

ORIGINAL ARTICLE

Survival after Treatment with Phenylacetate and Benzoate for Urea-Cycle Disorders

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ABSTRACT

BACKGROUND

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The combination of intravenous sodium phenylacetate and sodium benzoate has been shown to lower plasma ammonium levels and improve survival in small cohorts of patients with historically lethal urea-cycle enzyme defects.

METHODS

We report the results of a 25-year, open-label, uncontrolled study of sodium phenylacetate and sodium benzoate therapy (Ammonul, Ucylyd Pharma) in 299 patients with urea-cycle disorders in whom there were 1181 episodes of acute hyperammonemia.

RESULTS

Overall survival was 84% (250 of 299 patients). Ninety-six percent of the patients survived episodes of hyperammonemia (1132 of 1181 episodes). Patients over 30 days of age were more likely than neonates to survive an episode (98% vs. 73%, $P<0.001$). Patients 12 or more years of age (93 patients), who had 437 episodes, were more likely than all younger patients to survive (99%, $P<0.001$). Eighty-one percent of patients who were comatose at admission survived. Patients less than 30 days of age with a peak ammonium level above 1000 μmol per liter (1804 μg per deciliter) were least likely to survive a hyperammonemic episode (38%, $P<0.001$). Dialysis was also used in 56 neonates during 60% of episodes and in 80 patients 30 days of age or older during 7% of episodes.

CONCLUSIONS

Prompt recognition of a urea-cycle disorder and treatment with both sodium phenylacetate and sodium benzoate, in conjunction with other therapies, such as intravenous arginine hydrochloride and the provision of adequate calories to prevent catabolism, effectively lower plasma ammonium levels and result in survival in the majority of patients. Hemodialysis may also be needed to control hyperammonemia, especially in neonates and older patients who do not have a response to intravenous sodium phenylacetate and sodium benzoate.

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UREA-CYCLE DISORDERS ARE INBORN ERRORS of metabolism that are characterized by episodic, life-threatening hyperammonemia resulting from partial or complete inactivity of enzymes responsible for eliminating nitrogenous waste. Historically, mortality and morbidity have been very high, and survivors commonly have had devastating neurologic sequelae.¹ Initial efforts to remove accumulated ammonium in patients with hyperammonemic encephalopathy included lactulose therapy,² exchange transfusion,^{3,4} peritoneal dialysis,⁴ hemodialysis,⁵ and supplementation with nitrogen-free analogues of essential amino acids.⁶ These treatments prolonged survival in some patients, but the overall efficacy was disappointing — and mortality and morbidity remained high.

Current therapeutic strategies include reducing the production of nitrogenous waste with the use of a low-protein diet and preventing endogenous catabolism through the provision of adequate nutrition. In addition, exploitation of alternative pathways for excretion of waste nitrogen has played a critical role in the management of urea-cycle disorders since Brusilow and colleagues first suggested using endogenous biosynthetic pathways to eliminate non-urea-waste nitrogen as a substitute for defective urea synthesis.⁷ In theory, the total body load of nitrogen can be decreased, despite abnormal urea-cycle functioning, by promoting the synthesis of non-urea nitrogen-containing metabolites that have high excretion rates or rates that may be augmented.⁷⁻¹¹ The first successful demonstration of this concept was the use of arginine supplementation for the treatment of argininosuccinate lyase deficiency.⁹

An open-label, uncontrolled, multicenter study of intravenous sodium phenylacetate and sodium benzoate combined (Ammonul, Ucylyd Pharma) as an emergency treatment for hyperammonemia in patients with urea-cycle disorders was conducted in the United States and Canada from 1980 to 2005. The primary purpose of the study was to determine whether treatment with sodium phenylacetate and sodium benzoate reduced mortality due to acute hyperammonemia, as compared with historical data.

METHODS

STUDY DESIGN

We conducted an open-label, uncontrolled, nonrandomized study at 118 hospitals in the United States

and Canada between August 1980 and March 2005. The patients included in the study were hospitalized because of hyperammonemia resulting from a urea-cycle defect. A total of 299 patients with urea-cycle disorders and 1181 episodes of hyperammonemia were included. Four patients for whom demographic data were incomplete were excluded. To enroll a patient, the investigator contacted one of the authors (S.W.B.) at Johns Hopkins School of Medicine (from 1982 through 1996), or Ucylyd Pharma (from 1997 through 2005), which supplied the study drug and case-report forms. The institutional review board at each participating institution approved the study. Written informed consent was obtained from the parents or legal guardians of children enrolled and from adult patients.

TREATMENT

Infants and children (weighing up to 20 kg [44 lb]) who had carbamyl phosphate synthetase deficiency, ornithine transcarbamylase deficiency, or argininosuccinate synthetase deficiency were treated with an initial (loading) dose of sodium phenylacetate (250 mg per kilogram of body weight) and sodium benzoate (250 mg per kilogram) administered intravenously over a period of 90 to 120 minutes. Older children (weighing more than 20 kg) and adults were treated with sodium phenylacetate and sodium benzoate, 5.5 g per square meter of body-surface area, as an intravenous loading dose over a period of 90 to 120 minutes. After the loading dose, maintenance infusions of the same dose were continued over 24 hours until the patient no longer had hyperammonemia and oral therapy could be tolerated. Among the factors limiting tolerance were vomiting, decreased intestinal motility, and the presence of umbilical catheters. Intravenous ondansetron (Zofran, GlaxoSmithKline) (0.15 mg per kilogram) was used in some patients to prevent or treat hyperemesis. Guidelines for administering sodium phenylacetate and sodium benzoate were not available for the treatment of argininosuccinate lyase deficiency or arginase deficiency. Loading and maintenance infusions also contained arginine hydrochloride (210 mg per kilogram for patients with ornithine transcarbamylase deficiency or carbamyl phosphate synthetase deficiency, and 630 mg per kilogram for patients with argininosuccinate synthetase deficiency or argininosuccinate lyase deficiency). Although a dialysis protocol was not used, dialysis, as noted below, was recommended for any neonate with hyperammonemic encephalopathy or any oth-

er patient in whom the ammonium level did not decrease substantially within 8 hours after administration of the loading infusion. Not all investigators followed these treatment guidelines precisely.

ASSESSMENT

The primary end point was survival of the episode of hyperammonemia. When a patient died, the investigator was asked to identify the primary and secondary causes of the death and to assess the relationship of the death to the primary disease and to the study drug. Plasma ammonium data were collected and analyzed according to a schedule determined by each investigator.

STATISTICAL ANALYSIS

Data were summarized with the use of descriptive statistics. An episode was defined as a single hospitalization for hyperammonemia. For comparisons according to age and diagnosis, *P* values for survival were calculated with the use of Fisher's exact test for each category, as compared with all other categories. For the comparison according to peak ammonium level, *P* values for survival were calculated with the use of Fisher's exact test for each category of ammonium level, as compared with all categories of lower ammonium levels.

Outcome at discharge (survival vs. death) was also compared according to coma status at admission. Separate analyses according to coma status at admission were performed for all episodes and for different age groups and enzyme deficiency. *P* values were calculated with the use of the McNemar test for the comparison between outcome at discharge (alert vs. comatose vs. deceased) and coma status at admission (coma vs. no coma).

RESULTS

SURVIVAL

Over the 25 years of the study, 299 patients with urea-cycle disorders were treated with sodium phenylacetate and sodium benzoate for a total of 1181 episodes of hyperammonemia. The patients included 93 neonates (94 episodes) and 237 patients older than 30 days of age (1087 episodes) (Table 1 and Fig. 1). Thirty-one patients were treated both as neonates and as older patients and thus were included in the totals for both groups. The mean (\pm SD) number of episodes per patient was 3.3 ± 6.3 (range, 1 to 79). Dialysis (including standard hemo-

dialysis, various combinations of arteriovenous and venovenous hemofiltration, and peritoneal dialysis) was used during 136 of the 1181 episodes (12%) and in 105 of 299 patients (35%). Dialysis was used more commonly in neonates (56 neonates, 60% of episodes) than in older patients (80 patients, 7% of episodes). Peritoneal dialysis with no other form of dialysis was used in six neonates and was used in combination with hemodialysis, a form of hemofiltration, or both in four neonates and two older patients. Overall the rate of survival (defined as survival of all known episodes for each patient) was 84% (250 of 299 patients) (Table 1). The survival rate for hyperammonemic episodes was 96% (1132 of 1181 episodes). Patients more than 30 days of age were more likely to survive an episode of hyperammonemia than were neonates (survival rates, 98% and 73%, respectively; $P<0.001$). Patients more than 12 years of age (93 patients, 437 episodes) were most likely to survive an episode of hyperammonemia (survival rate, 99%; $P<0.001$, as compared with all other age groups) (Table 2).

The survival rate for episodes of hyperammonemia was significantly lower among male patients with ornithine transcarbamylase deficiency (91%) than among female patients with the same deficiency (98%) and among patients with a deficiency of carbamyl phosphate synthetase, argininosuccinate synthetase, or argininosuccinate lyase ($P<0.001$) (Table 2). The survival rate appeared to be lower among patients with arginase deficiency (80%) than among those with a deficiency of ornithine transcarbamylase, carbamyl phosphate synthetase, argininosuccinate synthetase, or argininosuccinate lyase but the difference did not reach statistical significance (Table 2); there were only five episodes reported in patients with arginase deficiency. Indeed, the single patient with arginase deficiency who died had neonatal sepsis and relatively mild hyperammonemia ($<200\ \mu\text{mol per liter}$ [$361\ \mu\text{g per deciliter}$]).

Thirteen of the 49 patients who died received sodium phenylacetate and sodium benzoate in amounts that were greater than the recommended doses. Of these 13 patients, 7 received a bolus dose of sodium phenylacetate and sodium benzoate ranging from 370 to 620 mg per kilogram. One patient was given a bolus dose of sodium phenylacetate and sodium benzoate approximately 9 times higher than that recommended (2310 mg of each medication per kilogram). In addition, seven patients were given multiple (range, one to

Table 1. Survival According to Diagnosis and Age at Presentation.

Variable	Carbamyl Phosphate Synthetase Deficiency	Ornithine Transcarbamylase Deficiency		Argininosuccinate Synthetase Deficiency	Argininosuccinate Lyase Deficiency	Overall Survival*
	All Patients (N=41)	Male Patients (N=86)	Female Patients (N=78)	All Patients (N=80)	All Patients (N=11)	All Patients (N=299)
	<i>number/total number (percent)</i>					
Survived first known episode	37/41 (90)	66/86 (77)	70/78 (90)	75/80 (94)	10/11 (91)	260/299 (87)
Age ≤30 days	9/12 (75)	24/40 (60)	2/3 (67)	28/32 (88)	5/5 (100)	68/93 (73)
Age >30 days	28/29 (97)	42/46 (91)	69/75 (92)	47/48 (98)	5/6 (83)	193/206 (94)
Survived all known episodes	34/41 (83)	61/86 (71)	69/78 (88)	73/80 (91)	10/11 (91)	250/299 (84)
Neonatal onset (age ≤30 days)	8/12 (67)	21/40 (53)	2/3 (67)	27/32 (84)	5/5 (100)	63/93 (68)
Presumed late onset (age >30 days)	27/29 (93)	40/46 (87)	68/75 (91)	46/48 (96)	5/6 (83)	188/206 (91)

* Three patients with arginase deficiency were treated with sodium phenylacetate and sodium benzoate; one had neonatal onset of the disease and died during the first episode, and two had a total of four episodes and survived. Because ornithine transcarbamylase deficiency is an X-linked disorder, male patients typically have a more severe clinical phenotype than do female patients, so for this disorder a distinction on the basis of sex was made.

seven) additional bolus infusions of sodium phenylacetate and sodium benzoate after administration of the initial bolus. Two other male patients with ornithine transcarbamylase deficiency were given high maintenance doses of each medication (an 18-year-old was given 6.25 g per square meter of body-surface area over a 23-hour period and a neonate 4380 mg per kilogram over a 25-hour period).

The majority of patients had adverse events during treatment for hyperammonemia; disorders of the metabolic system, the nervous system, and the respiratory system were most commonly reported (Table 3). In the 49 patients who died, coexisting conditions were common and included seizures (19 patients), infection (18), cerebral edema or increased intracranial pressure (16), disseminated intravascular coagulation (9), kidney failure (6), multiorgan system failure (5), and cerebral hemorrhage (5).

SURVIVAL AND COMA AT ADMISSION

Among 209 patients, there were 1020 episodes of hyperammonemia without coma at the time of admission. When coma was not present on admission, in the overwhelming majority (992) of these episodes (97%), coma was also absent at the time of discharge. However, 22 episodes in which coma was absent on admission resulted in death (2%), and in 6 episodes (<1%) coma persisted at the time

of discharge (five patients with coma at discharge were transferred to other hospitals for treatment with dialysis, and one was transferred to another center for liver transplantation). Among 82 patients, there were 120 episodes in which the patients were comatose on admission. Overall, when patients were comatose on admission, no coma was present at the time of discharge (97 episodes, 81%); 23 episodes in which the patients were comatose at admission resulted in death (19%) (Table 2).

The survival rate for hyperammonemic episodes was significantly lower among patients who were comatose at admission, both among neonates ($P=0.002$) and among older patients ($P<0.001$). Children 2 to 12 years of age who were comatose at admission had a relatively lower rate of survival of a hyperammonemic episode (79%) than those in other groups over 30 days of age. The survival rate was lowest among male patients with ornithine transcarbamylase deficiency who were comatose at admission (68%) (Table 2).

SURVIVAL AND PEAK AMMONIUM LEVEL

Survival was significantly improved for patients who had hyperammonemic episodes with a peak plasma ammonium level of 500 μmol per liter (902 μg per deciliter) or less than among those with higher peak ammonium levels ($P<0.001$). Patients less than 30 days of age with a peak ammonium

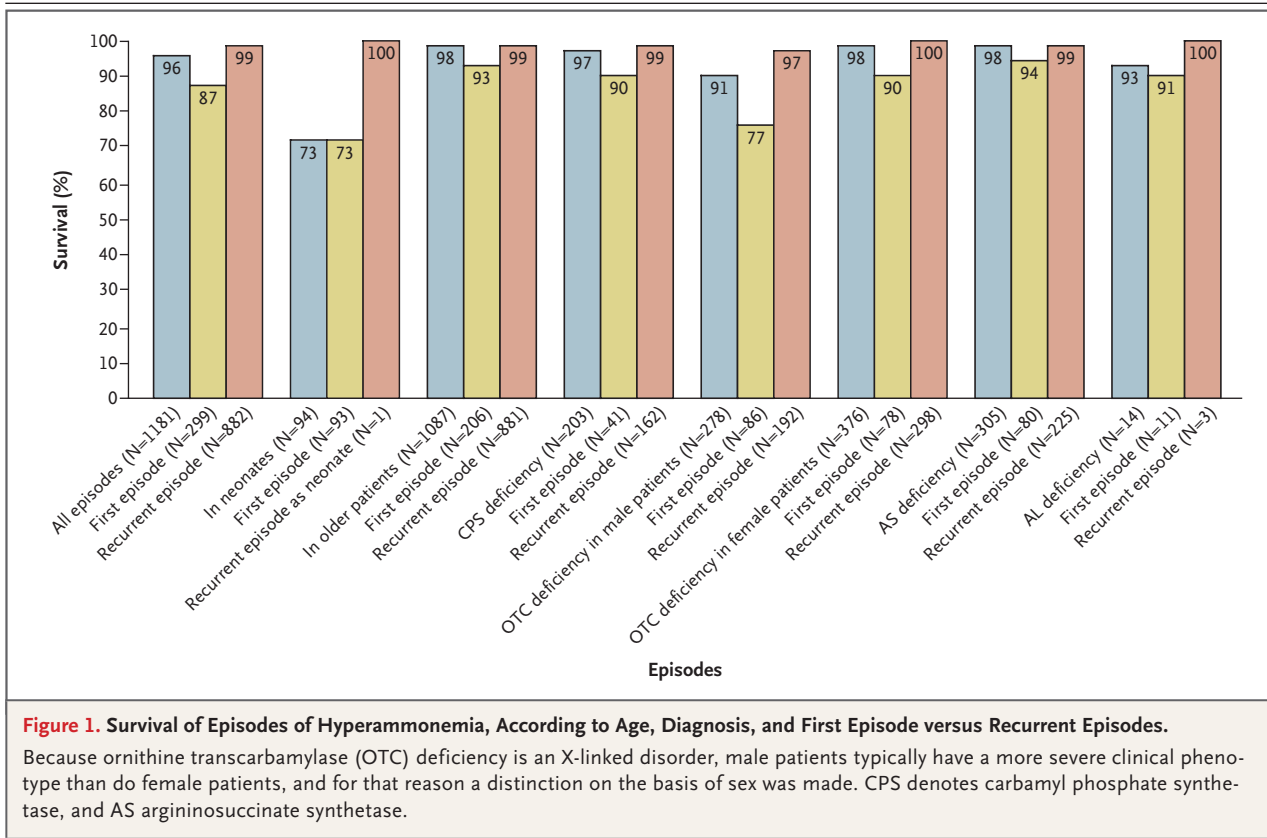


Figure 1. Survival of Episodes of Hyperammonemia, According to Age, Diagnosis, and First Episode versus Recurrent Episodes.

Because ornithine transcarbamylase (OTC) deficiency is an X-linked disorder, male patients typically have a more severe clinical phenotype than do female patients, and for that reason a distinction on the basis of sex was made. CPS denotes carbamyl phosphate synthetase, and AS argininosuccinate synthetase.

level greater than 1000 μmol per liter (1804 μg per deciliter) were least likely to survive a hyperammonemic episode (survival, 38%; $P < 0.001$) (Table 4 and Fig. 2).

CHANGES IN AMMONIUM LEVELS

Plasma ammonium levels decreased substantially in most patients after therapy with the use of the intravenous treatment protocol (alternative-pathway therapy for nitrogen excretion). For all episodes in which both a baseline ammonium level (the last value recorded before treatment with sodium phenylacetate and sodium benzoate plus arginine hydrochloride was begun) and the level measured after treatment was initiated were known (582 patients), the median ammonium level fell from 185 μmol per liter (334 μg per deciliter) to 36 μmol per liter (65 μg per deciliter) at the final assessment (–79% change from baseline). Plasma ammonium levels decreased substantially in both neonates and older patients, although the median ammonium levels were markedly higher in neonates than in older patients at baseline. Among patients who died, median ammonium levels were similar at baseline and at the final assessment

(334 and 364 μmol per liter [603 and 657 μg per deciliter] among neonates and 168 and 116 μmol per liter [303 and 209 μg per deciliter] among older patients, respectively). Median ammonium levels decreased substantially in patients who survived (from 374 to 24 μmol per liter [675 to 43 μg per deciliter] among neonates and 179 to 36 μmol per liter [323 to 65 μg per deciliter] among older patients).

DISCUSSION

Historically, survival among patients with urea-cycle disorders was poor after episodes of hyperammonemia; most children with a severe enzyme deficiency died as neonates — and few survived infancy.^{1,12,13} In 1979, Brusilow et al. hypothesized that hyperammonemic coma caused by urea-cycle disorders might be treated with a combination of sodium phenylacetate and sodium benzoate.⁷ The potential of the use of alternative pathways of nitrogen excretion to treat hyperammonemic coma was demonstrated soon thereafter; the administration of sodium benzoate either orally or intravenously in four patients

Table 2. Outcomes of 1181 Episodes of Hyperammonemia, According to Age, Diagnosis, and Coma Status at Admission.*

Variable	Status at Discharge			P Value†	Survival <i>no. of patients/ total no. (%)</i>	P Value‡
	Alert	Comatose	Dead			
	<i>no. of patients/total no. (%)</i>					
All episodes				<0.001	1132/1181 (96)	
Coma at admission	97/120 (81)	0	23/120 (19)			
No coma at admission	992/1020 (97)	6/1020 (<1)	22/1020 (2)			
Age group						
≤30 days (94 episodes)				0.002	69/94 (73)	<0.001
Coma at admission	28/43 (65)	0	15/43 (35)			
No coma at admission	37/46 (80)	0	9/46 (20)			
>30 days (1087 episodes)				<0.001	1063/1087 (98)	
Coma at admission	69/77 (90)	0	8/77 (10)			
No coma at admission	955/974 (98)	6/974 (<1)	13/974 (1)			
>30 days to 2 yr (171 episodes)				0.13	168/171 (98)	0.10
Coma at admission	8/8 (100)	0	0			
No coma at admission	155/159 (97)	1/159 (<1)	3/159 (2)			
>2 to 12 yr (479 episodes)				0.005	464/479 (97)	0.18
Coma at admission	22/28 (79)	0	6/28 (21)			
No coma at admission	430/439 (98)	2/439 (<1)	7/439 (2)			
>12 yr (437 episodes)				<0.001	431/437 (99)	<0.001
Coma at admission	39/41 (95)	0	2/41 (5)			
No coma at admission	370/376 (98)	3/376 (<1)	3/376 (<1)			
Diagnosis						
Carbamyl phosphate synthetase deficiency (203 episodes)				0.11	197/203 (97)	0.44
Coma at admission	10/12 (83)	0	2/12 (17)			
No coma at admission	177/184 (96)	3/184 (2)	4/184 (2)			
Ornithine transcarbamylase deficiency						
Male patients (278 episodes)				0.02	253/278 (91)	<0.001
Coma at admission	23/34 (68)	0	11/34 (32)			
No coma at admission	218/228 (96)	0	10/228 (4)			
Female patients (376 episodes)				0.001	367/376 (98)	0.04
Coma at admission	18/24 (75)	0	6/24 (25)			
No coma at admission	340/344 (99)	1/344 (<1)	3/344 (<1)			
Argininosuccinate synthetase deficiency (305 episodes)				<0.001	298/305 (98)	0.07
Coma at admission	37/40 (93)	0	3/40 (7)			
No coma at admission	250/256 (98)	2/256 (<1)	4/256 (2)			
Argininosuccinate lyase deficiency (14 episodes)				0.03	13/14 (93)	0.45
Coma at admission	7/7 (100)	0	0			
No coma at admission	5/6 (83)	0	1/6 (17)			

* Three patients with arginase deficiency were treated with sodium phenylacetate and sodium benzoate; one had neonatal onset of the disease and died during the first episode, and two had a total of four episodes and survived. Because ornithine transcarbamylase deficiency is an X-linked disorder, male patients typically have a more severe clinical phenotype than do female patients, so for this disorder a distinction on the basis of sex was made. Patient status at discharge was based on the number of episodes of hyperammonemia for which coma status at both admission and discharge were known (291 patients and 1140 episodes).

† P values were calculated with the use of the McNemar test for the comparison between survival status at discharge (alert plus comatose vs. deceased) and coma status at admission (coma vs. no coma).

‡ P values were calculated with the use of Fisher's exact test for the comparison between survival status in each age subgroup and all other age subgroups and between each subgroup according to diagnosis and all other subgroups according to diagnosis.

Table 3. Reported Adverse Events in Patients with Urea-Cycle Disorders Treated with Sodium Phenylacetate and Sodium Benzoate.*

Variable	Neonates		Older Patients	
	Patients (N=93)	Episodes of Hyperammonemia (N=94)	Patients (N=239)	Episodes of Hyperammonemia (N=1087)
	<i>number (percent)</i>			
Total no.†	50 (54)	50 (53)	125 (52)	299 (28)
Blood and lymphatic system disorders	11 (12)	11 (12)	20 (8)	21 (2)
Anemia	5 (5)	5 (5)	7 (3)	8 (<1)
Disseminated intravascular coagulation	3 (3)	3 (3)	6 (3)	6 (<1)
Thrombocytopenia	3 (3)	3 (3)	1 (<1)	1 (<1)
Cardiac disorders	9 (10)	9 (10)	17 (7)	23 (2)
Cardiac arrest	3 (3)	3 (3)	2 (<1)	2 (<1)
Tachycardia	2 (2)	2 (2)	8 (3)	13 (1)
Supraventricular tachycardia	2 (2)	2 (2)	0	0
Gastrointestinal disorders	5 (5)	5 (5)	42 (18)	94 (9)
Vomiting	3 (3)	3 (3)	29 (12)	70 (6)
Diarrhea	1 (1)	1 (1)	10 (4)	10 (<1)
General disorders and administration-site conditions	7 (8)	7 (7)	34 (14)	72 (7)
Injection-site reactions	1 (1)	1 (1)	30 (13)	43 (4)
Fever	0	0	16 (7)	25 (2)
Hepatobiliary disorders	3 (3)	3 (3)	5 (2)	5 (<1)
Infections and infestations	7 (8)	7 (7)	33 (14)	44 (4)
Urinary tract infection	0	0	11 (5)	11 (1)
Otitis media	0	0	5 (2)	6 (<1)
Metabolism and nutrition disorders	20 (22)	20 (21)	56 (23)	85 (8)
Hypokalemia	5 (5)	5 (5)	27 (11)	35 (3)
Hyperammonemia	5 (5)	5 (5)	13 (5)	22 (2)
Hyperglycemia	5 (5)	5 (5)	12 (5)	14 (1)
Acidosis	4 (4)	4 (4)	18 (8)	20 (2)
Nervous system disorders	17 (18)	17 (18)	63 (26)	90 (8)
Seizures	8 (9)	8 (9)	25 (10)	29 (3)
Cerebral edema	3 (3)	3 (3)	12 (5)	13 (1)
Mental impairment	1 (1)	1 (1)	22 (9)	27 (2)
Psychiatric disorders	1 (1)	1 (1)	20 (8)	31 (3)
Agitation	0	0	10 (4)	10 (<1)
Renal and urinary disorders	4 (4)	4 (4)	6 (3)	6 (<1)
Respiratory, thoracic, and mediastinal disorders	13 (14)	13 (14)	35 (15)	56 (5)
Respiratory distress or failure	7 (8)	7 (7)	13 (5)	15 (1)
Hyperventilation	1 (1)	1 (1)	5 (2)	8 (<1)
Skin and subcutaneous-tissue disorders	3 (3)	3 (3)	17 (7)	29 (3)
Vascular disorders	12 (13)	12 (13)	12 (5)	12 (1)
Hypotension	12 (13)	12 (13)	4 (2)	4 (<1)

* Reported adverse events are shown according to patient's age, frequency of occurrence event, and frequency of occurrence during episodes of hyperammonemia.

† Some patients had more than one adverse event.

Table 4. Outcomes of 823 Episodes of Hyperammonemia, According to Age and Peak Ammonium Level.*

Episode	Survival no. of episodes/total no. (%)	P Value†
Peak ammonium level		
≤200 μmol/liter	341/347 (98)	
>200–500 μmol/liter	361/366 (99)	0.77
>500–1000 μmol/liter	56/67 (84)	<0.001
>1000 μmol/liter	20/43 (47)	<0.001
Peak ammonium level at age ≤30 days (74 episodes)		
≤200 μmol/liter	9/10 (90)	
>200–500 μmol/liter	17/18 (94)	1.00
>500–1000 μmol/liter	13/17 (76)	0.18
>1000 μmol/liter	11/29 (38)	<0.001
Peak ammonium level at age >30 days to 2 yr (119 episodes)		
≤200 μmol/liter	49/50 (98)	
>200–500 μmol/liter	55/55 (100)	0.48
>500–1000 μmol/liter	5/6 (83)	0.11
>1000 μmol/liter	7/8 (88)	0.19
Peak ammonium level at age >2 yr to 12 yr (305 episodes)		
≤200 μmol/liter	140/143 (98)	
>200–500 μmol/liter	129/132 (98)	1.00
>500–1000 μmol/liter	23/28 (82)	0.001
>1000 μmol/liter	0/2	0.002
Peak ammonium level at age >12 yr (325 episodes)		
≤200 μmol/liter	143/144 (99)	
>200–500 μmol/liter	160/161 (99)	1.00
>500–1000 μmol/liter	15/16 (94)	0.14
>1000 μmol/liter	2/4 (50)	0.001

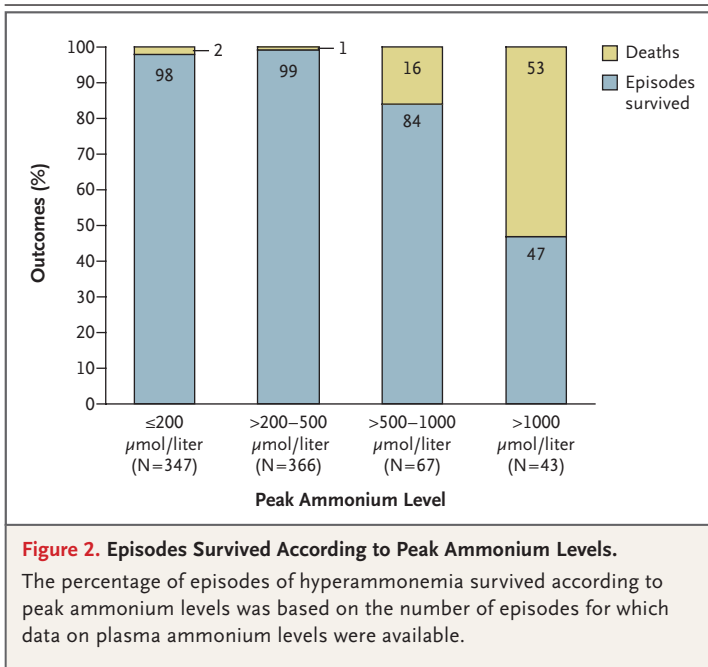
* Survival according to peak ammonium level was based on the number of episodes for which ammonium data were available. To convert values for ammonium to micrograms per deciliter, divide by 0.5543.

† P values were calculated by Fisher's exact test for the comparison between survival status for subgroups according to peak ammonium level and subgroups according to all lower peak ammonium levels (≤200 μmol/liter for the comparison with >200 to 500 μmol/liter; ≤200 μmol/liter and >200 to 500 μmol/liter for the comparison with >500 to 1000 μmol/liter).

with urea-cycle disorders who were in hyperammonemic coma resulted in a prompt decrease in the plasma ammonium level and clinical improvement.¹⁴ In an additional study involving 26 patients with urea-cycle disorders who had hyperammonemia, prolonged survival and improved clinical outcome were observed after treatment with intravenous sodium benzoate and arginine hydrochloride, dietary restriction of protein, provision of adequate calories, and peritoneal dialysis.¹⁵ Subsequently, a study involving seven children with urea-cycle disorders showed that a combination of intravenous sodium phenylacetate, sodium benzoate,

and arginine hydrochloride, with non-nitrogenous intravenous hyperalimentation, could lower plasma ammonium to normal or near-normal levels.¹⁶

The 299 patients with urea-cycle disorders in the present observational study sustained 1181 episodes of hyperammonemia over a 25-year period, with a survival rate of 96% (neonates, 73%; patients more than 30 days old, 98%) and a rate of overall survival of 84%. The use of alternative-pathway therapy in addition to provision of appropriate nutrition and, in some cases, the use of dialysis, clearly improved survival, as compared with historical data. Because the patients were treated



primarily at metabolic centers with experience in caring for acute hyperammonemia caused by urea-cycle disorders, the high rate of survival probably reflects, in part, the expertise available at the treating institutions. In addition, these survival statistics apply only to patients who received the study drug and may not apply to all patients with urea-cycle disorders. Some patients may not have been treated because their condition was poor on presentation, and others may have died without hospitalization. Despite these possibilities, the survival rate in our cohort is remarkable and confirms the promise of initial reports showing improved survival after alternative-pathway therapy in a relatively small number of patients with urea-cycle disorders.^{9,15,16} This point is further highlighted when data for the current cohort are compared with recently reported outcome data for 217 patients with urea-cycle disorders who did not receive alternative-pathway therapy for acute management of hyperammonemia.¹⁷ Of those patients, only 16% with neonatal onset of the disease survived overall, and survival among those with late onset of disease was 72%.¹⁷

Not surprisingly, patients were more likely to survive if they were not comatose at the time of admission. However, the majority (81%) of patients who were comatose at admission survived. Survival was also related to the peak plasma ammonium level and to age. Nearly all episodes in which

the ammonium level did not exceed 500 μmol per liter (902 μg per deciliter) resulted in survival, with survival decreasing with rising ammonium levels. A substantial decrease in plasma ammonium levels was noted in survivors, but not in those who died after a hyperammonemic crisis. This finding may reflect the presence of a severe accumulation of waste nitrogen that was refractory to treatment. It is also possible that treatment was withdrawn in some cases because of poor clinical status and prognosis, leading to persistently high ammonium levels.

Adverse events were reported in just over 50% of treated patients (Table 3). However, most adverse events were likely to be related to the underlying primary disease or the patient's clinical status. Among those who died, seizures, infection, and cerebral edema were the most common coexisting conditions. Cerebral edema or increased intracranial pressure was documented by investigators in 16 of 49 deaths but, given the reported elevated levels of ammonium, was likely to have been present in nearly all cases. An overdose of sodium phenylacetate and sodium benzoate was also reported relatively frequently in patients who died and was noted in 13 cases. Massive overdose was uncommon, with two instances of doses between 9 and 17 times the recommended dose of sodium phenylacetate and sodium benzoate documented. It is likely that many of the cases of mild overdosing (e.g., one or two additional bolus infusions given over several days) are a reflection of the severity of the episode of hyperammonemia and the poor clinical status of patients who eventually died. Continuous high rates of intravenous infusion may result in plasma phenylacetate levels that saturate the capacity for conversion of phenylacetate to phenylacetylglutamine, leading to rapid accumulation of phenylacetate and subsequent toxicity.^{18,19} Clearly written medical prescriptions and cross-checking of drug doses are important safeguards. Furthermore, because the *N*-acyltransferases that conjugate glutamine and glycine to phenylacetate and benzoate, respectively, are located in the liver and kidney, patients with liver or kidney failure or both may not be candidates for these medications.

Various neurologic outcomes among patients treated with sodium phenylacetate and sodium benzoate have been documented.^{15,20} Of 23 survivors of neonatal hyperammonemic coma treated with sodium phenylacetate and sodium benzoate,

10 had normal development, 7 had mild mental retardation, and 6 had moderate-to-severe mental retardation.¹⁵ Another study documented mental impairment in the majority of children (26) surviving neonatal episodes of hyperammonemic coma, with 79% having one or more developmental disabilities at 12 to 74 months of age.²⁰ Nevertheless, normal intelligence is clearly possible after a hyperammonemic event and appears to depend on the duration of coma and the extent of brain damage.^{15,20-22} The establishment of a network of specialized centers with expertise in providing state-of-the-art treatment for metabolic disorders offers the potential for improving neurologic outcomes.²³ To this end, the National Institutes of Health sponsored the formation of a Rare Disease Clinical Research Center Network for urea-cycle disorders. The prospective treatment of neonates at risk for hyperammonemia and the use of liver transplantation in patients with urea-cycle disorders both play a significant role in the treatment of such patients and may improve outcome.²⁴⁻²⁷ Hepatocyte transplantation has been attempted in a few patients with urea-cycle disorders and holds promise for the future.²⁸

Alternative-pathway therapy was effective in lowering plasma ammonium levels in most patients. However, dialysis was frequently used in neonates (60%) and used relatively rarely in older patients (7%), findings that reflect common clinical practice. One accepted type of therapy for neonates with hyperammonemic coma and ammonium levels greater than 300 μmol per liter (541 μg per deciliter) is to initiate hemodialysis concomitantly with sodium phenylacetate, sodium benzoate, and arginine therapy. Conventional hemodialysis has the highest ammonium clearance rate,

as compared with other methods such as peritoneal dialysis, exchange transfusion, and hemofiltration.^{24,29} In older patients, alternative-pathway therapy is the mainstay, and dialysis is used only when ammonium levels do not decline after maximal treatment or when obtundation or coma persist. We think that timely administration of alternative-pathway therapy may reduce or eliminate the need for hemodialysis, depending on the level and duration of the hyperammonemia, the stage of coma, and the presence or absence of brain edema, but prospective, multicenter trials involving patients of all ages are needed to address the role of hemodialysis further.

Although survival among patients with urea-cycle disorders has clearly been improved after treatment of episodes of hyperammonemia with sodium phenylacetate and sodium benzoate and other supportive care, overall neurologic outcomes remain to be evaluated in detail. Studies documenting long-term follow-up and careful developmental testing are needed.

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