De Lemos L, Utrera J, et al. Content and traffic of taurine in hippocampal reactive astrocytes. *Hippocampus* 2011; 21:185–197.
148. El Idrissi A, Trenkner E. Growth factors and taurine protect against excitotoxicity by stabilizing calcium homeostasis and energy metabolism. *J Neurosci* 1999; 19:9459–9468.
149. Wu H, Jin Y, Wei J, Jin H, Sha D, Wu JY. Mode of action of taurine as a neuroprotector. *Brain Res* 2005; 1038:123–131.
150. Paula-Lima AC, De Felice FG, Brito-Moreira J, Ferreira ST. Activation of GABA(A) receptors by taurine and muscimol blocks the neurotoxicity of beta-amyloid in rat hippocampal and cortical neurons. *Neuropharmacology* 2005; 49:1140–1148.
151. Takatani T, Takahashi K, Uozumi Y, et al. Taurine inhibits apoptosis by preventing formation of the Apaf-1/caspase-9 apoptosome. *Am J Physiol Cell Physiol* 2004; 287:C949–C953.
152. Atamna H, Kumar R. Protective role of methylene blue in Alzheimer's disease via mitochondria and cytochrome c oxidase. *J Alzheimers Dis* 2010; 20(suppl 2):S439–S452.
153. El Idrissi A. Taurine improves learning and retention in aged mice. *Neurosci Lett* 2008; 436:19–22.
154. Oja SS, Saransaari P. Taurine and epilepsy. *Epilepsy Res* 2013; 104:187–194.
155. Berson EL, Hayes KC, Rabin AR, Schmidt SY, Watson G. Retinal degeneration in cats fed casein. II. Supplementation with methionine, cysteine, or taurine. *Invest Ophthalmol* 1976; 15:52–58.
156. Beyranvand MR, Khalafi MK, Roshan VD, Choobineh S, Parsa SA, Piranfar MA. Effect of taurine supplementation on exercise capacity of patients with heart failure. *J Cardiol* 2011; 57:333–337.
157. Eby G, Halcomb WW. Elimination of cardiac arrhythmias using oral taurine with L-arginine with case histories: hypothesis for nitric oxide stabilization of the sinus node. *Med Hypotheses* 2006; 67:1200–1204.

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