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Impact of the Fukushima Daiichi Nuclear Power Plant Accident on Hemodialysis Facilities: An Evaluation of Radioactive Contaminants in Water Used for Hemodialysis

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Abstract: Following the crisis at the Fukushima Daiichi Nuclear Power Plant caused by the 2011 Tohoku earthquake and tsunami, radioactive substances (^{131}I, ^{134}Cs, ^{137}Cs) were detected in tap water throughout eastern Japan. There is now concern that internal exposure to radioactive substances in the dialysate could pose a danger to hemodialysis patients. Radioactive substances were measured in three hemodialysis facilities before and after purification of tap water for use in hemodialysis. Radioactive iodine was detected at levels between 13 and 15 Bq/kg in tap water from the three facilities, but was not detected by reverse osmosis membrane at any of the facilities. We confirmed that the amount of radioactive substances in dialysate fell below the limit of detection (7–8 Bq/kg) by reverse osmosis membrane. It is now necessary to clarify the maximum safe level of radiation in dialysate for chronic hemodialysis patients. **Key Words:** Hemodialysis, Nuclear accident, Radioiodine (^{131}I), Reverse osmosis, Radioactive decontamination.

A magnitude 9.0 earthquake and subsequent tsunami struck eastern Japan on March 11, 2011, causing unimaginable damage. A secondary result of the disaster was a Level-7 nuclear event—the worst on the International Nuclear and Radiological Event Scale (INES)—at the Fukushima Daiichi Nuclear Power Plant, which is owned by Tokyo Electric Power Co. Several explosions and other events scattered radioactive debris across much of eastern Japan. On March 22, 2011, radioactive iodine (^{131}I) was detected at 210 Bq/kg in tap water from a water purification facility in Tokyo, about 200 km from the plant.

Hemodialysis, in which the patient's blood comes into indirect contact with a dialysate via a dialysis membrane to accomplish diffusion and ultrafiltration, requires large volumes of purified tap water (120 to 150 L per session). Water quality is therefore critical. In addition, the dialysate must be pure to prevent complications due to reverse filtration from contaminated dialysate or the inflow of pyrogens in the dialysate via reverse diffusion. The European Renal Association–European Dialysis and Transplant Association (ERA–EDTA) (1) and the Association of Medical Instrumentation (AAMI) in the United States (2), among others, have proposed standards for the purity of dialysate. The Japanese Society for Dialysis Therapy released the Standard on Microbiological Management of Fluids for Hemodialysis and Related Therapies for use in Japan (3).

As the Fukushima Daiichi accident is only the world's third nuclear power accident resulting in widespread radioactive contamination of tap water, the ramifications of dialysate contamination have not been adequately clarified, and no related standards have been established.

Objectives

^{131}I, when used to treat thyroid cancer in hemodialysis patients, permeates the dialysis membrane, diffusing into the dialysate (4,5). ^{131}I in dialysate is therefore expected to permeate the dialysis membrane and to diffuse into the blood. Consequently, the

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TABLE 1. *Reverse osmosis (RO) membrane treatment conditions at the three facilities on sample collection days*

	Ohkubo Hospital (Tokyo)	Ikebukuro Kuno Clinic (Tokyo)	Sato Clinic (Chiba)
Membrane area (m^2)	74.4	39.5	148.8
RO pump pressure (MPa)	0.44	0.14	0.51
Permeate flow (L/h)	1327	1430	2960
RO waste flow (L/h)	804	840	1792
Recovery (%)	62.3	63.0	62.3
Source water temperature (°C)	20	10.8	25.9
Source water conductivity (μS/cm)	246	198	Not measured
RO water conductivity (μS/cm)	3.53	2.74	4.56

dialysate must be evaluated for radioactive contamination to prevent possible internal exposure to substantial amounts of radioactivity in patients undergoing hemodialysis.

In the present study, we aimed to determine the amount of radioactive contamination removed during the purification of tap water for use in hemodialysis.

MATERIALS AND METHODS

Samples were collected on March 24 and 25, 2011 from three hemodialysis facilities in the Kanto region, about 200 km from the plant (Ohkubo Hospital, Ikebukuro Kuno Clinic, and Credo Sato Clinic). The settings of the reverse osmosis (RO) equipment at these facilities at the time of measurement are shown in Table 1. The process for purifying tap water to RO water is shown in Figure 1.

At each of the three facilities, water for hemodialysis is prepared by first passing tap water through a prefilter to remove particulate matter, then softening the water with a cation exchange resin, removing chlorine with activated charcoal, and finally performing RO. Samples for analysis were collected before the start of treatment (tap water), after activated charcoal treatment, and after RO.

The RO membrane module system (MORSEP, Daicen Membrane Systems, Tokyo, Japan) used was equipped with a prefilter, water softener, activated charcoal filter, and RO membrane module. The mean demineralization rate of the RO membrane—a composite membrane composed of an aromatic polyamide separation membrane and a polysulfone support membrane—was ≥99.2%.

The Japan Chemical Analysis Center used gamma-ray spectrometry to measure radioactive substances (^{131}I, ^{134}Cs, ^{137}Cs) in samples collected on March 29, 2011.

Levels of radioactivity were calculated by measuring the samples for 1800 seconds using germanium semiconductor detectors (GEM-25185s and others by ORTEC). Such measurements are normally taken for 10 h, but the measurement time specified by the Japanese Ministry of Health, Labour, and Welfare was used in this time of emergency. Sensitivity varied according to the duration of measurement, and the limit of detection also differed across the measurements.

RESULTS

^{131}I was detected in the tap water at each facility (Table 2), but ^{134}Cs and ^{137}Cs levels were below the limits of detection under the analytical conditions used. ^{131}I was ineffectively adsorbed on activated charcoal but was below the limit of detection in all RO water samples.

DISCUSSION

Before it can be used for hemodialysis, tap water must be purified with activated charcoal treatment and RO. Activated charcoal consists of porous carbon with a large surface area, which makes it well suited to adsorbing dissolved matter from the liquid phase.

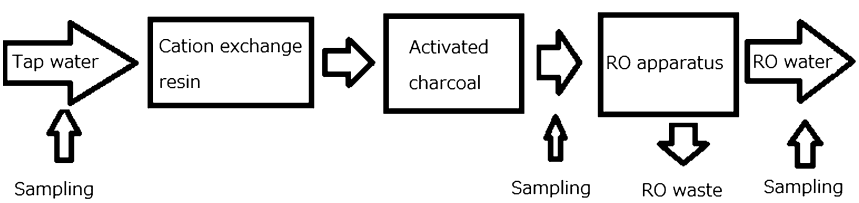

FIG. 1. Schematic of purification of tap water to reverse osmosis (RO) water.

TABLE 2. *Quantitative analysis of ^{131}I with gamma-ray spectrometry*

	Ohkubo Hospital (Tokyo)	Ikebukuro Kuno Clinic (Tokyo)	Sato Clinic (Chiba)
	^{131}I (Bq/kg)	^{131}I (Bq/kg)	^{131}I (Bq/kg)
Tap water	15 ± 2.8	13 ± 3.0	15 ± 3.0
After activated charcoal treatment	17 ± 2.6	16 ± 2.6	11 ± 2.8
RO water	N.D.	N.D.	N.D.
Limit of detection	8	8	6

N.D., not detected.

Non-ionic substances are adsorbed onto activated charcoal more effectively than ionic substances, as the adsorptive activity is attributable to van der Waals forces.

The pore theory and solution diffusion theory have been proposed to explain RO. Water molecules, which are about 0.38 nm in diameter, pass through the 0.5- to 0.7-nm pores of RO membranes (6). The radius of ions in solution generally increase as they undergo coordinate bonding with water molecules and the hydroxyl groups of other molecules. Iodine is slightly soluble in water, and the trace amounts that do dissolve are ionized (Pauling radius, 0.216 nm). I^- is oxidized by dissolved oxygen, chlorine, and other substances in solution to become, for example, IO^- (iodite ion; diameter, 0.593 nm), which then becomes IO_3^- (iodate ion; radius, 0.326 nm). These reactions increase the radius of molecules, including iodine and its aquo-ions, by several fold in the water. When organic substances are present in solution, substances such as methyl iodide are adsorbed on activated charcoal (7). Molecules with an affinity for RO membrane materials dissolve in the membrane; they then diffuse across the membrane and permeate under the pressure differential (chemical potential differential) present. In contrast, molecules with no affinity for RO membrane materials are not adsorbed. This forms the basis of separation with RO membranes.

Although the ^{131}I removal observed following activated charcoal treatment was minimal, ^{131}I was below the limit of detection after RO. The physical adsorptive activity of activated charcoal is attributable to van der Waals forces, meaning that adsorbed substances may detach when saturation is reached or with the passage of time. The degree of detachment is thought to depend on factors including temperature and pressure due to flux and flow rate. The elevated level of ^{131}I following activated charcoal treatment at the two facilities may be attributable to such factors. It is likely that ^{131}I fell below the limit of detection after RO because water molecules were separated from other molecules, including ^{131}I, by the RO membrane.

The present analyses were performed under emergency conditions, with measurement times much shorter than normal. The limits of detection of 8 Bq/kg and 6 Bq/kg were therefore larger than the limit associated with the 10-h analyses performed under normal circumstances. (The limit of detection in 10-h analyses is 4 Bq/kg.) Measurements must be taken with normal measurement times in further studies.

Guidelines for drinking water include the WHO Guidelines for Drinking-Water Quality (8), which are used under normal circumstances, and the IAEA Safety Standards (9), which are applicable in emergency situations, as well as the warning issued by the International Commission on Radiological Protection (ICRP). The WHO Guidelines for Drinking-Water set a guidance level for ^{131}I at $\leq$10 Bq/L; the IAEA Safety Standards set a guidance level of $\leq$3000 Bq/L, and the guidance level in the ICRP warning is $\leq$300 Bq/L. Although extending the time of ^{131}I analysis with germanium semiconductor detectors reduces the limit of detection, the resulting radioactivity measurements are not thought to change. Our data suggest that in emergency conditions, radioactively contaminated tap water treated with RO at hemodialysis facilities where RO equipment is available can be used as drinking water that satisfies the WHO Guidelines for Drinking Water, provided that levels of radioactivity measured for 1800 seconds meet the guidance levels.

CONCLUSIONS

Low concentrations of radioactive contamination were detected in tap water, but treatment with a water purification system for hemodialysis reduced the concentration of radioactive substances in the resulting dialysate to below the limit of detection.

In future studies, samples must be analyzed under conditions used in normal circumstances, and measurements must be taken at other hemodialysis facilities where high concentrations of radioactivity have been detected in tap water. Criteria for radioactive

substances must be added to the existing criteria for bacterial colony numbers, endotoxins, and chemical contaminants in dialysate to prevent internal radiation.

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