Uric Acid: A Danger Signal From the RNA World That May Have a Role in the Epidemic of Obesity, Metabolic Syndrome, and Cardiorenal Disease: Evolutionary Considerations

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Summary: All human beings are uricase knockouts; we lost the uricase gene as a result of a mutation that occurred in the mid-Miocene epoch approximately 15 million years ago. The consequence of being a uricase knockout is that we have higher serum uric acid levels that are less regulatable and can be readily influenced by diet. This increases our risk for gout and kidney stones, but there is also increasing evidence that uric acid increases our risk for hypertension, kidney disease, obesity, and diabetes. This raises the question of why this mutation occurred. In this article we review current hypotheses. We suggest that uric acid is a danger and survival signal carried over from the RNA world. The mutation of uricase that occurred during the food shortage and global cooling that occurred in the Miocene epoch resulted in a survival advantage for early primates, particularly in Europe. Today, the loss of uricase functions as a thrifty gene, increasing our risk for obesity and cardiorenal disease.

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Uric acid is a product of purine metabolism generated during the breakdown of nucleic acids (DNA and RNA) and adenosine triphosphate (ATP), and uric acid also can be generated from proteins. In most mammals uric acid is metabolized further by uricase (urate oxidase) to form 5-hydroxyisourate and later allantoin, which is excreted freely in the urine.[1] However, the uricase gene became nonfunctional in two primate lineages during the middle Miocene epoch approximately 9 and 15 million years ago, and as a result human beings, great apes, and lesser apes have higher serum uric acid levels that are also less regulatable than for other mammals.[2]

Today, serum uric acid levels vary greatly in human beings, and can range from 2.5 to 12 mg/dL or more. Patients with higher levels are at increased risk for developing gout and uric acid kidney stones. More importantly, an increased uric acid level also predicts the development of obesity,[3] metabolic syndrome and diabetes,[4] fatty liver,[5] hypertension,[6] and cardiovascular and renal diseases.[7,8] Recent studies have suggested that uric acid may have a participatory role in these latter conditions.[9] This has led to the key question of what the biological benefits of uric acid are, and why the mutation was naturally selected for our species.

PARALLEL MUTATIONS IN THE URICASE GENE

The Miocene epoch is famous for the introduction of the ape, which is distinct from monkeys by their larger head and body and absence of tail. The first apes, such as *Proconsul*, were identified in the early Miocene epoch (approximately 20-23 million years ago) and were limited to Africa. These early apes lived in tropical rain forests and subsisted almost entirely on fruits. Approximately 17 to 18 million years ago global cooling resulted in a lowering of the Tethys sea and the formation of a land bridge to Eurasia, and at this time the first apes entered Europe. As global cooling continued the apes living in Europe began to face a food shortage as a result of to the changing climate and flora, especially during the seasonal cooler periods. As such, these apes retreated to isolated sites (refugia) throughout Europe. In contrast, although global cooling also occurred in Africa, the major effect was a recession of the tropical forests, but they still remained such that changes in diet were not required.[10]

As global cooling continued, the apes in Europe began to show evidence of periodic starvation, as indicated by linear striations on the canines caused by enamel hypoplasia that has been shown to reflect periods of starvation in young apes while the canines are still enlarging.[11] A binary asteroid impact also occurred in southern Germany 15 million years ago, which showered detritus for up to 450 km from the site of impact,[12] although it is of uncertain significance because it is not thought to have altered the flora or fauna in Europe significantly. By 8 to

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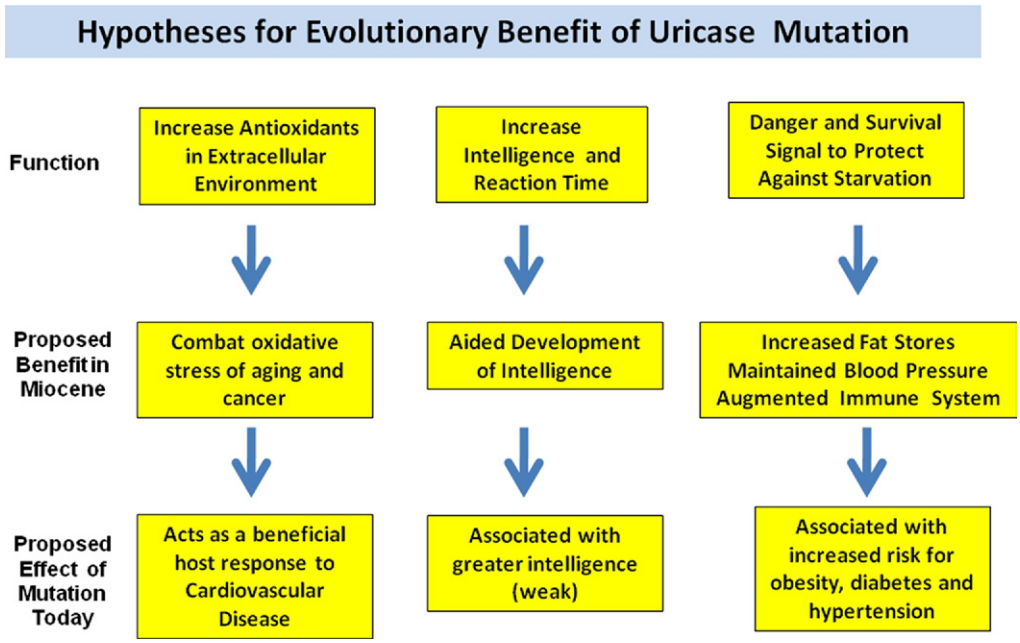

Figure 1. Hypotheses for evolutionary benefit of uricase mutation. The parallel mutations that occurred in early hominoid evolution in both ancestral human beings and great apes, and in lesser apes, suggests a natural selection advantage with the mutation. The primary hypotheses proposed for this mutation are shown. These include the possible role of uric acid as an extracellular antioxidant that would combat oxidative stress associated with aging, cancer, and cardiovascular disease, a role for uric acid in increasing intelligence and reaction time, and, finally, a potential role as a danger and survival signal to protect against starvation, but which in today's society translates into increased risk for obesity, diabetes, and cardiorenal disease.

9 million years ago the progressive cooling in Europe led to an extinction of ape species in Europe.[13]

Studies based on the fossil record suggest that the European apes have skeletal and dental features that are more similar to modern great apes, and as such has led to the proposal that some of the European apes may have migrated back to Africa before their extinction in Europe (the *Back to Africa* hypothesis).[14] Both *Kenyapithecus* and *Dryopithecus* have been considered potential candidates for being this ancestral species.[14,15]

It was during this period of climatic upheaval that the silencing of uricase occurred in the ancestral ape for human beings and the great apes. There is evidence that it occurred stepwise, first with progressive decrease in uricase activity as a result of mutations in the promoter region, followed by complete silencing of uricase as a result of a mutation in codon 33 of exon 2, the latter has been dated to approximately 15.4 million years ago.[2] A separate mutation involving the ancestral ape for lesser apes (gibbons and siamangs) occurred in codon 18 of exon 2 and has been dated to approximately 9.8 million years ago.[2] Some new world monkeys also may have had independent mutations in uricase, and the old world monkeys also show less uricase activity than many other mammals.[16] Therefore, there appears to be a general selection pressure favoring a loss of uricase in this order of mammals.

We have hypothesized that the uricase mutation benefitted survival by augmenting the fat-storing properties of fructose present in fruits.[10] We also have proposed that this mutation occurred in Europe because it would have provided a selection advantage here and would have taken over the population of a geographically isolated refugia rapidly. We therefore have suggested that this mutation supports the Back to Africa hypothesis.[10] Before we discuss this hypothesis, however, we briefly review other theories for why this mutation occurred (Fig. 1).

URIC ACID AND WATER CONSERVATION

The original interest in the evolutionary role of uricase related to studies of how nitrogenous waste products are excreted in different species.[17] Some animals excrete their nitrogenous wastes as ammonia, others as urea, and yet others as uric acid. Reptiles and birds compose this latter group and facilitate this by having a mutation in uricase. Smith[18] suggested that this mutation was critical for reptiles and birds so that they could excrete their nitrogenous wastes as uric acid. Because uric acid contains 4 nitrogens per molecule as compared with urea (2 nitrogens/molecule) and ammonia (1 nitrogen/molecule), the nitrogen waste can be concentrated more effectively in a small volume and thereby help preserve their total body water. Smith[18] argued that this was critical for these species to maintain terrestrial life, especially under arid conditions. However, the animal must have a cloaca that allows the precipitation of the uric acid (present in guano) that can be excreted safely without concern for blocking the urinary tract.

Although this certainly provides an evolutionary advantage for a uricase mutation in these species, it cannot explain why the uricase mutation occurred in human beings. Human beings continue to excrete almost all of their nitrogenous wastes as urea. Indeed, mammals in general conserve water via an elaborate loop of Henle concentration mechanism. Furthermore, although the mechanism for the uricase mutation with reptiles and birds suggest uric acid is simply a type of waste product, the observation that two different primate lineages also lost uricase suggests that uric acid also must have biological properties.

URIC ACID, INTELLIGENCE, AND REACTION TIME

Ellis[19] proposed in the early 1900s that uric acid might have a role in intelligence. He noted that gout was frequently a disease of the educated, and that many famous philosophers and scientists from the 1800s had gout. This concept was reintroduced in a letter to Nature in the 1950s by Orowan,[20] who noted that uric acid has chemical characteristics similar to caffeine. Subsequently, numerous studies were performed evaluating the uric acid levels of the general population and of special groups (university professors, students) to see if a general relationship between uric acid and intelligence quotient and other intelligence tests could be identified. Most studies showed either weak associations or none, but the strongest relationship was with reaction time.[21-23]

The possibility that uric acid may have central nervous system effects has not been completely ruled out. Acute hyperuricemia in rats induced by uricase inhibition does increase locomotor activity.[24] At least one study suggested that uric acid may increase dopamine levels in the brain.[25] Indeed, hyperuricemic individuals appear to have a decreased risk for Parkinson's disease.[26,27] Further studies are needed to assess the acute effects of hyperuricemia on the brain.

Although hyperuricemia may be associated with mild benefits on reaction time and intelligence, over time the reverse appears to be true. For example, increased uric acid is more common in subjects with vascular dementia[28,29] and stroke.[30-32] Whether this is causal has not been shown, but it is known that experimentally hyperuricemia can induce small-vessel disease in the kidney that can alter autoregulation. If such events also occur in the brain, as suggested by increased white matter disease in hyperuricemic subjects, then this would suggest that uric acid may be a cause of vascular dementia.

It seems likely that the original observation by Ellis[19] was not owing to uric acid being associated with higher intelligence, but rather because those subjects prone to developing gout in the 1700s and 1800s tended to be wealthy and sedentary, often with the ability to afford sugar, which is known to increase uric acid. Indeed, today gout is increasing in all populations, and if anything is more common among the poor and less educated.[33,34]

URIC ACID AS AN ANTIOXIDANT

Ames et al[35] proposed in the early 1980s that the uricase mutation provided a survival advantage because uric acid can function as an antioxidant. These investigators and others showed that uric acid could react with a wide variety of oxidants, especially peroxynitrite, superoxide, and hydroxyl radical.[35,36] Uric acid could be shown to protect cells from oxidant injury.[37] Infusing uric acid into human beings also was shown to acutely increase antioxidant capacity and to improve endothelial cell function.[38-40]

Ames et al[35] suggested that the mutation in vitamin C synthesis that had occurred 40 million years ago left early primates at increased risk for oxidative stress. Because oxidative stress could drive cancers, cardiovascular disease, and aging, the uricase mutation thus provided a survival advantage. In this scenario, the increase in uric acid observed in patients with cardiovascular disease likely was owing to a compensatory response by the host to combat oxidative stress.[41,42] Finally, the observation that species with higher uric acid levels tended to live longer was consistent with this hypothesis.[35]

For sure, uric acid is an antioxidant, at least in the extracellular environment. We and others have shown that uric acid potently reacts with superoxide to generate allantoin. Allantoin levels increase in human beings in response to oxidative stress.[43-45] Because human beings do not have uricase, this is evidence for a direct uric acid–superoxide reaction. Furthermore, uric acid can react with peroxynitrite to form triuret.[46] Triuret levels are increased in preeclampsia and likely reflect this pathway.[47] Uric acid also can react with nitric oxide to generate different products, particularly 5-aminouracil.[48]

Thus, it remains possible that the extracellular antioxidant effects of uric acid could explain why the uricase mutation resulted in a natural selection advantage. However, we and others have found that uric acid is a prooxidant inside the cell. This has been shown in a variety of cell types.[49-51] The mechanism may be owing to the selective stimulation of nicotinamide adenine dinucleotide phosphate oxidase.[51] However, uric acid also generates radicals when it reacts with peroxynitrite, including the triuret carbonyl radical and the aminocarbonyl radical.[52] The intracellular prooxidative effects of uric acid have been shown to mediate a host of proinflammatory effects, both in cell culture[53,54] and in animal models.[55] Furthermore, recent studies have challenged whether uric acid really functions as an important antioxidant in vivo.[56] In addition, an increased uric acid level in human beings is not associated with longevity, but rather correlates with increased cardiovascular mortality.[57] These findings, coupled with increasing experimental and clinical evidence for a role for uric acid in driving hypertension and metabolic syndrome, raises questions as to whether the antioxidant hypothesis can provide a viable mechanism for why human beings have the uricase mutation.

URIC ACID AS A MECHANISM FOR AMPLIFYING FRUCTOSE EFFECTS ON FAT FORMATION

As mentioned previously the primary food staple of apes during the mid-Miocene epoch was fruits, which are rich in fructose.[10] Fructose is distinct from glucose in its superior ability to increase fat stores, including in the liver, visceral fat, and plasma triglycerides.[58,59] As such, fruits were not simply a food source, but also have effects that can be helpful for an animal that may have intermittent bouts of food shortage.

The specific reason why fructose is superior than glucose in increasing fat stores likely relates to the unique first steps in fructose metabolism. When fructose enters the hepatocyte, it is metabolized by a specific enzyme, fructokinase C. Unlike glucokinase, which has a negative feedback system to prevent excessive phosphorylation, the phosphorylation of fructose by fructokinase will proceed uninterrupted, and as a consequence intracellular phosphate depletion and ATP depletion frequently occur.[60] The fall in intracellular phosphate results in the stimulation of adenosine monophosphate (AMP) deaminase, which helps accelerate the degradation of AMP to inosine monophosphate and later to uric acid.[60,61] In turn, the intracellular generation of uric acid results in oxidative stress.[61] These processes likely have a role in fatty liver formation and triglyceride generation. Evidence supportive of this is the condition of hereditary fructose intolerance, in which the subsequent enzyme in fructose metabolism, aldolase B, is mutated. In this circumstance, the fructose metabolism is blocked, but the subjects still develop fatty liver disease.[62,63]

In this regard, there is increasing evidence that the intracellular generation of uric acid may have a role in fat accumulation. First, we have reported that uric acid can induce proinflammatory changes in the adipocyte that are similar to that observed in the prediabetic subject.[51] Decreasing uric acid also can reduce hypertriglyceridemia and weight gain in rats exposed to fructose.[64] Moreover, we have unpublished data that uric acid regulates both the intestinal transporter for fructose, Glut 5, as well as the level of fructokinase C in the liver. These effects would accelerate fructose absorption and, in the presence of both increased substrate and metabolizing enzyme (fructokinase), would be expected to result in greater ATP depletion and a greater effect on fat production. Indeed, in collaboration with Dr. Abdelmalak and Dr. Anna Mae Diehl at Duke, we have found that subjects with higher uric acid levels show greater ATP depletion in their liver in response to intravenous fructose (unpublished data).

Given these circumstances, a loss of uricase would potentiate the ability of fructose to increase fat stores. Indeed, the inhibition of uricase increases the sensitivity of the rat to increase its serum uric acid[65] and develop insulin resistance to fructose.[66] Therefore, a mutation in uricase could have provided a survival advantage for Miocene apes during the progressive food shortage that occurred in Europe with global cooling.[10]

URIC ACID: A DANGER SIGNAL FROM THE RNA WORLD?

There is increasing evidence that the earliest life forms consisted solely of RNA.[67] Vestigial products from the RNA world that have key functions have carried over to current life, such as ATP (energy) and cyclic AMP (intracellular messenger). It is tempting to consider the breakdown of RNA to uric acid as a potential danger signal for the host, and that in turn the uric acid may act to increase survival by increasing fat stores and other functions.

Certainly conditions in which ATP depletion and energy crisis occur are associated with an increase in uric acid.[68] Uric acid is released from dying cells where it has been shown to activate inflammation via both the innate and adaptive immune system.[69-71] Uric acid is an adjuvant for activation of dendritic cells[69] and T cells.[72] Uric acid also increases in the setting of starvation or in the late stages of hibernation when fat stores are depleted and protein degradation occurs.[73-75] In this setting it generates a danger signal and results in a foraging response to get more food. Preeclampsia, a condition in which there is fetal compromise, also is associated with an increase in uric acid.[76] One wonders if the hypertension and fatty liver that occur in the mother in this condition may in part be owing to the increase in uric acid. Indeed, there is some evidence that uric acid may have a contributory role to the pathogenesis of preeclampsia.[76]

THRIFTY GENE HYPOTHESIS AND THE CURRENT OBESITY EPIDEMIC

An increase in uric acid may have some protective effects on survival in the setting of severe energy depletion, such as may occur with starvation, or with tissue injury and ischemia. We hypothesize that in early primates faced with intermittent starvation, the loss of uricase may have therefore provided a survival advantage.[10,77] An increase in uric acid may have potentiated fructose effects to gain fat, and may have led to a greater activation of the immune system. An increase in blood pressure and increased salt sensitivity, stimulation of the renin-angiotensin system, and the development of insulin resistance (which by maintaining increased blood glucose might preferentially provides fuel for the brain), all would have been beneficial.[78] The ability of uric acid to increase dopamine responses in the brain and to acutely stimulate increased locomotor activity also would have been helpful.

However, what was advantageous during starvation may not be beneficial in the setting of excessive food availability. With higher and less regulatable uric acid levels we are at marked increased risk for obesity, insulin resistance, and cardiovascular and renal diseases. We

have therefore proposed that the loss of uricase represents the "thrifty gene" originally proposed by Neel,[79] the loss of which results in a marked propensity for obesity.[77]

REFERENCES

1. Kahn K, Serfozo P, Tipton PA. Identification of the true product of the urate oxidase reaction. J Am Chem Soc. 1997;119:5435-42.
2. Oda M, Satta Y, Takenaka O, Takahata N. Loss of urate oxidase activity in hominoids and its evolutionary implications. Mol Biol Evol. 2002;19:640-53.
3. Masuo K, Kawaguchi H, Mikami H, Ogihara T, Tuck ML. Serum uric acid and plasma norepinephrine concentrations predict subsequent weight gain and blood pressure elevation. Hypertension. 2003;42:474-80.
4. Kodama S, Saito K, Yachi Y, et al. Association between serum uric acid and development of type 2 diabetes. Diabetes Care. 2009;32:1737-42.
5. Lonardo A, Loria P, Leonardi F, et al. Fasting insulin and uric acid levels but not indices of iron metabolism are independent predictors of non-alcoholic fatty liver disease. A case-control study. Dig Liver Dis. 2002;34:204-11.
6. Sundstrom J, Sullivan L, D'Agostino RB, Levy D, Kannel WB, Vasan RS. Relations of serum uric acid to longitudinal blood pressure tracking and hypertension incidence. Hypertension. 2005;45:28-33.
7. Weiner DE, Tighiouart H, Elsayed EF, Griffith JL, Salem DN, Levey AS. Uric acid and incident kidney disease in the community. J Am Soc Nephrol. 2008;19:1204-11.
8. Fang J, Alderman MH. Serum uric acid and cardiovascular mortality the NHANES I epidemiologic follow-up study, 1971-1992. National Health and Nutrition Examination Survey. JAMA. 2000; 283:2404-10.
9. Feig DI, Kang DH, Johnson RJ. Uric acid and cardiovascular risk. N Engl J Med. 2008;359:1811-21.
10. Johnson RJ, Andrews P. Fructose, uricase, and the Back to Africa hypothesis. Evol Anthro. 2010;19:250-7.
11. Skinner MF, Dupras TL, Moya-Sola S. Periodicity of linear enamel hypoplasia among Miocene Dryopithecus from Spain. J Paleopathol. 1995;7:195-222.
12. Stöffler D, Artemieva NA, Pierazzo E. Modeling the Ries-Steinheim impact event and the formation of the moldavite strewn field. J Meteoritic Plan Sci. 2002;37:1893-907.
13. Agusti J, Sanz de Siria A, Garces M. Explaining the end of the hominoid experiment in Europe. J Human Evol. 2003;45:145-53.
14. Begun DR. Middle Miocene hominoid origins. Science. 2000; 287:2375.
15. Andrews P, Kelley J. Middle Miocene dispersals of apes. Folia Primatol (Basel). 2007;78:328-43.
16. Wacker WE. Man: sapient but gouty. N Engl J Med. 1970;283: 151-2.
17. Gutman AB. Significance of uric acid as a nitrogenous waste in vertebrate evolution. Arthritis Rheum. 1965;8:614-26.
18. Smith HW. From fish to philosopher. Boston: Little, Brown and Co; 1953.
19. Ellis H. A study of British genius. London: Hurst and Blackett; 1903.
20. Orowan E. The origin of man. Nature. 1955;175:683-4.
21. Stetten D Jr, Hearon JZ. Intellectual level measured by army classification battery and serum uric acid concentration. Science. 1959;129:1737.
22. Montoye HJ, Mikkelsen WM. Serum uric acid and achievement in high school. Arthritis Rheum. 1973;16:359-62.
23. Inouye E, Park KS, Asaka A. Blood uric acid level and IQ: a study in twin families. Acta Genet Med Gemellol (Roma). 1984;33:237-42.
24. Barrera CM, Hunter RE, Dunlap WP. Hyperuricemia and locomotor activity in developing rats. Pharmacol Biochem Behav. 1989;33:367-9.
25. Guerreiro S, Ponceau A, Toulorge D, et al. Protection of midbrain dopaminergic neurons by the end-product of purine metabolism uric acid: potentiation by low-level depolarization. J Neurochem. 2009;109:1118-28.
26. Chen H, Mosley TH, Alonso A, Huang X. Plasma urate and Parkinson's disease in the Atherosclerosis Risk in Communities (ARIC) study. Am J Epidemiol. 2009;169:1064-9.
27. Schlesinger I, Schlesinger N. Uric acid in Parkinson's disease. Mov Disord. 2008;23:1653-7.
28. Schretlen DJ, Inscore AB, Jinnah HA, Rao V, Gordon B, Pearlson GD. Serum uric acid and cognitive function in community-dwelling older adults. Neuropsychology. 2007;21:136-40.
29. Schretlen DJ, Inscore AB, Vannorsdall TD, et al. Serum uric acid and brain ischemia in normal elderly adults. Neurology. 2007;69: 1418-23.
30. Seghieri G, Moruzzo D, Fascetti S, et al. Increase in serum uric acid is selectively associated with stroke in type 2 diabetes. Diabetes Care. 2002;25:1095.
31. Strasak AM, Kelleher CC, Brant LJ, et al. Serum uric acid is an independent predictor for all major forms of cardiovascular death in 28,613 elderly women: a prospective 21-year follow-up study. Int J Cardiol. 2008;125:232-9.
32. Weir CJ, Muir SW, Walters MR, Lees KR. Serum urate as an independent predictor of poor outcome and future vascular events after acute stroke. Stroke. 2003;34:1951-6.
33. Arromdee E, Michet CJ, Crowson CS, O'Fallon WM, Gabriel SE. Epidemiology of gout: is the incidence rising? J Rheumatol. 2002;29:2403-6.
34. Gresser U, Gathof B, Zollner N. Uric acid levels in southern Germany in 1989. A comparison with studies from 1962, 1971, and 1984. Klin Wochenschr. 1990;68:1222-8.
35. Ames BN, Cathcart R, Schwiers E, Hochstein P. Uric acid provides an antioxidant defense in humans against oxidant- and radical-caused aging and cancer: a hypothesis. Proc Natl Acad Sci U S A. 1981;78:6858-62.
36. Becker BF, Reinholz N, Leipert B, Raschke P, Permanetter B, Gerlach E. Role of uric acid as an endogenous radical scavenger and antioxidant. Chest. 1991;100:176S-81S.
37. Kuzkaya N, Weissmann N, Harrison DG, Dikalov S. Interactions of peroxynitrite with uric acid in the presence of ascorbate and thiols: implications for uncoupling endothelial nitric oxide synthase. Biochem Pharmacol. 2005;70:343-54.
38. Waring WS, Convery A, Mishra V, Shenkin A, Webb DJ, Maxwell SR. Uric acid reduces exercise-induced oxidative stress in healthy adults. Clin Sci (Lond). 2003;105:425-30.
39. Waring WS, McKnight JA, Webb DJ, Maxwell SR. Uric acid restores endothelial function in patients with type 1 diabetes and regular smokers. Diabetes. 2006;55:3127-32.
40. Waring WS, Webb DJ, Maxwell SR. Systemic uric acid administration increases serum antioxidant capacity in healthy volunteers. J Cardiovasc Pharmacol. 2001;38:365-71.
41. Nieto FJ, Iribarren C, Gross MD, Comstock GW, Cutler RG. Uric acid and serum antioxidant capacity: a reaction to atherosclerosis? Atherosclerosis. 2000;148:131-9.
42. Reyes AJ, Leary WP. The increase in serum uric acid induced by diuretics could be beneficial to cardiovascular prognosis in hypertension: a hypothesis. J Hypertens. 2003;21:1775-7.
43. Grootveld M, Halliwell B. Measurement of allantoin and uric-acid in human-body fluids—a potential index of free-radical reactions in vivo. Biochem J. 1987;243:803-8.
44. Hellsten Y, Tullson PC, Richter EA, Bangsbo J. Oxidation of urate in human skeletal muscle during exercise. Free Radic Biol Med. 1997;22:169-74.
45. Mikami T, Kita K, Tomita S, Qu GJ, Tasaki Y, Ito A. Is allantoin in serum and urine a useful indicator of exercise-induced oxidative stress in humans? Free Radic Res. 2000;32:235-44.

46. Robinson KM, Morre JT, Beckman JS. Triuret: a novel product of peroxynitrite-mediated oxidation of urate. Arch Biochem Biophys. 2004;423:213-7.
47. Kim KM, Henderson GN, Frye RF, et al. Simultaneous determination of uric acid metabolites allantoin, 6-aminouracil, and triuret in human urine using liquid chromatography-mass spectrometry. J Chromatogr B Analyt Technol Biomed Life Sci. 2009;877: 65-70.
48. Gersch C, Palii SP, Kim KM, Angerhofer A, Johnson RJ, Henderson GN. Inactivation of nitric oxide by uric acid. Nucleosides Nucleotides Nucleic Acids. 2008;27:967-78.
49. Corry DB, Eslami P, Yamamoto K, Nyby MD, Makino H, Tuck ML. Uric acid stimulates vascular smooth muscle cell proliferation and oxidative stress via the vascular renin-angiotensin system. J Hypertens. 2008;26:269-75.
50. Yu MA, Sanchez-Lozada LG, Johnson RJ, Kang DH. Oxidative stress with an activation of the renin-angiotensin system in human vascular endothelial cells as a novel mechanism of uric acid-induced endothelial dysfunction. J Hypertens. 2010;28:1234-42.
51. Sautin YY, Nakagawa T, Zharikov S, Johnson RJ. Adverse effects of the classic antioxidant uric acid in adipocytes: NADPH oxidase-mediated oxidative/nitrosative stress. Am J Physiol Cell Physiol. 2007;293:C584-96.
52. Imaram W, Gersch C, Kim KM, Johnson RJ, Henderson GN, Angerhofer A. Radicals in the reaction between peroxynitrite and uric acid identified by electron spin resonance spectroscopy and liquid chromatography mass spectrometry. Free Radic Biol Med. 2010;49:275-81.
53. Kanellis J, Watanabe S, Li JH, et al. Uric acid stimulates monocyte chemoattractant protein-1 production in vascular smooth muscle cells via mitogen-activated protein kinase and cyclooxygenase-2. Hypertension. 2003;41:1287-93.
54. Kang DH, Park SK, Lee IK, Johnson RJ. Uric acid-induced C-reactive protein expression: implication on cell proliferation and nitric oxide production of human vascular cells. J Am Soc Nephrol. 2005;16:3553-62.
55. Sanchez-Lozada LG, Soto V, Tapia E, et al. Role of oxidative stress in the renal abnormalities induced by experimental hyperuricemia. Am J Physiol. 2008;295:F1134-41.
56. Hershfield MS, Roberts LJ 2nd, Ganson NJ, et al. Treating gout with pegloticase, a PEGylated urate oxidase, provides insight into the importance of uric acid as an antioxidant in vivo. Proc Natl Acad Sci U S A. 2010;107:14351-6.
57. Johnson RJ, Kang DH, Feig D, et al. Is there a pathogenetic role for uric acid in hypertension and cardiovascular and renal disease? Hypertension. 2003;41:1183-90.
58. Tappy L, Le KA. Metabolic effects of fructose and the worldwide increase in obesity. Physiol Rev. 2010;90:23-46.
59. Stanhope KL, Schwarz JM, Keim NL, et al. Consuming fructose-sweetened, not glucose-sweetened, beverages increases visceral adiposity and lipids and decreases insulin sensitivity in overweight/obese humans. J Clin Invest. 2009;119:1322-34.
60. van den Berghe G, Bronfman M, Vanneste R, Hers HG. The mechanism of adenosine triphosphate depletion in the liver after a load of fructose. A kinetic study of liver adenylate deaminase. Biochem J. 1977;162:601-9.
61. Cirillo P, Gersch MS, Mu W, et al. Ketohexokinase-dependent metabolism of fructose induces proinflammatory mediators in proximal tubular cells. J Am Soc Nephrol. 2009;20:545-53.
62. Ali M, Rellos P, Cox TM. Hereditary fructose intolerance. J Med Genet. 1998;35:353-65.
63. Odievre M, Gentil C, Gautier M, Alagille D. Hereditary fructose intolerance in childhood. Diagnosis, management, and course in 55 patients. Am J Dis Child. 1978;132:605-8.
64. Nakagawa T, Hu H, Zharikov S, et al. A causal role for uric acid in fructose-induced metabolic syndrome. Am J Physiol. 2006; 290:F625-31.
65. Stavric B, Johnson WJ, Clayman S, Gadd RE, Chartrand A. Effect of fructose administration on serum urate levels in the uricase inhibited rat. Experientia. 1976;32:373-4.
66. Sanchez-Lozada L, Lopez-Molina R, Soto V, et al. Low fructose caloric intake concomitant to hyperuricemia induces hyperinsulinemia and renal structural damage in rats. J Am Soc Nephrol. 2007;18:184A.
67. Gesteland RF, Cech TR, Atkins JF. The RNA World: the nature of modern RNA suggests a prebiotic RNA world. 3rd ed. New York: Cold Spring Harbor Laboratory Press; 2006.
68. Fox IH, Palella TD, Kelley WN. Hyperuricemia: a marker for cell energy crisis. N Engl J Med. 1987;317:111-2.
69. Shi Y, Evans JE, Rock KL. Molecular identification of a danger signal that alerts the immune system to dying cells. Nature. 2003;425:516-21.
70. Martinon F, Petrilli V, Mayor A, Tardivel A, Tschopp J. Gout-associated uric acid crystals activate the NALP3 inflammasome. Nature. 2006;440:237-41.
71. Hu DE, Moore AM, Thomsen LL, Brindle KM. Uric acid promotes tumor immune rejection. Cancer Res. 2004;64:5059-62.
72. Shi Y, Galusha SA, Rock KL. Cutting edge: elimination of an endogenous adjuvant reduces the activation of CD8 T lymphocytes to transplanted cells and in an autoimmune diabetes model. J Immunol. 2006;176:3905-8.
73. Lennox WG. Increase of uric acid in the blood during prolonged starvation. JAMA. 1924;82:602-604.
74. Robin JP, Boucontet L, Chillet P, Groscolas R. Behavioral changes in fasting emperor penguins: evidence for a "refeeding signal" linked to a metabolic shift. Am J Physiol. 1998;274:R746-53.
75. Johnson RJ, Sautin YY, Oliver WJ, et al. Lessons from comparative physiology: could uric acid represent a physiologic alarm signal gone awry in western society? J Comp Physiol B. 2009; 179:67-76.
76. Bainbridge SA, Roberts JM. Uric acid as a pathogenic factor in preeclampsia. Placenta. 2008;29S:67-72.
77. Johnson RJ, Andrews P, Benner SA, Oliver WJ. Theodore E Woodward Award. The evolution of obesity: insights from the mid Miocene. Trans Am Clin Climatol Assoc. 2010;121: 295-308.
78. Watanabe S, Kang DH, Feng L, et al. Uric acid, hominoid evolution, and the pathogenesis of salt-sensitivity. Hypertension. 2002;40:355-60.
79. Neel JV. Diabetes mellitus: a "thrifty" genotype rendered detrimental by "progress"? Am J Human Genet. 1962;14:353-62.