Characterization of Renal Toxicity in Mice Administered the Marine Biotoxin Domoic Acid

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ABSTRACT
Domoic acid (DA), an excitatory amino acid produced by diatoms belonging to the genus Pseudo-nitzschia, is a glutamate analog responsible for the neurologic condition referred to as amnesic shellfish poisoning. To date, the renal effects of DA have been underappreciated, although renal filtration is the primary route of systemic elimination and the kidney expresses ionotropic glutamate receptors. To characterize the renal effects of DA, we administered either a neurotoxic dose of DA or doses below the recognized limit of toxicity to adult Sv128/Black Swiss mice. DA preferentially accumulated in the kidney and elicited marked renal vascular and tubular damage consistent with acute tubular necrosis, apoptosis, and renal tubular cell desquamation, with toxic vacuolization and mitochondrial swelling as hallmarks of the cellular damage. Doses $\geq 0.1$ mg/kg DA elevated the renal injury biomarkers kidney injury molecule-1 and neutrophil gelatinase-associated lipocalin, and doses $\geq 0.005$ mg/kg induced the early response genes c-fos and junb. Coadministration of DA with the broad spectrum excitatory amino acid antagonist kynurenic acid inhibited induction of c-fos, junb, and neutrophil gelatinase-associated lipocalin. These findings suggest that the kidney may be susceptible to excitotoxic agonists, and renal effects should be considered when examining glutamate receptor activation. Additionally, these results indicate that DA is a potent nephrotoxicant, and potential renal toxicity may require consideration when determining safe levels for human exposure.


Domoic acid (DA), a water-soluble, heat-stable tricarboxylic acid produced by diatoms belonging to the genus Pseudo-nitzschia, is responsible for a condition known as amnesic shellfish poisoning in humans.1–4 Shellfish, such as clams and mussels, and fish that accumulate DA serve as vectors of exposure to various species of birds and aquatic mammals in addition to humans.5,6 Initially recognized as a human toxicant when more than 100 people became ill after eating contaminated mussels in eastern Canada in 1987, DA poisoning was defined by the occurrence of gastrointestinal or neurologic symptoms ranging from abdominal cramps and headache to more severe cases of memory loss, seizures, coma, and even death.2,4 Increased awareness and governmental regulation, which set a limit of 20 $\mu$g DA/g in shellfish tissue, has reduced the incidence of DA toxicity in humans since the 1987 outbreak. However, there is concern that exposure will increase because of the growing presence of toxic diatom-producing algal blooms, which are often attributed to human factors, such as pollution, shipping, and global warming, leading to greater nutrient availability, greater distribution of algal species, and longer growth periods.7–14 Although the overt gastrointestinal and neurologic manifestations have defined the disease, emerging
evidence from animal and human studies support previously unrecognized threats and novel toxicologic syndromes caused by subclinical toxicity from acute and chronic DA exposures, which may ultimately challenge the adequacy of the current acceptable limit.15–18

DA is a potent activator of kainate receptors (KR) as well as a subpopulation of α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid receptors (AMPARs).19 The toxic response produced by DA is a coordinated effort, which involves initial activation of KR and AMPAR by DA and secondary activation of N-methyl-D-aspartate receptors (NMDARs) by glutamate, and it is associated with an influx of Ca2+ across the plasma membrane, inflammation, neuronal cell injury and death, and neurobehavioral alterations.19–22 Although they are extensively characterized in the central nervous system, glutamate receptors are also expressed at peripheral sites and have been shown to exhibit toxicity in multiple tissues, including the kidney, where NMDARs contribute to organ damage in models of ischemia-reperfusion injury and gentamicin nephrotoxicity.23–26 There is limited information about the effects of DA on the kidney; however, oral dosing in coho salmon has shown that the kidney is a primary site of DA accumulation in this species, and studies in rodents have shown that renal excretion is the exclusive route of systemic DA elimination.27,28 Examination of sea lions after DA poisoning has also revealed some evidence of interstitial nephritis, renal edema, and elevated BUN, although the exact cause of these findings cannot be definitively attributed to DA toxicity.29,30 Furthermore, sea lions with acute DA toxicosis seem to have an elevated hematocrit,31 suggesting that water reabsorption or red blood cell production could be affected, both of which are functions of the kidney. Despite this circumstantial evidence, a detailed examination of the renal response to DA administration has not been fully explored. The purpose of the current study was to characterize the acute renal effects of DA at doses that produce neurotoxicity and neurobehavioral changes (1.0–2.5 mg/kg) as well as several lower doses (0.0005–0.5 mg/kg), which are considered below the limit of toxicity.

RESULTS

DA Preferentially Accumulates in the Murine Kidney

Thirty minutes after injection, DA concentration ([DA]) in the kidney was fourfold higher compared with the liver, heart, and hippocampus. Although it decreased between 30 and 120 minutes, [DA] was still highest in the kidney at each time point, and it was undetectable after 24 hours (not shown). There was no difference in [DA] in the renal cortex compared with the medulla (Figure 1B). To determine the effect of renal secretion on DA elimination and tissue deposition, the organic anion transport inhibitor probenecid (PBN; 600 mg/kg) was administered 10 minutes before DA injection, and mice were euthanized 30 minutes after the injection of DA. At this time point, there were significantly higher levels of [DA] in the kidneys of mice exposed to PBN+DA compared with DA alone (Figure 1C). These results suggest that the route of elimination of DA by the kidney not only involves filtration but also tubular secretion.

KR Expression in the Kidney

Ionotropic glutamate receptors are expressed in the kidney; however, only a select number have been examined in detail, and a more complete analysis of the KR was necessary. Grik1 and Grik2 mRNA, which encodes the catalytic KR subtypes GluK1 and GluK2, respectively, were detected at varying levels in vehicle- and DA-treated kidneys, and Grik3 was not detected (Figure 2A). Grik4 and Grik5, which encode the high-affinity KR GluK4 and GluK5, respectively, were also detected in vehicle- and DA-treated kidneys (Figure 2A). AMPARs and NMDARs were also examined and detected by RT-PCR analysis, and there were no obvious differences between vehicle- and DA-treated kidneys (Figure 2A). By immunoblot analysis,
both GluK2 and GluK5 proteins were also detected in the kidney (Supplemental Figure 1). The distribution of GluK5 and GluK2 proteins was analyzed by immunohistochemistry (IHC) in kidney sections from vehicle- and DA-treated animals after 72 hours of exposure (Figure 2B). GluK5 was expressed throughout the cortex as well as the medullary region (primarily in tubules) in both vehicle- and DA-treated animals (Figure 2B). GluK2 protein was expressed predominantly in the renal vasculature (Figure 2B).

Renal Tissue Damage and Cell Death
Administration of DA (2.5 mg/kg) for 3 consecutive days produced histopathological alterations (Figure 3A), including cytoplasmic hypereosinophilia in proximal tubules (Figure 3, A, arrows, and B), which presented sporadically throughout the renal cortex, consistent with acute tubular cell death. Higher-magnification images showed eosinophils within the luminal space that are indicative of proximal tubule cell desquamation after DA-induced cell death (Figure 3A, arrows). Similar lesions were detected in animals administered 1 mg/kg DA, which could be visualized in hematoxylin and eosin– and Masson trichrome–stained sections (Supplemental Figure 2). Cell death was also examined by TUNEL assay, a marker of DNA damage and apoptosis (Figure 3C). TUNEL-positive cells were not detected in vehicle-treated kidneys (Figure 3C). In DA-treated kidneys, there were regions of TUNEL-positive nuclei, primarily within proximal tubules, at both 1.0- and 2.5-mg/kg doses (Figure 3C, arrows). At the time point examined, there was no evidence of TUNEL-positive staining in the CA3 region of the hippocampus from vehicle- or DA-treated mice (Figure 3C).

Cellular Damage Assessed by Transmission Electron Microscopy
With transmission electron microscopy (TEM), cellular damage was observed at 72 hours (Figure 4), including vascular toxicity, with evidence of endothelial cell swelling (Figure 4A, arrow) and epithelial cell vacuolization (Figure 4A, arrowhead). Additionally, we observed evidence of proximal tubule cell detachment from the basement membrane (Figure 4B) and the presence of luminal proteinaceous material and cellular debris after DA administration (Figure 4C). Higher-magnification views provided clear evidence of endothelial cell damage (Figure 4D, arrow), toxic vacuolization (Figure 4E), and mitochondrial swelling (Figure 4F, arrows), which likely contributed to the renal injury.

AKI Biomarkers
Serum creatinine (sCr) was not altered at 24 or 72 hours after DA administration (Figure 5A). To assess renal tubule damage from DA, urinary markers of tubule injury, neutrophil gelatinase-associated lipocalin (uNGAL), and kidney injury molecule-1 (uKIM-1) were examined. Both uNGAL and uKIM-1 were elevated at 24 and 72 hours after initial dose (Figure 5, B and C). A dose–response curve was generated by measuring uNGAL at 24 hours and uKIM-1 at 72 hours after 0.1 and 1.0 mg/kg DA exposure in addition to the 2.5-mg/kg dose (Figure 5, D and E). uNGAL elevated with 0.1 and 1.0 mg/kg but was only significantly increased with 2.5 mg/kg DA (Figure 5D).
uKIM-1 increased with 0.1, 1.0, and 2.5 mg/kg DA administration (Figure 5E). There is reason to believe that water restriction may exacerbate the toxic effects of DA on the kidney, and to test this finding, mice were dehydrated for 12 hours before DA exposure (2.5 mg/kg). Twenty-four hours after injection, uKIM-1 levels were elevated in the water-restricted animals exposed to DA compared with vehicle-treated mice or animals allowed full access to water before DA (Figure 5F). KIM-1 and NGAL were also examined by RT-PCR and immunoblot analysis in kidney tissue lysates, and both were found to be elevated in kidney tissue (Supplemental Figure 3).

Renal NGAL expression was examined by IHC to more specifically characterize the site(s) of injury and the source of NGAL production (Figure 6). Low-powered images revealed NGAL immunoreactivity primarily localized to the renal cortex within 2 hours of DA administration (2.5 mg/kg) (Figure 6A). From higher-magnification images, NGAL expression was noted in cortical tubules at 2, 24, and 72 hours after DA administration (Figure 6A). To determine if NGAL induction was driven by renal glutamate receptor activation, mice were pretreated with the broad spectrum excitatory amino acid antagonist kynurenic acid (KYNA; 12.5 mg/kg intraperitoneally) or vehicle 5 minutes before DA administration (1.0 mg/kg). KYNA pretreatment suppressed renal NGAL expression at 2 and 72 hours (Figure 6B). Consistent with this observation, uNGAL was also reduced in KYNA+DA animals compared with vehicle+DA (Figure 6C).

Renal \textit{c-fos} and \textit{junb} Induction

To further characterize the cellular response to DA in the kidney, the acute-phase genes \textit{c-fos} and \textit{junb}, which are induced in the brain after DA exposure,\textsuperscript{33,34} were examined by quantitative RT-PCR. \textit{c-fos} mRNA was minimally expressed in the kidney before DA treatment but robustly elevated at 30 and 60 minutes after DA injection (2.5 mg/kg), and it was back to normal by 2 hours (Figure 7A). Similarly, \textit{junb} was elevated at 30, 60, and 120 minutes after DA administration but back to normal by 24 hours (Figure 7A). Because we had observed evidence of nephrotoxicity as low as 0.1 mg/kg, we examined \textit{c-fos} and \textit{junb} expressions at this dose as well as doses several fold lower (Figure 7B). At 30 minutes, both \textit{c-fos} and \textit{junb} mRNA, were induced after as little as 0.005 and 0.05 mg/kg.
DA administration. Expectedly, induction at the lower doses was not as robust as it was at the 2.5-mg/kg dose, and induction was more transient as well, because mRNA was rapidly lost after 30 minutes. To examine the effect of glutamate receptor inhibition, $c$-fos and junb mRNA were examined in kidneys from mice pretreated with KYNA before DA administration. Thirty minutes after DA injection, $c$-fos and junb mRNA were elevated in both the KYNA+DA and the DA groups; however, KYNA pretreatment attenuated the response, indicating that the response was, at least partially, dependent on ionotropic glutamate receptor activity (Figure 7C).

DISCUSSION

After the 1987 outbreak, Health Canada established a limit of 20 ppm DA in shellfish for human consumption, which was subsequently adopted by the US Food and Drug Administration among other governing agencies. The limit is primarily based on a calculated safety factor determined by no observed adverse effect levels from neurologic and gastrointestinal case reports. Additionally, DA is poorly absorbed, because the majority ingested is excreted in the feces, it does not readily cross the blood–brain barrier, and it is rapidly cleared from systemic circulation; therefore, there are several physiologic factors in addition to the regulatory factors that limit DA toxicity. However, there is evidence of peripheral toxicity, as well as an emerging concern over the effects of subclinical toxicity in the absence of overt organ toxicity or acute neurobehavioral changes. In the current study, DA preferentially accumulated in the kidneys of mice, with limited amounts detected in the liver, heart, and hippocampus, and this observation alone provided a compelling reason to examine the effects of DA on the kidney. This finding was consistent with the findings in a study by Lefebvre et al., which found preferential accumulation in the kidneys of coho salmon after oral DA exposure, although the duration of tissue deposition in the fish was quite different compared with the time frame reported here. Despite previous reports containing circumstantial evidence of renal effects after DA exposure, including renal edema and elevated hematocrit levels, there has not been a systematic examination of the kidney after DA exposure. In the current study, renal toxicity was evident from histologic, electron microscopy, and biomarker analyses after intraperitoneal administration of 1.0 or 2.5 mg/kg. It was also discovered that doses as low as 0.1 mg/kg DA produced a toxic response based on uKIM-1 excretion, and 0.005 mg/kg DA induced $c$-fos and junb mRNA in the kidney. Presently, the cellular response that led to the induction of $c$-fos and junb in the kidney after DA administration is not known, although it is likely a stress response to elevated intracellular calcium,

Figure 4. DA administration produced subcellular renal damage. TEM of renal cell injury revealed vascular damage, including (A, arrow) endothelial cell swelling, (A, arrowhead) epithelial cell vacuolization, (B) proximal tubule cell detachment, and (C) luminal provenaceous material and cellular debris. Higher-magnification views more clearly showed (D, arrow) endothelial cell damage, (E) toxic vacuolization, and (F, arrows) mitochondrial swelling after DA administration.
cellular depolarization, and/or a proliferative response, all of which have been previously described in models of renal ischemia and toxicosis. In the brain, induction of c-fos has been described as a marker of seizure activity and an early sign of neuronal excitotoxicity after exposure to glutamate, kainic acid, and DA. Studies from Peng and Ramsdell and Xi et al. showed that c-fos mRNA was induced in the brain at concentrations as low as 1.0 mg/kg DA (with nuclear immunolocalization at 0.5 mg/kg) in adult mice and as low as 0.1 mg/kg in neonates. Determining a lower limit of DA toxicity is essential to understanding the potential risks of exposure, although extrapolating results obtained in rodent studies to equivalent DA exposure levels in humans or other mammals is difficult. Most experimental rodent models use parenteral administration instead of oral dosing, and rodents are more resistant to the effects of DA compared with humans, non-human primates, and even sea mammals. It is possible that the renal toxicity observed in the current study was subsequent to altered central nervous system activity. However, because the doses used were well below levels shown to produce neurologic effects, it is assumed that the effects were directly related to DA on the kidney rather than a secondary effect of seizure activity, which has been suggested in DA-induced cardiotoxicity.

Renal NGAL expression was isolated to tubules of the outer cortex after DA administration. This observation, combined with excretion of uKIM-1 and uNGAL and the localization of histopathology and TUNEL reactivity, suggests that cortical proximal tubules were the primary target of acute DA nephrotoxicity. It should be noted, however, that KIM-1 and NGAL are primarily associated with proximal tubule injury, and therefore, there may be additional injury to lower segments of the tubule that was not detected without markers specific to these regions. DA was equally distributed between the renal cortex and the medulla, and KRs were expressed in tubules from both regions; therefore, it is unclear why the cortex would be the primary region affected. Because GluK5, a high-affinity KR, must form a heteromer with the catalytic subtypes GluK1 or GluK2, it is possible that functional channels are limited to the cortex. Additionally, studies in the brain have determined that DA-induced neurotoxicity involves a concerted effort from both KRs/AMPARs as well as NMDARs, and thus, the relative distribution of these receptors would need to be considered as well. Using IHC techniques, Gill et al. found that GluN1 was preferentially distributed to the renal cortex; however, other groups have shown equal or higher levels in the outer medullary region. Currently, it is not known which receptors are necessary for DA-induced nephrotoxicity.

To our knowledge, this study is the first study to show renal toxicity associated with exposure to a KR agonist. By PCR and IHC analysis, it was determined that various subtypes of KR were expressed in the kidney. Furthermore, coadministration with the broad spectrum excitatory amino acid inhibitor KYNA before DA suppressed acute-phase gene induction and biomarker expression/excretion. These data would suggest that injury was mediated, at least partially, through glutamate

Figure 5. Urinary AKI biomarkers were elevated following acute DA administration. (A) No change in sCr was seen at 24 or 72 hours (n=6). V, vehicle. (B) uNGAL and (C) uKIM-1 were elevated at 24 and 72 hours after DA exposure, respectively (n=6). V, vehicle. (D) Dose-response curve was generated by measuring uNGAL at 24 hours after exposure to 0.1, 1.0, and 2.5 mg/kg (n=6–10). V, vehicle. (E) Dose–response curve was generated by measuring uKIM-1 at 72 hours after exposure to 0.1, 1.0, and 2.5 mg/kg (n=6–10). V, vehicle. (F) After 12 hours of dehydration, mice were exposed to 2.5 mg/kg DA, and uKIM-1 was measured in urine collected overnight after the single dose. *Data were significantly different from vehicle (P<0.05, ANOVA followed by Newman–Keuls for individual group comparisons). Veh, vehicle.
receptor activation, and it is likely that renal KRs were involved; however, it is possible that DA activated an alternative effector site and that KYNA had effects outside of excitatory amino acid inhibition. In addition to its inhibitory effects at ionotropic glutamate receptors, KYNA may also act as an inhibitor at α7-nicotinic cholinergic receptors or as an agonist at G protein-coupled receptor GPR35, which is thought to inhibit cytokine release from immune cells and suppress inflammation, although this mechanism of inhibition would seem unlikely considering the time course of the effects reported here.

In addition to acute DA toxicity, there is concern over the long-term consequences from repeated exposure, such as the chronic neurologic effects that have been identified in sea lions exposed to sublethal levels of DA, characterized by hippocampal atrophy and development of epilepsy. With respect to the kidney, there is convincing evidence that AKI incidence is a risk factor for CKD and ESRD. Because there was no change in renal function (i.e., sCr) and there was only modest histopathology, the clinical relevance associated with DA nephrotoxicity is unclear at this time. Even the AKI biomarkers KIM-1 and NGAL were only moderately elevated compared with insults that produce overt renal damage, such as ischemia-reperfusion injury or cisplatin nephrotoxicity. However, recent evidence suggests that even subclinical toxicity might lead to tubule damage and an overall decline in renal function. Indeed, elevated uNGAL or plasma NGAL, even in the absence of detectable changes in sCr, has been associated with the need for RRT and higher mortality rates. It is our position that subclinical renal toxicity associated with repeated DA exposure, particularly as an undetected injury from an unrecognized source, could contribute to the progression of renal disease. Furthermore, it is conceivable that the effects of DA may be compounded, or even masked, in populations with underlying renal disease or compromised renal function, such as aged or diabetic populations. Validation of these findings in other systems and species is needed, and confirmation may necessitate new discussions regarding acceptable exposure to humans. Finally, these results draw attention to the kidney as a potentially unrecognized target of excitatory drugs, toxins, and amino acids, and renal effects should be considered in studies examining these effector sites.

Figure 6. Acute DA administration induced renal cortical NGAL expression. (A) NGAL IHC at 2, 24, or 72 hours after DA or vehicle treatment in the renal cortex as viewed in low- (top panels; 5× objective) or higher-powered images (bottom panels; 20× objective). Diaminobenzidine chromogen with hematoxylin counterstain was used. Veh, vehicle. (B) NGAL IHC at 2 or 72 hours after DA or KYNA+DA treatment (20× objective). (C) uNGAL excretion 72 hours after DA or KYNA+DA treatment. *Data were significantly different from the 0-hour time point. #KYNA+DA treatment was significantly different from DA (n=3, P<0.05, ANOVA followed by Newman–Keuls for individual group comparisons).
CONCISE METHODS

Animals
All studies involving animals were done in accordance with the institutional guidelines of the Medical University of South Carolina. The study was performed using adult 128Sv/Black Swiss mice weighing approximately 25–30 g.

DA Administration
For tissue distribution studies, mice were exposed to DA (2.5 mg/kg intraperitoneally) and euthanized 30, 60, or 120 minutes after exposure; kidneys, liver, heart, hippocampus, and serum were harvested. For 72-hour toxicity studies, mice were exposed to a single daily dose of DA for 3 consecutive days (0.1–2.5 mg/kg intraperitoneally) or an equal volume of diluents (isotonic saline), and they were euthanized 24 hours after the third dose. For immediate response gene studies, mice were exposed to DA (2.5 mg/kg intraperitoneally) and euthanized 30 minutes after injection; kidneys and hippocampus were harvested and flash frozen. For PBN pretreatment studies, mice were given PBN (600 mg/kg intraperitoneally) or vehicle (saline) 5 minutes before DA (2.5 mg/kg intraperitoneally) and euthanized 30 minutes after DA injection; organs were collected for DA measurements. For KYNA pretreatment studies, mice were injected with KYNA (12.5 mg/kg intraperitoneally) or vehicle (isotonic saline) 5 minutes before DA (2.5 mg/kg intraperitoneally) and euthanized 30 minutes after DA injection; kidneys were harvested and flash frozen for RNA processing.

Figure 7. Immediate response genes c-fos and junb were elevated following DA administration. (A) c-fos and junb mRNA were examined by quantitative RT-PCR in kidneys from mice at 0.5, 1, 2, and 24 hours after DA exposure (2.5 mg/kg), with representative gel images shown in left panel and quantitative PCR analysis shown in right panel. Hip, hippocampus. (B) c-fos and junb mRNA were examined by quantitative RT-PCR in kidneys 30 minutes after exposure to 0.0005, 0.005, 0.05, or 2.5 mg/kg DA. (C) c-fos and junb mRNA were examined in kidneys by quantitative PCR analysis 30 minutes after mice were pretreated with KYNA (12.5 mg/kg) followed by DA administration (2.5 mg/kg). V, vehicle. *Data were significantly different from control (0 hour time point or V treatment); **P<0.05; ***P<0.01. #KYNA+DA was significantly different from DA (P<0.05). ANOVA followed by Newman–Keuls for individual group comparisons (n=3).
DA Measurements
DA concentration was measured by ELISA (Mercury Science, Durham, NC) using the method as previously described.57

RNA Isolation and RT-PCR
RNA was obtained using the RNeasy RNA Isolation Kit (Qiagen), and reverse transcription was performed with the iScript cDNA Synthesis Kit (Bio-Rad, Hercules, CA). RT-PCR experiments assessing ionotropic glutamate receptor expression were performed using GoTaq Green PCR Master Mix (Promega, Madison, WI) and primer sequences that have been previously reported.38 Quantitative RT-PCR experiments assessing c-fos and junb expression were performed using SsoAdvanced SYBR Green PCR Mix (Bio-Rad) and primer sequences that have been previously reported.34

Kidney Function and Injury Measurements
Terminal blood was collected by venepuncture of the inferior vena cava at time of euthanasia. Serum was extracted from collected blood and used to measure creatinine (QuantiChrom Creatinine Assay Kit; BioAssay Systems, Hayward, CA). Urine collected overnight after the first and third injections, was used to measure KIM-1 (Quantikine KIM-1 ELISA; R&D Systems, Indianapolis, IN) and NGAL (Lipocalin2; BioAssay Systems, Hayward, CA). Urine collected overnight after the first and third injections, was used to measure KIM-1 (Quantikine KIM-1 ELISA; R&D Systems, Indianapolis, IN) and NGAL (Biporto, Denmark).

Histology and IHC
Mice were exposed to DA for 3 days. At the time of euthanasia, organs were immersion-fixed in 10% formalin and paraffin-embedded. Histologic evaluations were determined from hematoxylin and eosin- and Masson trichrome-stained sections. For IHC experiments, tissue sections were dewaxed in xylenes followed by rehydration in a graded ethanol series, heat-mediated antigen retrieval in sodium citrate buffer, and blocking for 1 hour in 5% normal goat serum/1% BSA. Primary antibodies were incubated for 2 hours at room temperature using antibodies against GluK5 (Abcam, Cambridge, MA), GluK2 (Aviva Systems Biology, San Diego, CA), and NGAL (Lipocalin2; Abcam). After antibody incubation, the sections were incubated in biotinylated secondary antibody and horseradish peroxidase-conjugated avidin–biotin complex and developed with diaminobenzidine exposure using a Vectastain ABC Kit according to the manufacturer’s instructions (Vector Labs, Burlingame, CA). Sections were counterstained with hematoxylin (Vector Labs).

TUNEL Assay
Paraffin-embedded kidney sections from mice treated for 72 hours with 1.0 or 2.5 mg/kg DA were used for detection of apoptosis by TUNEL assay. The assay was performed using an ApopTag Peroxidase In Situ Apoptosis Detection Kit (Millipore, Billerica, MA) according to the manufacturer’s instructions and developed with dianaminobenidine. Negative control sections were incubated in buffer without terminal deoxynucleotidyl transferase enzyme. Positive control sections were incubated with DNase I at the beginning of the protocol.

TEM
After 72 hours of DA exposure, kidneys were harvested and immediately placed in a dish containing modified Karnovsky’s buffer (2.5% glutaraldehyde/2.5% formalin in PBS) followed by processing into resin blocks (Embed 812; Electron Microscopy Sciences, Hatfield, PA). The resin blocks are thick-sectioned at 1 μm with a histodiamond knife using an Ultracut UCT 7 (Leica, Bannockburn, IL); sections are then collected on slides and stained with Toluidine Blue. The appropriate blocks are then thin-sectioned using a diamond knife (Diatom; Electron Microscopy Sciences) at 70–90 nm (silver to pale gold using color interference), and sections are placed on copper grids. After drying, the sections are stained with the heavy metals uranyl acetate and lead citrate for contrast. After drying, the grids are then viewed on a Tecnai Spirit 120kv TEM (FEI, Hillsboro, OR). Digital images are taken with an AMT CCD camera.

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DISCLOSURES
None.

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Supplemental Information

METHODS

Animals and domoic acid exposure. All studies involving animals were done in accordance with the institutional guidelines of the Medical University of South Carolina. For tissue distribution studies, adult 128Sv/Black Swiss mice were exposed to domoic acid by intraperitoneal injection at a dose of 2.5 mg/kg body weight (DA; 2.5 mg/kg; i.p.), and were euthanized 30, 60, or 120 min after exposure. Kidneys, liver, heart, hippocampus, and serum were harvested at each time point to measure DA concentration. For toxicity studies, mice were exposed to a single dose of DA for three consecutive days (0.1-2.5 mg/kg; ip) or an equal volume of diluents (isotonic saline), and were euthanized 24 h after the third dose. During toxicity studies, mice were housed in metabolic cages overnight following the initial dose and again following the third dose for urine collection and analysis. For immediate response gene expression studies, mice were exposed to a single dose of DA (0.0005-2.5 mg/kg; ip), and were euthanized 30 min after injection, and kidneys and hippocampus were harvested and flash frozen. In probenecid (PBN) pretreatment studies, mice were given PBN (600 mg/kg; i.p.) or vehicle (saline) five minutes prior to DA (2.5 mg/kg, i.p.). Mice were euthanized 30 min after DA injection and organs were collected for DA measurements. For kynurenic acid (KYNA) pretreatment studies, mice were injected with KYNA (12.5 mg/kg; i.p.) or vehicle (isotonic saline) five minutes prior to DA (2.5 mg/kg; i.p.). Mice were euthanized 30 min after DA injection, and kidneys were harvested and flash frozen for RNA processing.

Domoic acid measurements. DA concentration in tissues was measured by ELISA (Mercury Science, Durham, NC). Extraction of DA was performed using a modified version of a previously described protocol, which was adapted for use in mouse tissues. Extraction was performed by lyzing flash frozen tissue sections in 10X (w:v) 50% methanol using a pestle followed by sonication. The lysates were centrifuged for 20 min at 10,000 X g, and supernatant was taken for
analysis. The ELISA was performed according to the manufacturer’s instructions.

**RNA isolation and RT-PCR.** RNA was obtained using an RNeasy RNA isolation kit (Qiagen) according to manufacturer’s protocol. 1 µg of total RNA was converted to cDNA using an iScript cDNA synthesis kit (Bio-Rad, Hercules, CA). cDNA was diluted 10-fold with nuclease-free water prior to PCR reactions. For RT-PCR experiments, cDNA was combined with GoTaq Green PCR Master Mix (Promega, Madison, WI) and 400 nM each forward and reverse primers. The primer sequences for the receptor subtypes that were examined in this study have been previously reported 49, and were obtained from Integrated DNA Technologies (IDT, Coralville, IA). For qRT-PCR experiments, cDNA was combined with SsoAdvanced SYBR Green PCR Mix (Bio-Rad, Hercules, CA) and 400 nM each primer. The primer sequences for *c-fos*, *junb*, and *tubulin* were previously reported 33 and were obtained from IDT. For qRT-PCR experiments, reactions were subjected to 30 s at 95 °C, followed by 40 cycles of 5 s at 95 °C and 30 s at 55 °C, in an Eppendorf Mastercycler Realplex 4s (Hauppauge, NY).

**Kidney function and injury measurements.** Terminal blood was collected by venepuncture of the inferior vena cava at time of euthanasia. Serum was extracted from collected blood and used to measure creatinine (QuantiChrom Creatinine Assay Kit; BioAssay Systems, Hayward, CA) and cystatin c (Quantikine Cystatin C ELISA; R&D Systems, Indianapolis, IN). Urine collected overnight following the first and third injections was used to measure kidney injury molecule-1 (Quantikine KIM-1 ELISA; R&D Systems, Indianapolis, IN), neutrophil gelatinase-associated lipocalin (NGAL; Bioporto, Denmark), total protein (BCA assay), albumin (QuantiChrom Albumin Assay Kit; BioAssay Systems), and cystatin c.

**Histology and immunohistochemistry (IHC).** Mice were exposed to DA for three days. At time of euthanasia, organs were immersion-fixed in 10% formalin and paraffin-embedded.
Paraffin sections were then processed and stained with hematoxylin and eosin or Masson trichrome stain for histological analysis. GluK2 and GluK5 IHC was performed by dewaxing the sections in xylenes and rehydration in a graded ethanol series. The sections were subjected to heat-mediated antigen retrieval in citrate buffer, followed by blocking in 5% normal goat serum, and incubation in primary antibody (Rabbit anti-GluK5, Abcam; Rabbit anti-GluK2, Aviva Biosystems; Rabbit anti-NGAL, Abcam) overnight at 4 °C. Following antibody incubation, the sections were incubated in biotinylated secondary antibody, HRP-linked avidin-biotin complex, and developed with diaminobenzidine (DAB) exposure using a Vectastain ABC kit (Vector Labs). The sections were counterstained with hematoxylin, dehydrated in ethanol and xylenes, and mounted with permount (Vector Labs).

**Terminal deoxynucleotidyl transferase dUTP nick end labeling (TUNEL) assay.** Paraffin-embedded kidney sections from mice treated for 72 h with 1.0 or 2.5 mg/kg DA were used for detection of apoptosis by TUNEL assay. The assay was performed using an ApopTag® Peroxidase In Situ Apoptosis Detection Kit (Millipore, Billerica, MA) according to the manufacturer’s instructions, and developed with diaminobenzidine (DAB). Negative control sections were incubated in buffer without TdT enzyme. Positive control sections were incubated with DNase I at the beginning of the protocol.

**Transmission electron microscopy (TEM).** Following 72 h DA exposure, kidneys were harvested and immediately placed in a dish containing a modified Karnovsky’s buffer (2.5% glutaraldehyde/2.5% formalin in PBS). After fixation the specimens were rinsed several times with sodium cacodylate buffer pH 7.4 0.1M followed by post fixation with 1% osmium tetroxide in cacodylate buffer for one hour in dark. After rinsing again with Cacodylate buffer, the specimens were dehydrated through a series of graded ethyl alcohols from 50 to 100%. After dehydration the infiltration process requires steps through an intermediate solvent, 2 changes of
100% propylene oxide (P.O.) for 10 minutes each and finally into a 50:50 mixture of P.O. and the embedding resin (Embed 812, Electron Microscopy Sciences, Hatfield, PA) for 12-18 hours. The specimen is transferred to fresh 100% embedding media. The following day the specimen is then embedded in a fresh change of 100% embedding media. Blocks polymerize overnight in a 60 degree C embedding oven and are then ready to section. The resin blocks are first thick sectioned at 1 micron with a histo diamond knife using an Ultracut UCT 7 (Leica, Bannockburn, IL) sections are collected on slides and stained with Toluidine Blue. These sections are used as a reference to trim blocks for thin sectioning. The appropriate blocks are then thin sectioned using a diamond knife (Diatome, Electron Microscopy Sciences, Hatfield, PA) at 70-90nm (silver to pale gold using color interference) and sections are then placed on copper grids. After drying, the sections are stained with the heavy metals uranyl acetate and lead citrate for contrast. After drying the grids are then viewed on a Tecnai Spirit 120kv TEM (FEI, Hillsboro, OR). Digital images are taken with an AMT CCD camera.
Supplemental Figure 1. Kainate receptor expression in the kidney. (A) GluK5 expression was examined by IHC in the cortex and medulla of mice treated with DA (2.5 mg/kg, 72 h) or vehicle. (B) GluK2 and GluK5 protein expression was examined by immunoblot analysis in kidneys from vehicle- and DA-treated mice at 72 h. Hippocampal lysates (Hip) were used for positive control.
Supplemental Figure 2. Renal histopathology after DA exposure. Renal histopathology was examined by H&E and Masson trichrome stains at 72 h after exposure to either 1.0 or 2.5 mg/kg DA. Note intense hypereosinophilic tubules after either dose (arrows) in the H&E sections. Similar structures were also noticeable in Masson trichrome sections at both doses (asterisks).
Supplemental Figure 3. KIM-1 and NGAL mRNA and protein expression in kidneys after DA. (A) KIM-1 and NGAL mRNA abundance was examined by RT-PCR in kidneys from vehicle- and DA-treated mice 72 h after DA administration. (B) KIM-1 and NGAL protein expression was examined by immunoblot analysis in kidneys from vehicle- and DA-treated mice 72 h after DA administration. Several bands were detected in the KIM-1 blots corresponding to different glycosylated forms of the protein. In NGAL blots, the 25 kD band corresponds to the form that is upregulated after ischemia-reperfusion injury.