Ionization of Ammonia in Seawater: Effects of Temperature, pH, and Salinity

CAROL E. BOWER

Sea Research Foundation, Institute for Aquarium Studies, P.O. Box 7-495, West Hartford, Conn. 06107, USA

AND JOSEPH P. BIDWELL

Aquarium Systems, Eastlake, Ohio 44094, USA

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Previous studies have shown that the toxicity of ammonia to freshwater fishes depends on the ambient concentration of the un-ionized fraction (NH_3) and have quantified the percent NH_3 in solution as a function of temperature and pH. If NH_3 is also toxic to marine fishes, the effect of salinity on the ionization of ammonia must also be considered. The percent NH_3 over ranges of temperature, pH, and salinity common in seawater-culture situations is presented here.

Key words: ammonia, ammonia analysis, ammonia ionization, ammonia toxicity, pH, salinity, temperature

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La toxicité de l'ammoniac chez les poissons d'eau douce dépend de la concentration ambiante de la fraction non ionisée (NH_3), et des études antérieures ont déterminé le pourcentage de NH_3 en fonction de la température et du pH. Si le NH_3 est aussi toxique chez les poissons marins, il faut considérer aussi l'effet de salinité sur l'ionisation de l'ammoniac. Nous présentons ici les pourcentages de NH_3 dans les intervalles ordinaires de température, de pH et de salinité dans les aquariums marins.

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THE influence of environmental conditions on the toxicity of ammonia to freshwater fishes has been studied extensively (see European Inland Fisheries Advisory Commission 1973, for a comprehensive review). Although the accumulation of ammonia undoubtedly represents a major problem in seawater culture, particularly in recirculating aquariums during the "run-in period," i.e. the preestablishment phase of biological filtration by nitrifying bacteria (Saeki 1958; Kawai et al. 1965; Hirayama 1974), the toxicity of ammonia to marine teleosts apparently has not been studied.

In aqueous solution ammonia is present in two forms, ionized (NH_4^+) and un-ionized (NH_3), represented by the equilibrium equation

$$NH_4^+ + H_2O \rightleftharpoons NH_3 + H_3O^+.$$

NH_3 is regarded as the form of ammonia that is toxic to freshwater fishes (Wuhrmann and Woker 1948; Downing and Merkens 1955) because it is uncharged and lipid soluble, whereas the permeability of plasma membranes to charged, hydrated ammonium ions is relatively low (Jacobs 1940; Milne et al. 1958). The relative proportions of NH_3 and NH_4^+ in solution depend chiefly on temperature and pH and, to a lesser extent, on salinity; concentrations of NH_3 increase with elevated temperatures and pH values and decrease with higher salinities. If NH_3 is the toxic ammonia species in seawater, it is important to know how its concentration is influenced by variations of these conditions.

Values for total ammonia ($NH_3 + NH_4^+$) in natural waters can be determined analytically by several methods (e.g. Grasshoff and Johannsen 1972; Gilbert and Clay 1973; Beckett and Wilson 1974; Hampson 1977a),

TABLE 1. Mean values for pK_a^s in seawater at 25°C and 1 atm pressure, assuming $pK_a^0 = 9.245$ (Bates and Pinching 1949). (Adapted from Whitfield 1974.)

Molal ionic strength	Salinity (‰)	pK_a^s
0.4	18–22	9.29±0.02
0.5	23–27	9.32±0.02
0.6	28–31	9.33±0.02
0.7	32–36	9.35±0.02
0.8	37–40	9.35±0.02

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TABLE 2. Percent un-ionized ammonia in seawater (S = 18–22‰) at different temperatures and pH's.

Temp (°C)	pK_a^s	pH 7.5	7.6	7.7	7.8	7.9	8.0	8.1	8.2	8.3	8.4	8.5
0	10.10	0.251	0.315	0.397	0.499	0.627	0.788	0.990	1.24	1.56	1.96	2.45
1	10.07	0.270	0.340	0.427	0.537	0.675	0.849	1.07	1.34	1.68	2.11	2.64
2	10.04	0.291	0.366	0.460	0.578	0.727	0.914	1.15	1.44	1.81	2.26	2.83
3	10.00	0.313	0.394	0.495	0.623	0.783	0.984	1.24	1.55	1.94	2.44	3.05
4	9.97	0.337	0.424	0.534	0.671	0.843	1.06	1.33	1.67	2.09	2.62	3.27
5	9.94	0.363	0.457	0.575	0.723	0.908	1.14	1.43	1.80	2.25	2.82	3.52
6	9.91	0.391	0.492	0.619	0.778	0.978	1.23	1.54	1.93	2.42	3.03	3.78
7	9.87	0.422	0.530	0.667	0.838	1.05	1.32	1.66	2.08	2.60	3.25	4.06
8	9.84	0.454	0.571	0.718	0.902	1.13	1.42	1.78	2.24	2.80	3.50	4.36
9	9.81	0.489	0.615	0.773	0.971	1.22	1.53	1.92	2.41	3.01	3.76	4.69
10	9.78	0.527	0.662	0.832	1.05	1.31	1.65	2.07	2.59	3.23	4.04	5.03
11	9.74	0.567	0.713	0.896	1.13	1.41	1.77	2.22	2.78	3.48	4.34	5.40
12	9.71	0.611	0.768	0.965	1.21	1.52	1.91	2.39	2.99	3.74	4.66	5.79
13	9.68	0.658	0.827	1.04	1.31	1.64	2.05	2.57	3.21	4.01	5.00	6.21
14	9.65	0.709	0.891	1.12	1.40	1.76	2.21	2.76	3.45	4.31	5.37	6.66
15	9.61	0.763	0.959	1.20	1.51	1.90	2.37	2.97	3.71	4.63	5.76	7.14
16	9.58	0.822	1.03	1.30	1.63	2.04	2.55	3.19	3.99	4.97	6.18	7.65
17	9.55	0.885	1.11	1.40	1.75	2.19	2.75	3.43	4.28	5.33	6.62	8.20
18	9.52	0.953	1.20	1.50	1.88	2.36	2.95	3.69	4.60	5.72	7.10	8.78
19	9.48	1.03	1.29	1.62	2.03	2.54	3.17	3.96	4.94	6.14	7.61	9.39
20	9.45	1.11	1.39	1.74	2.18	2.73	3.41	4.26	5.30	6.58	8.15	10.0
21	9.42	1.19	1.49	1.87	2.35	2.93	3.67	4.57	5.69	7.06	8.73	10.7
22	9.39	1.28	1.61	2.01	2.52	3.15	3.94	4.91	6.10	7.56	9.34	11.5
23	9.35	1.38	1.73	2.17	2.71	3.39	4.23	5.27	6.54	8.10	9.99	12.3
24	9.32	1.48	1.86	2.33	2.92	3.64	4.54	5.65	7.02	8.67	10.7	13.1
25	9.29	1.60	2.00	2.51	3.14	3.91	4.88	6.07	7.52	9.28	11.4	14.0

TABLE 3. Percent un-ionized ammonia in seawater (S = 23–27‰) at different temperatures and pH's.

Temp (°C)	pK_a^s	pH 7.5	7.6	7.7	7.8	7.9	8.0	8.1	8.2	8.3	8.4	8.5
0	10.13	0.234	0.294	0.370	0.466	0.585	0.736	0.925	1.16	1.46	1.83	2.29
1	10.10	0.252	0.317	0.399	0.501	0.630	0.792	0.996	1.25	1.57	1.97	2.46
2	10.07	0.271	0.341	0.429	0.540	0.679	0.853	1.07	1.35	1.69	2.12	2.65
3	10.03	0.292	0.368	0.463	0.582	0.731	0.919	1.15	1.45	1.82	2.28	2.85
4	10.00	0.315	0.396	0.498	0.626	0.787	0.989	1.24	1.56	1.95	2.45	3.06
5	9.97	0.339	0.427	0.537	0.675	0.848	1.07	1.34	1.68	2.10	2.63	3.29
6	9.94	0.365	0.460	0.578	0.726	0.913	1.15	1.44	1.81	2.26	2.83	3.54
7	9.90	0.394	0.495	0.622	0.782	0.983	1.23	1.55	1.94	2.43	3.04	3.80
8	9.87	0.424	0.533	0.670	0.842	1.06	1.33	1.67	2.09	2.62	3.27	4.08
9	9.84	0.457	0.574	0.722	0.907	1.14	1.43	1.79	2.25	2.81	3.52	4.39
10	9.81	0.492	0.618	0.777	0.977	1.23	1.54	1.93	2.42	3.03	3.78	4.71
11	9.77	0.530	0.666	0.837	1.05	1.32	1.66	2.08	2.60	3.25	4.06	5.06
12	9.74	0.571	0.717	0.901	1.13	1.42	1.78	2.23	2.80	3.49	4.36	5.43
13	9.71	0.615	0.772	0.970	1.22	1.53	1.92	2.40	3.01	3.76	4.68	5.82
14	9.68	0.662	0.832	1.05	1.31	1.65	2.06	2.58	3.23	4.03	5.03	6.25
15	9.64	0.713	0.896	1.13	1.41	1.77	2.22	2.78	3.47	4.33	5.39	6.70
16	9.61	0.767	0.964	1.21	1.52	1.91	2.39	2.99	3.73	4.65	5.79	7.18
17	9.58	0.826	1.04	1.30	1.64	2.05	2.57	3.21	4.01	5.00	6.21	7.69
18	9.55	0.890	1.12	1.40	1.76	2.21	2.76	3.45	4.31	5.36	6.66	8.24
19	9.51	0.958	1.20	1.51	1.89	2.37	2.97	3.71	4.62	5.75	7.14	8.82
20	9.48	1.03	1.30	1.63	2.04	2.55	3.19	3.98	4.97	6.17	7.65	9.44
21	9.45	1.11	1.39	1.75	2.19	2.74	3.43	4.28	5.33	6.62	8.19	10.1
22	9.42	1.20	1.50	1.88	2.36	2.95	3.69	4.60	5.72	7.09	8.77	10.8
23	9.38	1.29	1.62	2.03	2.54	3.17	3.96	4.93	6.13	7.60	9.38	11.5
24	9.35	1.39	1.74	2.18	2.73	3.41	4.25	5.30	6.58	8.14	10.0	12.3
25	9.32	1.49	1.87	2.34	2.93	3.66	4.57	5.68	7.05	8.72	10.7	13.1

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TABLE 4. Percent un-ionized ammonia in seawater (S = 28–31‰) at different temperatures and pH's.

Temp (°C)	pK_a^s	pH 7.5	7.6	7.7	7.8	7.9	8.0	8.1	8.2	8.3	8.4	8.5
0	10.14	0.229	0.288	0.362	0.455	0.572	0.719	0.904	1.14	1.43	1.79	2.24
1	10.11	0.246	0.310	0.390	0.490	0.616	0.775	0.973	1.22	1.53	1.92	2.41
2	10.08	0.265	0.334	0.420	0.528	0.664	0.834	1.05	1.32	1.65	2.07	2.59
3	10.04	0.286	0.359	0.452	0.568	0.715	0.898	1.13	1.42	1.78	2.23	2.79
4	10.01	0.308	0.387	0.487	0.612	0.770	0.967	1.21	1.52	1.91	2.39	3.00
5	9.98	0.332	0.417	0.524	0.659	0.829	1.04	1.31	1.64	2.06	2.57	3.22
6	9.95	0.357	0.449	0.565	0.710	0.892	1.12	1.41	1.77	2.21	2.77	3.46
7	9.91	0.385	0.484	0.608	0.765	0.961	1.21	1.51	1.90	2.38	2.98	3.72
8	9.88	0.414	0.521	0.655	0.823	1.03	1.30	1.63	2.04	2.56	3.20	4.00
9	9.85	0.446	0.561	0.706	0.887	1.11	1.40	1.75	2.20	2.75	3.44	4.29
10	9.82	0.481	0.604	0.760	0.955	1.20	1.51	1.89	2.36	2.96	3.70	4.61
11	9.78	0.518	0.651	0.818	1.03	1.29	1.62	2.03	2.54	3.18	3.97	4.95
12	9.75	0.558	0.701	0.881	1.11	1.39	1.74	2.18	2.73	3.42	4.27	5.31
13	9.72	0.601	0.755	0.949	1.19	1.50	1.88	2.35	2.94	3.67	4.58	5.70
14	9.69	0.647	0.813	1.02	1.28	1.61	2.02	2.53	3.16	3.95	4.92	6.11
15	9.65	0.697	0.875	1.10	1.38	1.73	2.17	2.72	3.40	4.24	5.28	6.56
16	9.62	0.750	0.943	1.18	1.49	1.86	2.33	2.92	3.65	4.55	5.66	7.03
17	9.59	0.808	1.02	1.27	1.60	2.01	2.51	3.14	3.92	4.89	6.08	7.53
18	9.56	0.870	1.06	1.37	1.72	2.16	2.70	3.38	4.21	5.25	6.52	8.07
19	9.52	0.937	1.18	1.48	1.85	2.32	2.90	3.63	4.52	5.63	6.99	8.64
20	9.49	1.01	1.27	1.59	1.99	2.50	3.12	3.90	4.86	6.04	7.49	9.24
21	9.46	1.09	1.36	1.71	2.14	2.68	3.35	4.19	5.21	6.48	8.02	9.89
22	9.43	1.17	1.47	1.84	2.31	2.89	3.61	4.50	5.60	6.94	8.59	10.6
23	9.39	1.26	1.58	1.98	2.48	3.10	3.87	4.83	6.00	7.44	9.19	11.3
24	9.36	1.35	1.70	2.13	2.67	3.33	4.16	5.18	6.44	7.97	9.83	12.1
25	9.33	1.46	1.83	2.29	2.87	3.58	4.47	5.56	6.90	8.54	10.5	12.9

TABLE 5. Percent un-ionized ammonia in seawater (S = 32–40‰) at different temperatures and pH's.

Temp (°C)	pK_a^s	pH 7.5	7.6	7.7	7.8	7.9	8.0	8.1	8.2	8.3	8.4	8.5
0	10.16	0.218	0.275	0.346	0.435	0.547	0.687	0.863	1.09	1.36	1.71	2.14
1	10.13	0.235	0.296	0.372	0.468	0.589	0.740	0.930	1.17	1.47	1.84	2.30
2	10.10	0.253	0.319	0.401	0.504	0.634	0.797	1.00	1.26	1.58	1.98	2.48
3	10.06	0.273	0.343	0.432	0.543	0.683	0.858	1.08	1.35	1.70	2.13	2.66
4	10.03	0.294	0.370	0.465	0.585	0.735	0.924	1.16	1.46	1.83	2.29	2.86
5	10.00	0.317	0.398	0.501	0.630	0.792	0.995	1.25	1.57	1.97	2.46	3.08
6	9.97	0.341	0.429	0.540	0.678	0.852	1.07	1.34	1.69	2.11	2.65	3.31
7	9.93	0.367	0.462	0.581	0.730	0.918	1.15	1.45	1.82	2.27	2.85	3.56
8	9.90	0.396	0.498	0.626	0.787	0.988	1.24	1.56	1.95	2.45	3.06	3.82
9	9.87	0.426	0.536	0.674	0.847	1.06	1.34	1.68	2.10	2.63	3.29	4.11
10	9.84	0.459	0.577	0.726	0.912	1.15	1.44	1.80	2.26	2.83	3.54	4.41
11	9.80	0.495	0.622	0.782	0.982	1.23	1.55	1.94	2.43	3.04	3.80	4.74
12	9.77	0.533	0.670	0.842	1.06	1.33	1.67	2.09	2.61	3.27	4.08	5.08
13	9.74	0.574	0.721	0.906	1.14	1.43	1.79	2.25	2.81	3.51	4.38	5.46
14	9.71	0.618	0.777	0.976	1.23	1.54	1.93	2.42	3.02	3.78	4.71	5.85
15	9.67	0.665	0.836	1.05	1.32	1.66	2.07	2.60	3.25	4.06	5.05	6.28
16	9.64	0.717	0.900	1.13	1.42	1.78	2.23	2.79	3.49	4.36	5.42	6.73
17	9.61	0.772	0.970	1.22	1.53	1.92	2.40	3.00	3.75	4.68	5.82	7.22
18	9.58	0.831	1.04	1.31	1.64	2.06	2.58	3.23	4.03	5.02	6.24	7.73
19	9.54	0.895	1.12	1.41	1.77	2.22	2.78	3.47	4.33	5.39	6.69	8.28
20	9.51	0.963	1.21	1.52	1.90	2.39	2.98	3.73	4.65	5.78	7.17	8.87
21	9.48	1.04	1.30	1.63	2.05	2.57	3.21	4.01	4.99	6.20	7.69	9.49
22	9.45	1.12	1.40	1.76	2.20	2.76	3.45	4.30	5.36	6.65	8.23	10.1
23	9.41	1.20	1.51	1.89	2.37	2.97	3.71	4.62	5.75	7.13	8.81	10.8
24	9.38	1.29	1.62	2.04	2.55	3.19	3.98	4.96	6.17	7.64	9.43	11.6
25	9.35	1.39	1.75	2.19	2.74	3.43	4.28	5.32	6.61	8.18	10.1	12.4

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but there is no direct way to assess the concentration of un-ionized ammonia. The percent un-ionized ammonia in freshwater is calculated, usually from the value obtained for total ammonia, by using the equation

$$\% \text{ un-ionized Ammonia} = 100/[1 + \text{antilog}\,(pK_a^0 - pH)],$$

where pK_a^0 is the negative logarithm of the ionization constant at zero salinity. Values for the percent un-ionized ammonia in freshwater at different temperatures and pH values have been tabulated by Trussell (1972) and Emerson et al. (1975). Because of the effect of salinity on the ammonia–water equilibrium, however, these tables are not reliable for estimations in seawater. Skarheim (1973) prepared tables in which the effect of salinities up to 35‰ was taken into consideration, but according to Emerson et al. (1975) his reported equilibrium constants were based on "questionable assumptions," and his method of calculation was not made clear.

Using several different ionic interaction models, Whitfield (1974) calculated the effects of ionic strength, temperature, and pressure on the hydrolysis of ammonium ions. The tables presented in this paper follow Whitfield's recommendation that the overall mean values for his models at 1 atm pressure, 25°C, and different ionic strengths (Table 1) be considered as representative of the overall acid hydrolysis constants of ammonium ions in seawater ($= pK_a^s$). Hampson (1977b) described a computer program, based on Whitfield's data, for calculating the concentration of NH_3 in natural waters, but for reasons unknown to us, his pK_a^s values were different from those recommended by Whitfield.

Salinities ($S‰$) corresponding to the molal ionic strength (I) of seawater were calculated from the equation (Whitfield 1974)

$$I = 19.9273\, S‰/(100 - 1.005109\, S‰).$$

The percent un-ionized ammonia at different temperatures, pH values, and salinities (Tables 2–5) was calculated from the following equation derived from Whitfield's calculations:

$$\% \text{ un-ionized Ammonia} = 100/[1 + \text{antilog}\,(pK_a^s(T) - pH)],$$

in which

$$pK_a^s(T) = pK_a^s(T = 298°K) + 0.0324(298 - T°K).$$

The pH range used in the present study includes the upper and lower extremes found in natural ocean waters (Sverdrup et al. 1942) and is thus considerably more narrow than that intended for application in freshwater.

By using Tables 2–5, the concentration of NH_3 in seawater at temperatures from 0 to 25°C, pH's from 7.5 to 8.5, and salinities from 18 to 40‰ can be estimated from values for total ammonia obtained by conventional analytical methods. Values for the percent NH_3 at the lowest salinity studied are virtually the same as values given for freshwater by Emerson et al. (1975), especially at lower temperatures; but at salinities common in seawater culture (32–40‰) there is up to one-fifth less un-ionized ammonia than in freshwater at the same temperature and pH.

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BATES, R. G., AND G. D. PINCHING. 1949. Acidic dissociation constant of ammonium ion at 0 to 50°C, and the base strength of ammonia. J. Res. Natl. Bur. Stand. 42: 419–430.

BECKETT, M. J., AND A. L. WILSON. 1974. The manual determination of ammonia in fresh waters using an ammonia-sensitive membrane-electrode. Water Res. 8: 333–340.

DOWNING, K. M., AND J. C. MERKENS. 1955. The influence of dissolved oxygen concentration on the toxicity of un-ionized ammonia to rainbow trout (*Salmo gairdnerii* Richardson). Ann. Appl. Biol. 43: 243–246.

EMERSON, K., R. C. RUSSO, R. E. LUND, AND R. V. THURSTON. 1975. Aqueous ammonia equilibrium calculations: effect of pH and temperature. J. Fish. Res. Board Can. 32: 2379–2383.

EUROPEAN INLAND FISHERIES ADVISORY COMMISSION. 1973. Water quality criteria for European freshwater fish. Report on ammonia and inland fisheries. Water Res. 7: 1011–1022.

GILBERT, T. R., AND A. M. CLAY. 1973. Determination of ammonia in aquaria and in sea water using the ammonia electrode. Anal. Chem. 43: 1757–1759.

GRASSHOFF, K., AND H. JOHANNSEN. 1972. A new sensitive and direct method for the automatic determination of ammonia in sea water. J. Cons. Int. Explor. Mer 34: 516–521.

HAMPSON, B. L. 1977a. The analysis of ammonia in polluted sea water. Water Res. 11: 305–308.

1977b. Relationship between total ammonia and free ammonia in terrestrial and ocean waters. J. Cons. Int. Explor. Mer 37: 117–122.

HIRAYAMA, K. 1974. Water control by filtration in closed culture systems. Aquaculture 4: 369–385.

JACOBS, M. H. 1940. Some aspects of cell permeability to weak electrolytes. Cold Spring Harbor Symp. Quant. Biol. 8: 30–39.

KAWAI, A., Y. YOSHIDA, AND M. KIMATA. 1965. Biochemical studies on the bacteria in the aquarium with a circulating system. II. Nitrifying activity in the filter sand. Bull. Jpn. Soc. Sci. Fish. 31: 65–71.

MILNE, M. D., B. H. SCRIBNER, AND M. A. CRAWFORD. 1958. Non-ionic diffusion and the excretion of weak acids and bases. Am. J. Med. 24: 709–729.

SAEKI, A. 1958. Studies on fish culture in filtered closed-circulation aquaria. Fundamental theory and system design standards. Bull. Jpn. Soc. Sci. Fish. 23: 684–695. (Transl. from Japanese)

SKARHEIM, H. P. 1973. Tables of the fraction of ammonia in the undissociated form for pH 6 to 9, temperature 0 to 30°C, TDS 0 to 3,000 mg/l and salinity 5 to 35 g/kg. Sanitary Eng. Res. Lab., Univ. California, Berkeley, Calif. SERL Rep. 73–5: 33 p.

J. Fish. Res. Bd. Can. Downloaded from www.nrcresearchpress.com by YORK UNIV on 08/06/13
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SVERDRUP, H., M. JOHNSON, AND R. FLEMING. 1942. The oceans: their physics, chemistry and general biology. Prentice-Hall, Inc., New York, N.Y. 1987 p.

TRUSSELL, R. P. 1972. The percent un-ionized ammonia in aqueous ammonia solutions at different pH levels and temperatures. J. Fish. Res. Board Can. 29: 1505–1507.

WHITFIELD, M. 1974. The hydrolysis of ammonium ions in sea water. A theoretical study. J. Mar. Biol. Assoc. U.K. 54: 565–580.

WUHRMANN, K., AND H. WOKER. 1948. Beiträge zur Toxikologie der Fische. II. Experimentelle Untersuchungen über die Ammoniak-und Blausäurevergiftung. Schweiz. Z. Hydrol. 11: 210–244.

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