J Vet Intern Med 2003;17:304–310

Diazepam as a Treatment for Metronidazole Toxicosis in Dogs: A Retrospective Study of 21 Cases

Jason Evans, Donald Levesque, Kim Knowles, Randy Longshore, and Scott Plummer

The currently recommended treatment for metronidazole toxicosis is drug discontinuation and supportive therapy. Reported recovery times are 1–2 weeks. The records of 21 dogs with metronidazole toxicosis were retrospectively analyzed to determine whether diazepam improved recovery. The dosage and duration of metronidazole therapy and the response and recovery times of 13 dogs treated with diazepam were compared to those of 8 dogs receiving only supportive care. Response time was defined as the time to resolution of the debilitating clinical signs. Recovery time was the time to resolution of all residual clinical signs. The average dosage and duration of metronidazole administration for the diazepam-treated and untreated groups were 60.3 mg/kg/d for 44.9 days and 65.1 mg/kg/d for 37.25 days. The protocol for diazepam administration consisted of an initial IV bolus and then diazepam PO q8h for 3 days. The average dosage of both the IV and PO diazepam was 0.43 mg/kg. The average response time for the diazepam-treated dogs was 13.4 hours compared to 4.25 days for the untreated group. Recovery time also was markedly shorter for the diazepam-treated dogs (38.8 hours) compared to the untreated group (11 days). Results of this study showed that dogs with metronidazole toxicosis recover faster when treated with diazepam. Although the mechanism of metronidazole toxicosis or how diazepam exerts its favorable effect is not known, it is likely related to modulation of the γ-aminobutyric acid (GABA) receptor within the cerebellar and vestibular systems.

Key words: Benzodiazepine; Cerebellar disease; Drug toxicity; γ-Aminobutyric acid; Vestibular syndrome.

Metronidazole[a] is a nitroimidazole antibacterial and antiprotozoal compound[1] used routinely in the treatment of giardiasis,[2] anaerobic infections,[3,4] and inflammatory bowel disease.[5] It has high bioavailability for most tissues, including bone and the central nervous system. Metronidazole is metabolized by the liver and has a half-life of 3–13 hours in the dog.[1] The adverse effects of metronidazole in humans, which include seizures, ataxia, peripheral neuropathy, and hematuria, are well documented.[1,6,7] Adverse effects of metronidazole in the dog[8,9] and cat[10,11] have been reported and include vomiting, hepatotoxicity, neutropenia, and neurologic signs such as seizures, head tilt, falling, paresis, ataxia, vertical nystagmus, tremors, and rigidity.[8–10] Neurologic adverse effects in cats have a greater tendency to reflect forebrain dysfunction (disorientation and seizures) than brain stem dysfunction.[10,11]

Neurologic toxicity from metronidazole has been reported in dogs receiving >60 mg/kg/d for an average of 3–14 days,[8] but reports of toxicity at lower dosages have been cited.[10,11] The mechanism of the toxic effects of metronidazole has not been identified. The currently recommended therapy for treating metronidazole toxicosis is discontinuation of the drug and supportive therapy. No specific treatment to counteract the toxic effects of metronidazole has been reported. Reported recovery times of dogs with neurologic manifestations of metronidazole toxicosis are 1–2 weeks.[1,4,10,12]

From the Veterinary Neurological Center, Las Vegas, NV (Evans, Levesque); and the Veterinary Neurological Center, Phoenix, AZ (Knowles, Longshore, Plummer). The work was performed at both of the above addresses. A poster abstract was presented at the 2002 ACVIM Forum in Dallas, TX.

Reprint requests: Jason Evans, DVM, MS, Veterinary Neurological Center, 4445 N Rainbow Boulevard, Las Vegas, NV 89108; e-mail: vetneuro@aol.com.

Submitted July 12, 2002; Revised September 12, 2002; Accepted November 4, 2002.

0891-6640/03/1703-0006/$3.00/0

In humans, the centrally acting benzodiazepine diazepam[b] has long been used in the symptomatic treatment of vertigo or disequilibrium secondary to diseases of the vestibular system such as benign paroxysmal vertigo (BPV)[13,14] and endolymphatic hydrops (Meniere's disease).[15] Diazepam is believed to exert its antivertiginous effects by facilitating the effects of the inhibitory neurotransmitter γ-aminobutyric acid (GABA) within the vestibular system.[16–21] Diazepam is principally used in veterinary medicine for its anticonvulsant, muscle-relaxant, sedative, anxiolytic, and appetite-stimulating properties.[22,23] It has been suggested for use as a sedative in animals with severe disequilibrium secondary to vestibular syndromes,[24] but reports suggesting its application as an antidote to a specific toxicity are lacking.

At the Veterinary Neurological Center (VNC), dogs presenting with signs of metronidazole toxicosis that were treated symptomatically with diazepam appeared to have a more rapid resolution of clinical signs than dogs in various published reports that had been treated with conservative therapy alone. To evaluate potential differences in the recovery time between dogs with metronidazole toxicosis treated with diazepam and a similar group that did not receive diazepam as part of the therapy, the following parameters were compared: dosage of metronidazole, duration of therapy, time to resolution of the debilitating clinical signs (response time), and time to final resolution of all residual clinical signs (recovery time).

Although the exact mechanism of metronidazole toxicity is not known, the neurologic adverse effects are indicative of cerebellar and central vestibular dysfunction. The neuroinhibitory actions of benzodiazepines on the brain have been shown to be mediated by GABA. Because GABA is the major inhibitory neurotransmitter of the cerebellar and vestibular systems[25–27] and because benzodiazepines such as diazepam have their major effect on this neurotransmitter,[16–21] a possible relationship between metronidazole and diazepam was postulated. Further speculation for metronidazole's affinity for the GABA receptor site was based on the similarity of both the chemical structure and clinical

Table 1. Summary statistics of dogs with metronidazole toxicosis in the treated and untreated groups.[a]

Parameter	Untreated Group	Treated Group
Number	8	13
Age (years)	7.5 (3–13)	6.7 (0.8–13)
Weight (kg)	13.4 (4.2–30)	20.4 (4.1–47.3)
Metronidazole dosage (mg/kg/d)	65.1 ± 23.3 (39.3–110)	60.3 ± 17.5 (33.3–83)
Metronidazole duration (days)	37.3 ± 34.9 (10–120)	127.5 ± 295.5 (7–1099)
Diazepam IV (mg/kg)	N/A	0.43 ± 0.14 (0.2–0.69)
Diazepam PO (mg/kg)	N/A	0.43 ± 0.13 (0.3–0.69)
Response time[b]	4.25 ± 2.8 days (2–10)	13.05 ± 9.8 hours (0.3–24)
Recovery time[b]	11.6 ± 5.9 days (5–21)	38.8 ± 15.6 hours (24–72)

N/A, not applicable.

[a] Mean ± standard deviation.

[b] The response and recovery times for the untreated group are listed in days, and the response and recovery times for the treated group are listed in hours.

signs of toxicity of metronidazole and the benzodiazepine antagonist flumazenil,[c] which also is known to attach to the GABA receptor.[21]

Materials and Methods

Criteria for Case Selection

Medical records of 33 dogs at the VNC with a diagnosis of metronidazole toxicosis between 1997 and 2001 were reviewed. Twenty-one dogs were selected for this study on the basis of the availability of data regarding metronidazole dosage and duration of therapy before the onset of clinical signs, response time, and recovery time. Thirteen of the 21 dogs had been treated with diazepam, whereas the other 8 dogs had not received diazepam as part of their therapy. Response time was defined as the time to resolution of debilitating clinical signs and was determined by physical examination. For the purpose of this study, debilitating clinical signs were those signs that resulted in the loss of vestibular function, motor function, or both to the degree that ambulation, eating, or drinking could not be performed. Debilitating clinical signs typically were related to the profound disequilibrium often associated with vestibular syndromes. Recovery time was defined as the time to resolution of residual clinical signs of metronidazole toxicosis, which was the point at which the dog was considered normal by either clinical examination or owner evaluation. Data concerning breed, age, history, manifestations of metronidazole toxicosis, and previous treatments were collected but not considered in the statistical analysis.

Treatment

The treatment for 13 patients with a tentative diagnosis of metronidazole toxicosis at the VNC included an initial bolus of diazepam administered IV and then PO q8h for 3 days. Metronidazole was discontinued in all animals, and supportive care including IV fluid administration was given to animals that were admitted to the hospital. Treatment for the group of dogs that did not receive diazepam after a diagnosis of metronidazole toxicosis primarily consisted of discontinuation of the drug and supportive care. Summary information of the dosages of both IV and PO diazepam administered is listed in Table 1.

Diagnosis of Metronidazole Toxicosis

Blood concentrations of metronidazole were not measured, but all dogs in this study were diagnosed with metronidazole toxicosis on the basis of a history of having received metronidazole, clinical signs compatible with metronidazole toxicosis, absence of other clinical disease, and eventual recovery of all dogs upon discontinuation of metronidazole administration.

Statistical Analysis

All statistical comparisons between the 2 groups were made by the Student's *t*-test. The level of significance was chosen as $P < .05$. Correlation analysis was applied to the scatterplot (Fig 1) to measure the correlation coefficient (r) of the relationship between dosage and duration of metronidazole administration and the onset of clinical signs of metronidazole toxicosis.

Results

The ages of the dogs in this study ranged from 10 months to 13 years, and the weight of the dogs ranged from 4.1 to 47.3 kg. Only 1 breed of dog (Shih Tzu) was represented more than once (twice) in this study.

The results of routine physical examinations did not identify any other major abnormality except for the neurologic signs. Nearly all of the neurologic problems were acute, and the dogs were presented to a veterinarian within 24 hours of the onset of signs. Additionally, the final dose of metronidazole had been given to all dogs within 24 hours of presentation to the VNC for examination. CBCs and serum biochemistry were performed in 11 of 21 dogs, and the most common abnormalities were mild-to-moderate increases in alkaline phosphatase activity and stress leukograms. Serum titers for *Coccidioides immitis* and *Ehrlichia canis* had been performed on 7 and 8 dogs, respectively, and were negative. In addition, serum bile acid concentrations had been measured in 3 dogs, whereas computed tomography[d] brain scans and cerebrospinal fluid analyses were performed on 2 dogs. All results were within normal limits.

The most common neurological signs were vertical nystagmus (17 of 21), truncal ataxia (15 of 21), inability to walk (10 of 21), upper motor neuron (UMN) paraparesis (7 of 21), hypermetria (5 of 21), extensor rigidity of all 4 limbs (5 of 21), UMN tetraparesis (5 of 21), intention tremors (4 of 21), right head tilt (2 of 21), left head tilt (1 of 21), right torticollis (2 of 21), and opisthotonos (2 of 21). Of the 10 dogs that were nonambulatory, 5 were unable to walk without assistance because of cerebellovestibular dysfunction, but these dogs were not tetraparetic.

The most common reasons for administration of metronidazole were for treatment of gastrointestinal signs such as diarrhea (7 of 21) or vomiting (4 of 21), for suspected inflammatory bowel disease (5 of 21), for high liver en-

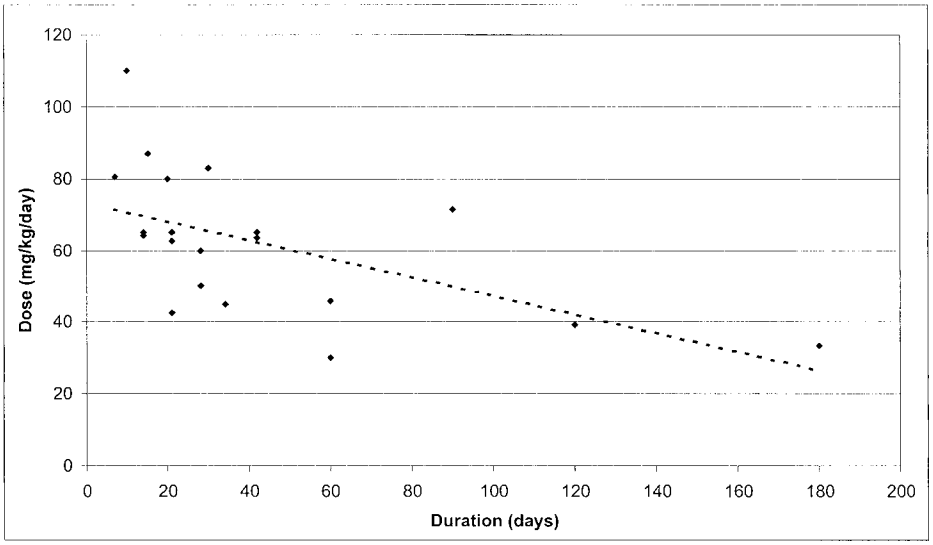

Fig 1. A scatterplot analysis of the doses and durations of metronidazole therapy for the dogs in this investigation. Higher dosages generally require shorter duration of administration to produce clinical signs of metronidazole toxicosis ($r = -.56$). The data from dog 13 of the treated group were omitted from this chart because the dog had been on metronidazole therapy for 1,099 days, which was, individually, markedly different from the other dogs in this study.

zyme activities (2 of 21), for giardiasis (2 of 21), and for dental disease (1 of 21). Before the diagnosis of metronidazole toxicosis, medical treatments for the neurologic signs consisted of one or more of the following: corticosteroids (16 of 21), antibiotics (8 of 21), methocarbamol[e] (5 of 21), carprofen[f] (3 of 21), meclizine[g] (2 of 21), and butorphanol[h] (2 of 21).

Table 1 lists the summary statistics of dosages and duration of metronidazole administration, dosages of IV and PO diazepam, if applicable, and response and recovery times for dogs in the untreated and treated groups.

The average daily dosage of metronidazole for dogs that received diazepam was 60.3 mg/kg/d; for dogs that were not treated with diazepam, the average daily dosage of metronidazole was 65.1 mg/kg/d. The range of the individual dosages of metronidazole for dogs that were given diazepam was 33–83 mg/kg/d. The range of the metronidazole dosages for dogs in the untreated group was 45–110 mg/kg/d. The average daily dosage of metronidazole was not significantly different between the 2 groups ($P > .05$).

The average duration of metronidazole administration for dogs treated with diazepam was 127 days, with a range of 7–1,099 days. The average duration of metronidazole administration was 37 days for animals in the untreated group, with a range of 10–120 days. If the data from dog 13 of the diazepam-treated group that had been on metronidazole therapy for 1,099 days are disregarded, the average duration of metronidazole use for the diazepam-treated group becomes 44 days. The resulting calculation is closer to the 37-day average of the untreated group; however, including the data from this dog does not alter the statistical analysis in comparing the 2 groups. The duration of metronidazole administration was not significantly different between the 2 groups ($P > .05$).

The average single, initial IV dosage of diazepam was 0.43 mg/kg, and the average subsequent PO dosage was 0.43 mg/kg. The range for IV and PO administration of diazepam was 0.2–0.625 and 0.31–0.69 mg/kg, respectively.

Dogs treated with diazepam had an average response time of 13 hours and an average recovery time of 38.7 hours. The response times for dogs treated with diazepam ranged from 20 minutes to 24 hours, and the recovery times ranged from 24 to 72 hours. Dogs that were not treated with diazepam had an average response time of 4.25 days and an average recovery time of 11.6 days. Response times for the dogs in the untreated group ranged from 2 to 10 days, and recovery times ranged from 5 to 21 days. Both the response and recovery times for the animals treated with diazepam were significantly shorter than those for the untreated group ($P < .05$).

Discussion

The neurologic adverse effects of metronidazole are well documented in humans[1,7] and companion animals.[8–11] There is currently no recommended treatment other than withdrawing the drug and providing supportive care. Diazepam, a centrally acting benzodiazepine, is used in human medicine for symptomatic treatment of signs of vestibular system dysfunction,[13–15,28,29] but reports have not indicated any curative effect for an underlying disease or toxicity. In one study, guinea pigs undergoing unilateral labyrinthectomy and treated with diazepam had milder signs than the untreated group, but there was no marked difference between the groups in the time to complete vestibular compensation.[28] Similar findings regarding vestibular compensation are reported in humans with BPV treated with diazepam.[14,29] Diazepam has been recommended for alleviating signs of vestibular dysfunction in humans and animals, but indications for the use of diazepam other than for palliative therapy have not been reported.

The results of this investigation demonstrate that diazepam dramatically improves recovery times for dogs with

metronidazole toxicosis. Recovery times for dogs in this study that did not receive diazepam were consistent with previous reports. Dogs 1 and 3 in the untreated group had prolonged recovery times, which greatly increased the average overall recovery time for animals in this group. Both of these dogs suffered pronounced paraparesis, which lingered long past the resolution of the acute vestibular signs. Although these 2 dogs may have adversely influenced the average overall time to clinical resolution for the untreated group, there still was a marked difference in the response and recovery times compared to the diazepam-treated animals if data from these 2 dogs are discarded.

The results of this investigation show a positive correlation between dosage and duration of treatment relative to the time of onset of signs of metronidazole toxicosis (Fig 1). There did not appear to be an increased susceptibility to adverse effects of metronidazole administration on the basis of either age or breed. The average dosage of metronidazole that induced toxicity in the dogs of this study (60.3 and 65.1 mg/kg/d for diazepam-treated and untreated groups, respectively) was consistent with published reports.

Ours was a retrospective study, and a specific protocol for the administration of diazepam was not used. All animals in the diazepam-treated group, however, received an initial, single IV bolus and then diazepam PO q8h for 3 days. The average dosage of both the IV and PO diazepam was 0.43 mg/kg, but there was no apparent correlation between the dosages of either the IV or PO routes and the response or recovery times.

Neither the mechanism of metronidazole toxicity nor the precise mechanism of action of diazepam in the reversal of signs is known. Because the neurological effects of metronidazole are referable to both cerebellar and central vestibular dysfunction, literature regarding the histology and physiology of these systems was reviewed for a relationship between metronidazole and diazepam.

Histological examinations of brain tissue in dogs with metronidazole toxicosis have demonstrated Purkinje cell loss[8,30] and axonal degeneration in vestibular tracts.[8] Histopathologic studies in mice given toxic dosages of metronidazole showed cerebellar Purkinje cell loss and degenerative changes in the vestibular, cochlear, deep cerebellar, and olivary nuclei as well as in the rostral colliculi.[31] These nuclei and their associated tracts are involved primarily with equilibrium, hearing, and fine motor control.[32,33] These nuclei, particularly the Purkinje cells, mediate an inhibitory influence on postsynaptic receptors,[34,35] and their principal neurotransmitter is GABA,[25,26,34] which is the major inhibitory neurotransmitter of the central nervous system.[25–27,36] Activation of the GABA receptor by GABA or GABA mimetics, such as benzodiazepines, increases chloride (Cl^-) conductance at the postsynaptic membrane, resulting in hyperpolarization (Fig 2).[37] The majority of GABA-minergic receptors in the central nervous system are located between the neurons of the cerebellum and their associated brainstem nuclei, especially the Purkinje cells and the lateral vestibular nuclei. Other major sites of GABA receptors are in the tracts between the vestibular nuclei and the trochlear motor neurons and within the olfactory bulbs, cuneate nuclei, hippocampus, and lateral septal nuclei.[27] GABA also facilitates inhibitory transmission in the cerebral cortex and between the substantia nigra and caudate nucleus.[27,34]

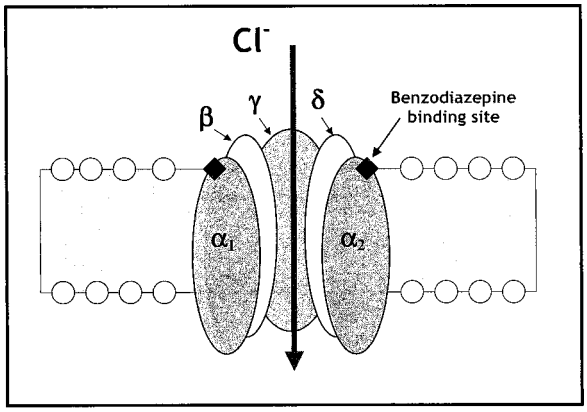

Fig 2. Diagrammatic representation of a γ-aminobutyric acid (GABA) receptor. The GABA receptor is a multisubunit ligand-gated chloride (Cl^-) ion channel composed of α, β, γ, and δ subunits. An increase in chloride conductance from the release of GABA from the presynaptic membrane results in the inhibitory modulation of neural activity through membrane hyperpolarization.

Because of the prevalence of GABA-minergic receptors in those tracts damaged by metronidazole and the known relationship of GABA receptors and benzodiazepines, the following mechanism may be postulated: benzodiazepines, such as diazepam, potentiate GABA influence on chloride conductance, thereby enhancing an inhibitory effect on excitatory neurons.[38–40] Conversely, inhibition of GABA release, such as seen in the neurological adverse effects of enrofloxacin,[i] ciprofloxacin,[j] and imipenem,[k] can lead to hyperexcitability of the central nervous system, resulting in seizures or tremors.[41,42] It may therefore be speculated that interference of the GABA receptor at the postsynaptic membrane also may result in central nervous system hyperexcitability.

The benzodiazepines have specific binding sites on GABA receptors within the brain, particularly in the cerebellum, cerebral cortex, and limbic system.[41,43] The imidazobenzodiazepine flumazenil is a selective, competitive antagonist (also known as an inverse agonist) of the benzodiazepine receptor.[40,41,44–47] Both flumazenil and metronidazole have an imidazole component, and it is possible that metronidazole also may bind specifically to benzodiazepine sites on GABA receptors in the cerebellar and central vestibular systems, resulting in loss of inhibition, similar in effect to flumazenil (Fig 3). That the adverse reactions of flumazenil in humans, such as seizures, vertigo, and ataxia,[45–47] are similar to the neurological adverse effects of metronidazole in dogs lends additional credence to this proposed mechanism of metronidazole toxicity. Regardless of whether metronidazole specifically binds to the benzodiazepine receptor inhibiting the effects of GABA or selectively destroys these cells by another mechanism, it is the GABA-dependent interactions of the cerebellar and central vestibular systems that are affected. It can be therefore postulated that diazepam either competes with metronidazole for the benzodiazepine receptor site or supplements GABA propagation via unaffected receptors, whereas the remain-

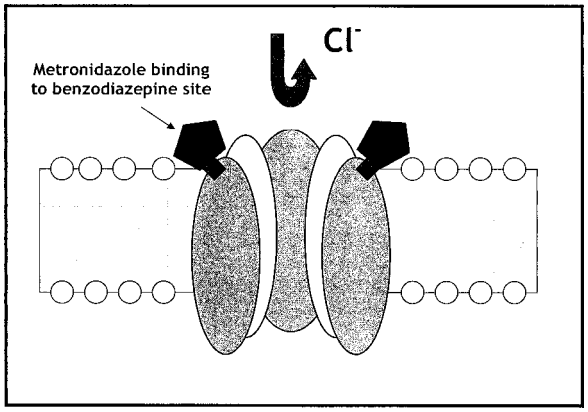

Fig 3. Diagrammatic representation of the proposed mechanism of metronidazole toxicity. Metronidazole binds to the γ-aminobutyric acid (GABA) receptor on the postsynaptic membrane and disrupts the inhibitory influence of GABA. Benzodiazepine antagonists, such as flumazenil, bind to the benzodiazepine site, competitively inhibiting the actions of benzodiazepines. Metronidazole and flumazenil share both similar chemical structure and toxic adverse effects such as ataxia and vertigo.

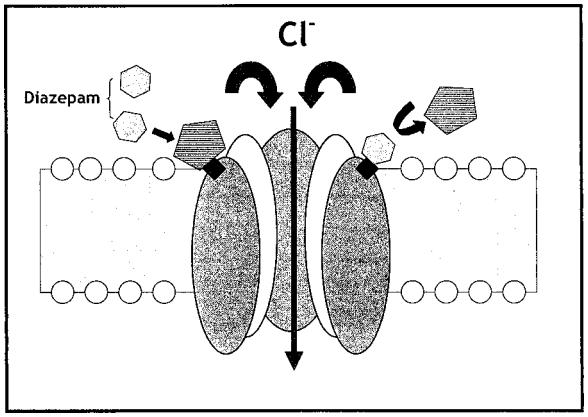

Fig 4. Diagram of the proposed mechanism for the therapeutic effect of diazepam in metronidazole toxicosis. Metronidazole produces its toxic effects by binding to the benzodiazepine site on the γ-aminobutyric acid (GABA) receptor on the postsynaptic membrane, disrupting inhibitory neurotransmission. We postulate that diazepam has a higher affinity for the benzodiazepine site than metronidazole and therefore displaces metronidazole. Removal of metronidazole not only restores normal chloride conductance but also increases benzodiazepine-induced chloride conductance (inhibition).

der of the metronidazole in the system is metabolized. It is more likely that diazepam at therapeutic concentrations competitively reverses the binding of metronidazole to the benzodiazepine site on the GABA receptor, because rebound manifestations of metronidazole toxicosis were not observed in the dogs of this study (Fig 4).

The average response time for the resolution of debilitating clinical signs in animals receiving diazepam in this study was 13 hours, with a final resolution of the remaining clinical signs (usually mild ataxia) over the next 24–48 hours. The plasma half-life of metronidazole in the dog is 3–13 hours[1]; given this fact, the question of why the clinical signs of metronidazole toxicosis are not resolved in this time simply after discontinuation of the drug also is raised. It is possible that metronidazole at toxic doses either alters the GABA receptor sufficiently to prevent a return to normal function within the anticipated time or firmly binds to the receptor and therefore is not subject to normal metabolism. From the similarities in the plasma half-life of metronidazole and the average response time of the diazepam-treated group, it could be speculated that once metronidazole is displaced from the benzodiazepine receptor by diazepam, normal metabolism of the displaced drug then occurs, resulting in the rapid clinical improvement observed. Furthermore, once metronidazole is displaced, the exogenous benzodiazepine not only restores but also enhances normal benzodiazepine-induced chloride conductance. Blood metronidazole concentrations were not measured in the dogs of this study but may have been useful as an ancillary test to further confirm the diagnosis of metronidazole toxicosis; additionally, serial posttreatment concentrations could give additional insight into the metabolic fate of metronidazole after administration of diazepam.

Nineteen of the 21 dogs of this investigation received 1 or more medications as treatment for the acute onset of neurological signs before definitive diagnosis of metronidazole toxicosis, but the influence of these medications on the results of this study was thought to be minimal to nonexistent. The 2 dogs that had received the H_1-antagonist meclizine, which generally is used to treat signs of motion sickness in humans,[48] and the 2 dogs that underwent general anesthesia all were in the untreated group. Four dogs from each group had been given either an aminopenicillin or a 1st-generation cephalosporin; methocarbamol had been given to 3 dogs of the treated group and 2 dogs of the untreated group; and butorphanol had been administered to 1 dog from each group. Neurological adverse effects such as seizures, sedation, and ataxia have been described for each of these medications, but these adverse effects have been reported rarely and only with prolonged use or very high dosages.[42,49–51] Corticosteroids, which had been administered to 6 of 8 dogs in the untreated group and to 10 of 13 dogs in the diazepam-treated group, could theoretically have induced the oxidative metabolism of metronidazole,[52] but the effect of corticosteroids was not believed to be important because their use was common in both groups, and only 1–2 doses had been given. All dogs in this study had neurological manifestations consistent with metronidazole toxicosis before administration of any of these drugs and were diagnosed with metronidazole toxicosis within 24 hours of the onset of the neurological signs. Administration of the above ancillary medications was discontinued after the diagnosis was established, making it unlikely any medication other than diazepam influenced the outcome of these dogs.

A dose-dependent or duration-dependent relationship between actual neuronal cell death or leukomalacia of the vestibulocerebellar tracts and metronidazole administration could not be determined from this study because no histopathologic evaluations were performed. Clinical and experimental studies reported neuronal changes in subjects receiving much higher dosages than the 60.3-mg/kg/d dosage received by dogs in this investigation.[8,30,31] Vestibulocerebellar axonal degeneration with no loss of neurons, however, has been reported in dogs receiving 63 mg/kg/d.[8] Al-

though the animals in this investigation recovered, the potential for permanent, subclinical damage to neurons and white matter tracts in all cases of metronidazole toxicosis exists, thereby increasing the probability that these animals will be more susceptible to the adverse effects of metronidazole in the future. Administration of metronidazole to animals previously diagnosed with metronidazole toxicosis is not recommended.[8–11]

Although the exact mechanism is not known, the use of diazepam markedly improved the recovery of animals with metronidazole toxicosis. Consequently, we recommend the use of diazepam for the treatment of metronidazole toxicosis in dogs.

Footnotes

[a] Metronidazole, Flagyl®, GD Searle & Co, Chicago, IL
[b] Diazepam, Valium®, Roche, Division of SmithKline Beecham, Exton, PA
[c] Flumazenil, Romazincon®, Roche, Division of SmithKline Beecham, Exton, PA
[d] Model 9800 GE HiLite Advantage® CT Scanner, GE Medical Systems, Milwaukee, WI
[e] Methocarbamol, Robaxin®, Fort Dodge Animal Health, Fort Dodge, IA
[f] Carprofen, Rimadyl®, Pfizer Animal Health Inc, New York, NY
[g] Meclizine, Antivert®, Solvay Animal Health Inc, Mendota Heights, MN
[h] Butorphanol, Torbugesic®, Fort Dodge Animal Health, Fort Dodge, IA
[i] Enrofloxacin, Baytril®, Miles Inc, Shawnee, KS
[j] Ciprofloxacin, Cipro®, Miles Inc, Shawnee, KS
[k] Imipenem-Cilastatin, Primaxin®, Merck & Co, West Point, PA

References

1. Finegold SM. Metronidazole. Ann Intern Med 1980;93:585–587.
2. Johnson G. Giardiasis. In: Kirk RW, ed. Current Veterinary Therapy VI. Philadelphia, PA: WB Saunders; 1977:969.
3. Garvey MS, Aucoin DP. Therapeutic strategies involving antimicrobial treatment of disseminated bacterial infection in small animals. J Am Vet Med Assoc 1984;185:1185–1189.
4. Dow SW, Jones RL, Adney WA. Anaerobic infections in dogs and cats and response to treatment: 36 cases (1985–1986). J Am Vet Med Assoc 1986;189:930–934.
5. Tams TR. Feline inflammatory bowel disease. In: Kirk RW, ed. Current Veterinary Therapy IX. Philadelphia, PA: WB Saunders; 1986: 884.
6. Rosenblatt JE, Edson RS. Metronidazole. Mayo Clin Proc 1983; 58:1564–1570.
7. Kusumi RK, Plouffe JF, Wyatt RH, et al. Central nervous system toxicity associated with metronidazole therapy. Ann Intern Med 1980; 93:59.
8. Dow SW, LeCouter RA, Poss ML, Beadleston D. Central nervous system toxicosis associated with metronidazole treatment of dogs: Five cases (1984–1987). J Am Vet Med Assoc 1989;195:365–368.
9. Fitch R, Moore M, Roen D. A warning to clinicians: Metronidazole neurotoxicity in a dog. Prog Vet Neurol 1991;2:307–309.
10. Saxon B, Magne M. Reversible central nervous system toxicosis associated with metronidazole therapy in three cats. Prog Vet Neurol 1993;4:25–27.
11. Caylor KB, Cassimatis MK. Metronidazole neurotoxicosis in two cats. J Am Anim Hosp Assoc 2001;37:258–262.
12. Dow SW. Management of anaerobic infections. Vet Clin North Am 1988;186:1167–1181.
13. McClure JA, Lycett P, Baskerville JC. Diazepam as an antimotion sickness drug. J Otolaryngol 1982;4:253–259.
14. McClure JA, Willett JM. Lorazepam and diazepam in the treatment of benign paroxysmal vertigo. J Otolaryngol 1980;6:472–477.
15. Uchide K, Suzuki N, Takiguchi T, et al. The possible effect of pregnancy on Meniere's disease. J Otorhinolaryngol Relat Spec 1997; 59:292–295.
16. Matsuoka I, Chikamori Y, Takaori S, Morimoto M. Effects of chlorpromazine and diazepam on neuronal activities of the lateral vestibular nucleus in cats. Arch Otorhinolaryngol 1975;209:89–95.
17. Pettorossi VE, Troiani D, Petrosini L. Diazepam enhances cerebellar inhibition on vestibular neurons. Acta Otolaryngol 1982;93: 363–373.
18. Matsuoka I, Takahashi H, Sasa M, Takaori S. Experimental vestibular pharmacology: A minireview with special reference to neuroactive substances and antivertigo drugs. Acta Otolaryngol 1984; 419(Suppl):62–70.
19. Barmack NH, Pettorossi VE. The influence of diazepam on the activity of secondary vestibular neurons in the rabbit. Neurosci Lett 1980;16:33–44.
20. Ryu JH, McCabe BF. Effects of diazepam and dimenhydrinate on the resting activity of the vestibular neuron. Aerospace Med 1974; 10:1117.
21. Steiner FA, Felix D. Antagonistic effects of GABA and benzodiazepines on vestibular and cerebellar neurons. Nature 1976;260: 346.
22. Overall KL. Fears and phobias—Dogs. In: Tiley LP, Smith FWK, ed. The Five-Minute Veterinary Consult. Baltimore, MD: Williams & Wilkins; 1997:66–67.
23. Polzin DJ, Osborne CA. Diseases of the urinary tract. In: Davis LE, ed. Handbook of Small Animal Therapeutics. New York, NY: Churchill Livingstone; 1985:333–395.
24. Cochrane SM. Geriatric vestibular disease. In: Tiley LP, Smith FWK, ed. The Five-Minute Veterinary Consult. Baltimore, MD: Williams & Wilkins; 1997:1150–1151.
25. MacDonald RL, McLean MJ. Cellular basis of barbiturate and phenytoin anticonvulsant drug action. Epilepsia 1982;23:s7–s18.
26. Bonanno G, Raiteri M. Multiple $GABA_b$ receptors. Trends Pharmacol Sci 1993;14:259–261.
27. Bloom F. Neurotransmission and the central nervous system. In: Hardman JG, Limbird LE, ed. Pharmacological Basis for Therapeutics, 9th ed. New York, NY: McGraw Hill; 1996:267–293.
28. Martin J, Gilchrist DP, Smith PF, Darlington CL. Early diazepam treatment following unilateral labyrinthectomy does not impair vestibular compensation of spontaneous nystagmus in guinea pig. J Vestib Res 1996;6:135–139.
29. Ishikawa K, Igarashi M. Effect of diazepam on vestibular compensation in squirrel monkeys. Arch Otorhinolaryngol 1984;240:49–54.
30. Scharer K. Selective Purkinje-Zellschadigungen nach oraler Verabreichung grosser Dosen von Nitroimidazol-Derivaten am Hund. Verh Dtsch Ges Pathol 1972;56:407–410.
31. Rogulja PV, Kovac W, Schmid H. Metronidazol-Encephalopathie der Ratt. Acta Neuropathol (Berl) 1973;25:36–45.
32. Jenkins TW. Functional Mammalian Neuroanatomy, 2nd ed. Philadelphia, PA: Lea & Febiger; 1978:238–251.
33. DeLahunta A. Veterinary Neuroanatomy and Clinical Neurology, 2nd ed. Philadelphia, PA: WB Saunders; 1983:255–278.
34. Chan-Palay V, Palay SL, Wu JY. Gamma amino butyric acid pathways in the cerebellum studied by retrograde and anterograde transport of glutamic decarboxylase antibody after in vivo injections. Anat Embryol 1979;157:1.
35. Henneman E. The cerebellum. In: Mountcastle VB, ed. Medical Physiology, 13th ed. St Louis, MO: CV Mosby; 1974:633–655.

36. Bowery NG. $GABA_b$ receptor pharmacology. Annu Rev Pharmacol Toxicol 1993;33:109–147.

37. Otsuka M. Gamma amino butyric acid and some other transmitter candidates in the nervous system. In: Acheson GH, Bloom FE, ed. Pharmacology and the Future of Man. Proceedings of the Fifth International Congress on Pharmacology, San Francisco, CA, 1973;4: 186–201.

38. Schofield PR, Darlison MG, Fujita N, et al. Sequence and functional expression of the $GABA_a$ receptor shows a ligand-gated receptor superfamily. Nature 1987;328:221–227.

39. Pritchett DB, Sonthiemer H, Shivers BD, et al. Importance of a novel GABAa receptor subunit for benzodiazepine pharmacology. Nature 1989;338:582–585.

40. Burt DR, Kamatchi GL. $GABA_a$ receptor subtypes: From pharmacology to molecular biology. FASEB J 1991;5:2916–2923.

41. Gardner CR. Functional in vivo correlates of the benzodiazepine agonist-inverse agonist continuum. Prog Neurobiol 1988;31:425–476.

42. Semel JD, Allen N. Seizures in patients simultaneously receiving theophylline and imipenem or ciprofloxacin or metronidazole. South Med J 1991;84:465–468.

43. Potokar J, Nutt DJ. Anxiolytic potential of benzodiazepines receptor partial agonists. CNS Drugs 1994;1:305–315.

44. Haefely W. Antagonists of benzodiazepines: Functional aspects. Adv Biochem Psychopharmacol 1983;38:73–93.

45. Roncari G, Timm U, Zell M, et al. Flumazenil kinetics in the elderly. Eur J Clin Pharmacol 1993;45:585–587.

46. Brogden RN, Goa KL. Flumazenil: A preliminary review of its benzodiazepine antagonist properties, intrinsic activity and therapeutic use. Drugs 1988;35:448–467.

47. Hoffman EJ, Warren EW. Flumazenil: A benzodiazepine antagonist. Clin Pharmacol 1993;12:814–828.

48. Cohen B, DeJong JMBV. Meclizine and placebo in treating vertigo of vestibular origin. Relative efficacy in a double-blinded study. Arch Neurol 1972;27:129–135.

49. Mandell GL, Petri WA. Penicillins, cephalosporins and other beta-lactam antibiotics. In: Hardman JG, Limbird LE, ed. Pharmacological Basis for Therapeutics, 9th ed. New York, NY: McGraw Hill; 1996:1073–1101.

50. Fingeroth JM. Treatment of canine intervertebral disk disease: Recommendations and controversies. In: Kirk RW, ed. Current Veterinary Therapy XII. Philadelphia, PA: WB Saunders; 1995:1148.

51. Jenkins WL. Pharmacological aspects of analgesic drugs in animals: An overview. J Am Vet Med Assoc 1987;191:1231–1240.

52. Lau AH, Lam NP, Piscitelli SC, et al. Clinical pharmacokinetics of metronidazole and other nitroimidazole anti-infectives. Clin Pharmacokinet 1992;23:328–364.