Human Fatalities from Cyanobacteria: Chemical and Biological Evidence for Cyanotoxins


1Department of Biological Sciences, Wright State University, Dayton, Ohio, USA; 2Instituto de Biofisica Carlos Chagas Filho, Universidade do Brasil, Rio de Janeiro, Brazil; 3Instituto Tecnologico de Pernambuco, Recife, Brasil; 4Hospital Infections Program, National Center for Infectious Diseases, Centers for Disease Control and Prevention, Atlanta, Georgia, USA; 5Roger Adams Laboratory, School of Chemical Sciences, University of Illinois, Urbana, Illinois, USA; 6National Research Center for Environmental Toxicology, Coopers Plains, Queensland, Australia; 7Queensland Health Scientific Services, Coopers Plains, Queensland, Australia

An outbreak of acute liver failure occurred at a dialysis center in Caruaru, Brazil (8°17’S, 35°58’W), 134 km from Recife, the state capital of Pernambuco. At the clinic, 116 (89%) of 131 patients experienced visual disturbances, nausea, and vomiting after routine hemodialysis treatment on 13–20 February 1996. Subsequently, 100 patients developed acute liver failure, and of these 76 died. As of December 1996, 52 of the deaths could be attributed to a common syndrome now called Caruaru syndrome. Examination of phytoplankton from the dialysis clinic’s water source, analyses of the clinic’s water treatment system, plus serum and liver tissue of clinic patients led to the identification of two groups of cyanobacterial toxins, the hepatotoxic cyclic peptide microcysts and the hepatotoxic alkaloid cylindrospermopsin. Comparison of victims’ symptoms and pathology using animal studies of these two cyanotoxins leads us to conclude that the major contributing factor to death of the dialysis patients was intravenous exposure to microcysts, specifically microcystin-YR, -LR, and -AR. From liver concentrations and exposure volumes, it was estimated that 19.5 μg/L microcystin was in the water used for dialysis treatments. This is 19.5 times the level set as a guideline for safe drinking water supplies by the World Health Organization. Key words: cyanobacteria, cyanotoxins, cylindrospermopsin, microcystins, toxins. Environ Health Perspect 109:663–668 (2001). [Online 20 June 2001] http://ehpnet1.niehs.nih.gov/docs/2001/109p663-668carmichael/abstract.html

Poisonings by waterblooms of toxic cyanobacteria (cyanobacteria toxin poisonings; CTP) are a significant part of the concern over harmful algal blooms (1–4). The toxins, called cyanotoxins, are responsible for intermittent but repeated widespread poisonings of wild and domestic animals and aquacultured fish. Cyanotoxins include neurotoxic anatoxin-a and anatoxin-a-s, paralytic shellfish poisons (PSP; saxitoxin and analogues), and hepatotoxic microcystins, nodularins, and cylindrospermopsins (1). Human poisonings have, in the past, been suspected but not confirmed due to a lack of information regarding vectors or circumstances that would confirm the presence of cyanotoxins in human food or water supplies, plus a shortage of appropriate methods of detection. Because most CTP occur only when waterblooms accumulate as thick surface scums, humans do not experience acute intoxication because they generally avoid contact with such high cell concentrations. In addition, drinking water supplies usually receive a degree of treatment that prevents high concentrations of cyanotoxins from being present. This spares humans from severe poisoning episodes by the oral route. However, the oral route of exposure is not the only one possible for humans. This article provides biological and chemical evidence for the first documented lethality to humans from cyanobacterial hepatotoxins, occurring via the intravenous route, in a dialysis clinic in the city of Caruaru, Brazil, during 1996.

Caruaru is a city of about 350,000 people 2 hr west of Recife, the capital of the Brazilian state of Pernambuco. Two renal dialysis centers (A and B) serve the population, with center A receiving water from the city’s water treatment plant, which is delivered by truck. Center B obtains reticulated water from the city’s water treatment plant. Beginning on 13 February 1996, center A patients receiving routine renal dialysis treatment began to complain of headache, eye pain, blurred vision, nausea, and vomiting. The first patient died suddenly on 20 February at center A. Fifty-one patients died by the middle of April, and a total of 76 deaths were reported in the course of our studies, which ended in October 1997. Through the cooperation of health and medical authorities in Pernambuco and the Centers for Disease Control and Prevention (CDC) in Atlanta, Georgia, we obtained liver samples from 52 of these 76 victims. From these case reports, a pattern of disease was described that is now referred to as Caruaru syndrome. Caruaru syndrome is characterized by painful, extreme hepatomegaly, jaundice, and a bleeding diathesis manifested by ecchymosis, epistaxis, and methorrhagia; elevated transaminases, variable hyperbilirubinemia, prolonged prothrombin time, and severe hypertriglyceridemia; and disruption of liver plates, liver cell deformity, necrosis, apoptosis, cholestasis, cytoplasmic vacuolization, mixed leukocyte infiltration and multinucleated hepatocytes observed upon light microscopy and intracellular edema, mitochondrial changes, rough and smooth endoplasmic reticulum injuries, lipid vacuoles, and residual bodies observed upon electron microscopy (5–7). This outbreak received much attention from the media and public health authorities in Brazil and has been reported in many countries. The background of this case and a summary of the epidemiology have been published (6,7). Over the intervening period, we have examined the limnological and case report data and analyzed most of the liver tissues provided and some of the serum samples. These results have allowed us to address some important questions regarding these human fatalities: What were the possible toxigenic cyanobacteria present in the reservoir that supplied water to Caruaru and the dialysis clinic? Which cyanotoxins were present, and at what concentrations? Were the concentrations of cyanotoxins present in the dialysis center high enough to produce liver failure and death?

Materials and Methods

Phytoplankton collections and identifications. Water treatment personnel were not doing phytoplankton counts or identification during the outbreak.

Address correspondence to W. W. Carmichael, Department of Biological Sciences, Wright State University, 3640 Colonel Glen Highway, Wright State University, Dayton, OH 45435, USA. Telephone (937) 775-3173, Fax (937) 775-3320. E-mail: wayne.carmichael@wright.edu

We thank F.S. Chu for helping to confirm ELISA analysis of serum. We also thank C. H. Olmes, D. M. Cardo, L.A. Carmichael, S.T. Cookson, W. R. Jarvis, M. B. de C. Antunes, D. A. de M. Filho, and T. M. Lyra for assistance with epidemiology, database management, specimen collection, and shipment.

Partial support for specimen analysis was provided to W. W. C. by the Centers for Disease Control and Prevention. MALDI mass spectra were obtained on instruments supported by grants from the National Institute of General Medical Sciences (GM 27029), the National Institutes of Health (RR 01575), and the National Science Foundation (PCM 8121494) to K.L.R. Received 16 August 2000; accepted 30 January 2001.
the month of February 1996, and so samples of phytoplankton were not available from the time of the initial outbreak. Subsurface phytoplankton samples from Tabocas Reservoir (Caruaru water supply) were, however, collected retrospectively at the end of March 1996, identified, and quantified. Subsamples used for phytoplankton identification and quantification were preserved with Lugol’s iodine solution. Direct counting of preserved cells was carried out with Utermohl’s counting techniques using a counting chamber and inverted microscope.

Analyzes for cyanotoxins. Samples of carbon, sand, and cation/anion exchange resin from the in-house filters at both clinics A and B were analyzed using a polyclonal antibody against the cyclic peptide hepatotoxins, the microcystins, in an enzyme-linked immunosorbent assay (ELISA) (8,9). This antibody was raised against microcystin-LR but cross-reacts with many of the known microcystin analogues. Blood sera and liver from affected and control patients provided by state health personnel in Recife, Caruaru, and Atlanta, and the diluted serum was loaded onto a C18 silica cartridge. The C18 cartridge was washed with 0.1% trifluoroacetic acid, 1:1 methanol/water and 100% methanol eluates were collected and assayed by ELISA.

We used 52 liver samples representing 39 victims (covering February–December 1996) in our analyses (13 replicate samples were also analyzed). Liver samples were homogenized in 100% methanol (2 times over 24 hr) using a volume of 10 mL for liver < 1 g and 10 mL/g for tissue > 1 g. Extracts were centrifuged at 7000 × g. M ethanol supernatants were combined and mixed with a 3-times volume of hexane. The hexane layer was discarded and the methanol extract was placed in 40 mL distilled water and applied to C18 silica cartridges. Water and 20 and 100% methanol eluates were collected. The 100% methanol extracts were dried and reconstituted with 1:1 methanol/H2O and diluted 10–1, 10–2, and 10–3 with phosphate-buffered saline and assayed by ELISA.

We used 17 serum samples representing 12 victims in our analyses reported here. Serum samples (200 µL–1 mL) were diluted 4 times with double-distilled H2O, and the diluted serum was loaded onto a C18 silica cartridge. The C18 cartridge was processed as described above for liver samples and assayed by ELISA.

We obtained control liver samples from five persons from the pathology unit at the Federal University of Pernambuco. These samples represented persons not associated with dialysis treatment in Caruaru. Control sera (n = 12) were from volunteer health personnel in Caruaru, Recife, and Atlanta. These samples were extracted for analyses in the same way as victim samples were.

Chemical analyses for microcystins in liver and serum samples were done by ELISA-guided HPLC–photodiode array (PDA) separation of microcystins from liver tissues. HPLC chromatograms were obtained on a Waters 2690 M millenium system (Waters, Milford, MA, USA). HPLC column conditions were: column, Waters uBondapak C18, 3.9 × 300 mm; mobile phase, isocratic-60% methanol/40% 0.05% trifluoroacetic acid; flow rate, 1 mL/min; Waters 996 DPA detector. The separated microcystins were further analyzed by matrix-assisted laser desorption ionization/time of flight (MALDI/TOF) and electrospray ionization (ESI) mass spectrometry (M.S.). MALDI spectra were acquired on a VG TofSpec mass spectrometer (VG Analytical, Fisons Instruments, Manchester, UK) in the linear mode, using a 337 nm N2 laser.
laser. The MALDI/TOF ionization method has emerged as a powerful analytical method (10), with a high sensitivity and tolerance for small amounts of salt and buffer that allow low-level detection of analyses (sub-femtomole) in complex mixtures. The thin-film coating method was used in these analyses (11). ESI spectra were acquired on a VG Quattro mass spectrometer (VG Biotech, Fisons, Manchester, U.K.). Caesium chloride was used for the calibration.

During the time in which microcystins were being analyzed, it became apparent that we should also examine the samples for other cyanotoxins. After the first analyses for microcystins, other studies demonstrated a wide occurrence of microcystins, other studies confirmed that toxic cyanobacteria, especially Cylindrospermopsis, are present in Brazilian water supplies (14–16). Microcystis and Anabaena are known producers of microcystins, while Cylindrospermopsis can produce cylindrospermopsin. For this reason we analyzed samples for these two cyanotoxins. Although the literature reports the neurotoxins anatoxin-a and a(s) to be present in the reservoir during the summer months since at least 1990 (Figure 1), the most common genera during this time period were Microcystis, Anabena, and Anabaenopsis (Cylindrospermopsis). Other studies confirm that toxic cyanobacteria, especially Cylindrospermopsis, are present in other Brazilian water supplies (14–16). Microcystis and Anabaena are known producers of microcystins, while Cylindrospermopsis can produce cylindrospermopsin. For this reason we analyzed samples for these two cyanotoxins. Although the literature reports the neurotoxins anatoxin-a and a(s) to be produced by Anabaena and certain PSPs to be produced by Cylindrospermopsis (3), the lack of reported neurotoxic symptoms in most of the Caruaru victims meant that these toxins were not likely present and therefore we did not analyze samples for those toxins.

Analyses for cyanotoxins. Examination of carbon, sand, and cation/anion resin exchange filters from the clinic using a polyclonal antibody in an ELISA against microcystin-LR showed microcystin in the microgram per gram range (Table 2). Further examination of methanolic extracts from these carbon, sand, and resins performed by HPLC-electrospray MS/MS provided chemical evidence for CYN contamination in this material. The highest concentration of this hepatotoxic alkaloid was found in the carbon extract (Table 2).

Blood sera and liver from affected and control patients provided by state health officials in Pernambuco and sent through the CDC were examined by ELISA. All patient sera and tissue were positive for microcystins (Table 3). ELISA-guided HPLC-PDA separation of microcystins from liver tissues provided a profile of microcystins present (Figure 2). MALDI/TOF (Figure 3) and ESI (Table 4) MS analysis were used to identify isolated microcystins from liver. Microcystins

<table>
<thead>
<tr>
<th>AU</th>
<th>Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.00</td>
</tr>
<tr>
<td>0.05</td>
<td>10.00</td>
</tr>
<tr>
<td>0.10</td>
<td>15.00</td>
</tr>
</tbody>
</table>

**Figure 2.** HPLC/PDA spectrum from liver extract of a Caruaru dialysis patient. (A) Retention times of labeled peaks correspond to retention times of authentic microcystin-YR, -LR, and -AR standards; detection was done at 238 nm. (B) Microcystin peaks showing their characteristic 238-nm ultraviolet chromophore.
identified were microcystins-YR, -LR, and -AR. MALDI MS analysis of finished water from dialysis center B also showed the presence of these microcystins (data not shown).

Analysis of liver samples for CYN by HPLC-M S did not reveal the parent compound at molecular mass 416 (M + H+). These liver extracts had been prepared for M CYST analyses, and the method may not have selected for the more polar alkaloid CYN. Due to limited sample availability, further analyses of remaining liver tissue and sera for CYN is pending while a method is developed for detecting this cyanotoxin in these matrices.

**Calculation of microcystin exposure.** The average microcystin value in 52 liver samples from 39 victims who died from February to December 1996 was 223 ng/g (Table 3). This compares well with values reported in laboratory test animals receiving acute exposure of microcystin-LR (17). ELISA detected 125 ng/g of microcystin-LR in the livers of mice exposed to a lethal intraperitoneal injection of 100 µg/kg (18). We used the average liver concentration of 223 ng/g to estimate the amount of microcystin present in the source water from clinic A. Using an average liver weight for an adult human of 1,500 g gives 335 µg of possible M CYST burden in an average liver from the Caruaru victims. We then used two correction factors that could affect the amount of M CYST in the source water. The first was the amount of M CYST in the liver as a percentage of the total exposure. Laboratory experiments indicate that from 10% to 90% of the total exposure can be found in the liver of mice and rats receiving an acute or lethal dose of M CYST (19,20). Therefore, an application factor of 2 (estimate of 50% uptake in the liver) was used. The second factor was based on the finding that since microcystin is covalently bound to protein phosphatase 1 and protein phosphatase 2A, as much as 80% of the M CYST exposure might not be recognized by the ELISA assay (21,22). Although this estimate is conservative, it means that the M CYST exposure might have been about 7 times higher (2 times and 5 times, respectively). Using this value and dividing by the amount of water used during a typical dialysis treatment (120 L), and assuming 100% dialysis of M CYST across the hollow fiber dialysis filter gives an estimated concentration in the source water of 19.5 µg/L. Although there are several assumptions in estimating this value, it does mean that an environmentally feasible level of M CYST in the source water would have been adequate to cause acute liver failure and death in humans by the intravenous route. If this concentration of M CYST is an accurate estimate, then there was no significant contribution to the toxicity from CYN. This M CYST value is about 20 times higher than the 1 µg/L proposed by the World Health Organization as a safe level for oral consumption of M CYST in drinking water (23).

Histology and pathology of liver tissues revealed a pattern of liver plate disruption identical to that found in previous laboratory animal experiments of microcystin exposure (5,24–26). M CYSTs are potent inhibitors of eukaryotic protein serine/threonine phosphatases 1 and 2A (27,28). Substances that inhibit these protein phosphatases are considered to be nonphorbol ester-type tumor promoters (29,30). This means that survivors of Caruaru syndrome could be at higher risk for liver cancer and should be monitored (3); however, the degree to which CYN contributed to the deaths of the dialysis patients is less clear. Until we can evaluate whether CYN is present in the victims’ livers, we cannot estimate the possible toxicity due to this cyanotoxin. CYN is a hepatotoxic alkaloid first studied from Australian water supplies. In a retrospective study it has been held as the cause of hepatoenteropathy and...
environment—a process that involved sand filtration, center for treatment in its in-house water system, they relied on water that was trucked to the treatment procedures including sedimentation, coagulation, filtration, and chlorination?

The available biological and chemical evidence supports cyanotoxins from the Tabocas renals damage to 148 indigenous peoples using an Australian water supply (31). Comparison of the Caruaru victims’ lives with published studies in animals dosed with CYN did not reveal a pattern indicating that this toxin contributed to the toxicity. Because the victims in Caruaru were undergoing renal dialysis, we cannot evaluate whether CYN contributed to renal toxicity. A better understanding of CYN toxicology and biochemistry, both alone and in combination with MCYST, is needed before we can confirm (or rule out) a contributing toxicity factor from this toxin.

Discussion

The available biological and chemical evidence supports cyanotoxins from the Tabocas Reservoir water supply as being the major factor in the deaths of dialysis patients at clinic A. One important question was how could lethal levels of MCYST (and possibly CYN) be present in waters receiving standard water treatment procedures including sedimentation, coagulation, filtration, and chlorination? This is not understood how center A did not have water directly piped to its facility. Instead, they relied on water that was trucked to the center for treatment in its in-house water system—a process that involved sand filtration, carbon filtration, and cation/anion exchange

The results show that many patients with MCYST or CYN exposure, another study treated one clinic A patient with charcoal hemoperfusion. Liver samples from this victim were analyzed in our study, and the level was 250 and 430 ng/g (two separate liver samples).

We have learned significant information concerning human exposure from MCYST and CYN in this first confirmed outbreak of human poisoning involving cyanotoxins. Because many of the world’s reservoir- and lake-based water supplies are subject to increasing levels of nutrients, it is highly probable that repeat episodes of cyanotoxin poisoning will occur unless measures are taken to better understand their role in water-based disease. These measures should consist of programs for watershed management to reduce nutrient inputs, cyanotoxin monitoring programs to alert authorities to the presence of cyanotoxins, and improvements in water treatment techniques to reduce or to remove cyanotoxins from potable water supplies.

References and Notes

7. Pouria S, Andrade A, Barbosa J, Cavalcanti RL, Barreto
Vestergaard et al.


Carmichael WW, An J S. Unpublished data.


