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Design of Water Treatment Plants in the Year 2000 and Beyond

Cappelli G, Perrone S, Inguaggiato P, Ferramosca E, Albertazzi A.

Division of Nephrology, Dialysis and Transplantation,
University Hospital of Modena, Italy

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Introduction

During the last decade, a consensus has been reached among nephrologists on water quality being an essential key factor in modern dialysis. Since 1982, the Association for Advancement of Medical Instrumentation (AAMI) has set standards to avoid clinical problems of tap water from municipal supplies but most of the interest was focused on chemical contamination.[1,2] Studies on biocompatibility during the 80s drew more attention to the microbial contaminants.[3,4] At present, there is evidence on the pyrogenic substances of bacterial origin derived from the contaminated dialysate, which penetrate the intact dialyzer membranes and induce an inflammatory response in the patients. This reaction leads to the development or worsening of chronic complications such as bone disease, anemia, encephalopathy and amyloidosis.[5,6] Therefore, water treatment represents a fundamental aspect of the modern hemodialysis and technical aspects are of vital importance.

Reprint requests and correspondence to:

Prof. Gianni Cappelli
Division of Nephrology
University Hospital of Modena
Via Del Pozzo, 71, 41100 Modena, Italy

The Standard Setting

A proper water quality is usually defined as the one fulfilling the most up-to-date standards. This is a basic requirement as standards are derived from the official health care institutions and usually entered in national legislation. On the other hand, national standards may differ in the number and accepted levels of contaminants from one set of standards to another, with the risk of potentially toxic compounds not being included. This is due partly to the different basal levels of contaminants in tap water in different countries and partly to the slow procedure in setting or modifying a standard level. Table 1 shows the recommended limit values for USA (AAMI-RD5)[1] and Europe (European Pharmacopoeia 3rd Edition) and Renal Association in UK[7,8] as well as variations proposed for the United States by AAMI with new standards to be released in the next few months (AAMI-RD62). Anyway, it remains difficult to achieve a perfect chemical purity as new pollutants are released every year to the air by industry or dispersed by agriculture to the groundwater. Toxicological knowledge is linked to the development in analytical methods as well as to the

Table 1. Comparison of standards for water to prepare dialysate.

Substance (ppm)	AAMI RD5 (1)	European Pharmacopoeia 3rd Ed. (7)	Renal Association (8)	AAMI RD62
Aluminum	0.01	0.01	0.01	0.01
Ammonium		0.2		
Antimony				0.005
Arsenic	0.005			0.005
Barium	0.01			0.1
Beryl				0.0004
Cadmium	0.001			0.001
Calcium	2	2	2	2
Cyanide				0.02
Chlorine (free)	0.5			0.5
Chlorine (total)		0.1	0.5	
Chloramines	0.1		0.1	0.1
Chloride		50		
Chromium	0.014			0.014
Copper	0.1		0.1	0.1
Fluoride	0.2	0.2	0.2	0.2
Formaldehyde			0	
Magnesium	4	2	4	4
Mercury	0.0002	0.001		0.0002
Nitrate	2	2	2	2
Lead	0.005	0.1	0.005	0.005
Potassium	8	2	8	8
Selenium	0.09			0.09
Silver	0.005		0.005	0.005
Sodium	70	50	70	70
Sulfate	100	50	50	100
Tallium				0.002
Zinc	0.1	0.1	0.1	0.1
Bacteria CFU/ml	200	100	100	200
Endotoxins EU/ml		0.25	0.25	2

effects of a toxic exposure to a specific clinical picture. Therefore, the definition of an acceptable level of contamination could be sometimes inadequate or impossible to define. For example the accepted level of certain pesticides, fertilizers, aromatic hydrocarbons, several trace elements or radionuclides in dialysis fluids are awaited even though some limits have been determined for the drinking water. Moreover, responsibility in complying with standards has been defined in some countries. The AAMI, for example, states that it is the physician in charge of the unit that has the ultimate responsibility for selecting the maximum allowable levels of contaminants and for monitoring the treated water. On the other hand, the topic is not so clearly defined in Europe.[1]

Water treatment modalities

Due to the great variation in feed water quality, the requirements of water purification in individual dialysis clinics may vary. The system has to be customized for each single center, depending on the feeding water quality and the required capacity. There are several possibilities, but it is the responsibility of the manufacturers or suppliers of the purification system to recommend the components that are able to meet the requirements. The water purifycation system for hemodialysis in the United States needs to comply with the Food and Drug Administration (FDA) regulation of class II devices; while in Europe, it should comply with the rules for medical devices in risk class IIb.

The most frequently used components are represented by mechanical filters, oxidizing filters, cartridge filters, ultrafilters, carbon filters, ion exchanger and reverse osmosis units.[9] To ensure removal of all possible contaminants (particulate matter, soluble and insoluble inorganic compounds, soluble organic substances, heavy metals, trace elements, bacteria and pyrogens) the system is composed of several serially oriented components usually divided into a pre-treatment section and a final production unit. Table 2 shows the efficiency of different methods in removing the most common chemical contaminants. Mechanical filters are used to remove large particles and turbidity from the incoming water, and therefore they protect the following components from clogging or being damaged by particulate matter. Oxidizing filters remove excessive iron, manganese and sulfides by oxidizing and adsorbing these ions. Cartridge filters are used to protect components from small particles and they usually work in the range from 50 up to 5 or 3 microns. Ultrafiltration cartridges remove bacteria, pyrogens and other macromolecular compounds, by a combined mechanism of filtration and absorption. They are used to obtain ultrapure water or to avoid back contamination from distribution loop to the final osmosis unit. Ultrafilters reject contaminants in the range of 1000 Dalton to 0.1 μm particles, allowing most ions and small organics, such as glucose, to permeate the porous structure. Carbon filters absorb low molecular weight organic compounds such as chlorine, chloramines and some pyrogens from the water. The most common ion-exchangers used in dialysis are water softeners; they exchange calcium and magnesium present in the water with sodium salts, thus changing hard water to soft water with a proportional increase in sodium ions. Similarly ion exchange deionizers use two types of synthetic resins: one to remove the positively charged ions (cations) and another to remove the negatively charged ions (anions). Resins have limited capacities and need to be regenerated upon exhaustion. A demineralization or deionization unit is typically used on water that has already been prefiltered and uses a two-stage process to remove virtually all ionic material remaining in water. Deionizers have usually two-bed or mixed-bed configuration in which the cationic and anionic resins are in separate or single tank, respectively. Recently an electrical current has been used to reduce the ionic content of water, using special semipermeable membranes based on the charges of the ions. This component is called electrodialysis, which improves the efficiency of the classic deionizers, avoiding the troubles of using chemicals for regeneration. Two flat sheet membranes, to preferentially permeate cations and anions, respectively, are stacked alternatively with flow channels between them. Cathode and anode electrodes are placed on each side of the alternating stack of membranes to draw most ions through the membranes. This leaves much lower concentrations of the ions in water in the alternate channels. A recent development has improved the efficiency of electrodialysis by reducing scaling and fouling problems on membranes.

Table 2. Water treatment components: effect on contaminants removal.

	Mechanical filter	Micro filtration	Ultra filtration	Charcoal filter	Softener	Deionizer	Reverse osmosis	Distillation
Calcium Magnesium	0	0	0	0	+ + +	+ + +	(+ + +)	(+ + +)
Chlorine	0	0	0	+ + +	0	0	+	++
Chloramines	0	0	0	+ + +	0	0	+	++
Colloids	0	0	+ + +	0	0	0	+ + +	++
Fluoride	0	0	0	0	0	+ + +	++	+ + +
Heavy metals	0	0	0	0	++	++	+ + +	+ + +
Inorganic substances	0	0	0	0	0	+ + +	++	++
Nitrate	0	0	0	0	0	+ + +	+	+ + +
Organic substances	0	0	++	++	0	0	++	++
Particles	+++	+ + +	+ + +	+	0	0	+ + +	+ + +
Bacteria	0	+ + +	+ + +	0	0	0	+ + +	+ + +
Pyrogens	0	0 / +	+ + +	+	0	0	+ + +	+ + +

+++ = very efficient, ++ = efficient, + = poorly efficient, 0 = not efficient

Table 3. Selection of the components based on the contaminant removal ratios.

Substance	Ratio 0-1	Ratio >1-<10	Ratio >10
Aluminum	No treatment	DI or RO	RO+RO or RO+DI
Arsenic	No treatment	RO	RO+RO or RO+DI
Barium	No treatment	RO	RO+RO or RO+DI
Cadmium	No treatment	RO	RO+RO or RO+DI
Calcium	No treatment	Softener or RO	Softener+RO/DI/Softener
Chlorine (free)	No treatment	Carbon	Carbon+Carbon
Chloramines	No treatment	Carbon	Carbon+Carbon
Chromium	No treatment	RO	RO+RO or RO+DI
Fluoride	No treatment	RO	RO+RO or RO+DI
Lead	No treatment	RO	RO+RO or RO+DI
Magnesium	No treatment	Softener or RO	Softener+RO/DI/Softener
Mercury	No treatment	RO	Carbon+RO or RO+RO
Nitrate	No treatment	RO	RO+RO or RO+DI
Potassium	No treatment	RO	RO+RO or RO+DI
Silver	No treatment	RO	RO+RO or RO+DI
Sodium	No treatment	RO	RO+RO or RO+DI
Sulfate	No treatment	RO	RO+RO or RO+DI
Zinc	No treatment	RO	RO+RO or RO+DI

This has been obtained by reversing the polarity of the electrodes periodically and is called electrodialysis reversal.

Reverse osmosis removes virtually all organic compounds; 90 to 99% of all ions, and 99.9% of viruses, bacteria and pyrogens. Reverse osmosis membranes represent the heart of any water treatment system. They may sometimes differ in the efficiency of rejection or resistance to disinfectants. The membranes are sensitive and can be easily damaged by excessive hardness, iron and chlorine in the feeding water; hence a correct pretreatment is essential for the membranes to function properly.

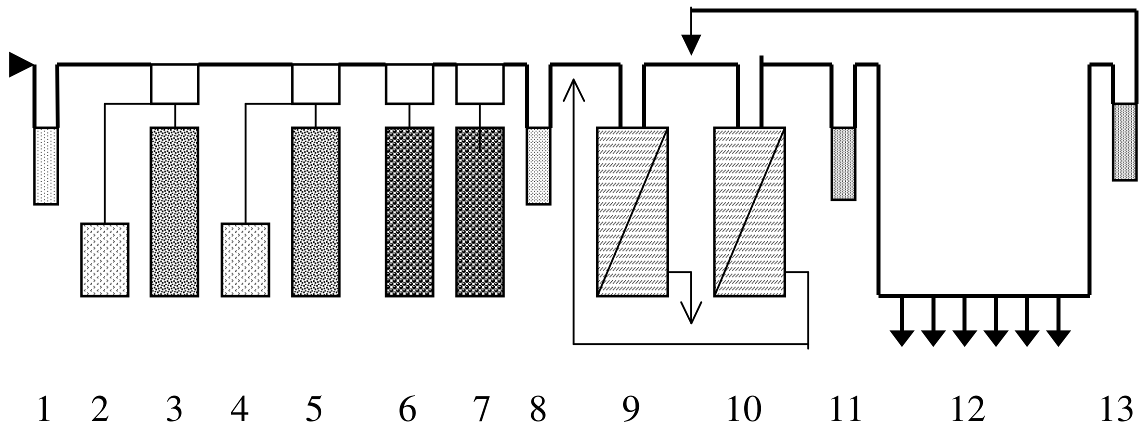

Figure 1. Schematic view of a modern water treatment system. See text for details.

The design of the water treatment plant

The key elements to be considered for choosing the most appropriate components to include in the water system are the feed water contamination levels and the maximum allowed or wished-for levels of contaminants in the final product water. One has also to take into account the amount of water required and the flow rate for each device. Based on removal ratio, that is the ratio for each known contaminant of feed water value to the standard level, it is possible to select the most appropriate component. Table 3 illustrates the possible selections based on removal ratio**.** Figure 1 shows a flow diagram of a typical water treatment system used in the production of highly purified water. Starting from the tap water a pressure reducer is sometimes needed to enter water into the pre-treatment section (Figure 1: shows the components from 1 to 13, which include a 25 µm cartridge filter (1), dual water softener (3,5) with brine tanks (2,4), two carbon adsorption filter in series (6,7) and a final 5 µm cartridge filter (8). The components 9 and 10 are a double reverse osmosis in series, where rejected water from the second osmosis is not discharged but is sent back to the pre-treatment section to spare it. The final component is a loop distribution system, where sampling points (12) are included between the 0.2 µm-antibacterial microfilters (11,13) to avoid back-contamination of the loop or of the osmosis membrane. This is a general description of the commonly used water treatment plant. Different plants, however, can achieve, in special situations, better results.[10,11] In general a pre-treatment with filters, softeners and activated carbons is always necessary. Placement of the activated carbon as the last component ensures a higher level of chlorine to disinfect softeners. However, the carbon resins will last less, and therefore it represents a solution with a higher maintenance cost. For the final treatment section, the combination of a single reverse osmosis with ultrafiltration or a deionizer unit has been reported. The first combination is especially active on bacterial contamination, while the second one on chemical contaminants.[12] The combination of the two reverse osmosis units in series is preferable[13,14] since in case of breakdown of any single osmosis component, the remaining unit can still serve to get reasonably good water quality while awaiting repair.

How to avoid bacterial contamination

Several studies have demonstrated that many dialysis complications are caused not only by bacteria or endotoxins but also by small derived fractions of bacterial origin able to induce cytokines production.[15] Current water treatment plants are effective chemical purifiers but many of them are, at the same time, good breeding grounds for bacteria. Reverse osmosis membranes offer 99.9% rejection of bacterial pyrogens, which could be inadequate in the presence of high contamination in the pretreatment section. Resin beds, multimedia filters, porous surfaces of some plastic and metal piping and areas of stagnant or laminar water flow (Reynolds number < 2000) are excellent in promoting bacterial growth.[3] Moreover, reverse osmosis membranes could be made of different synthetic polymers with variable performances in rejection rate for ionic species, temperature limit of stability, oxidation resistance (chemical resistance to the oxidizing agents such as chlorine), and, most importantly, biological resistance (the ability to withstand bacterial attack). If bacterial colonisation occur, the performance of even the best reverse osmosis membrane (modified polyamide, thin film composite) may decrease. Therefore, a new concept of hygienic chain has emerged. According to this concept, every section of the water treatment system has to have as low contamination as possible. To achieve this goal, the design of the water treatment system and its materials represent key points. Storage tanks should be avoided, due to difficulties in disinfection, as well as dead legs. Unprotected sampling or drain ports should be abandoned, and adequate drainage should be assured to the pipe. A constantly moving water is considered an essential factor to avoid bacterial growth; therefore a close loop distribution system represents the optimum design. Material used for piping has to offer smooth surfaces and good resistance to the disinfection procedure and to the release of chemicals or particles.[16] Medical grade polyvinyl chloride (PVC) has been the most used piping material. However, the AISI 316L stainless steel, cross-linked polyethylene (PEX) or polyvinylidene fluoride (PVDF) offer more advantages and are increasingly used. Notwithstanding the best water system, bacterial contamination will appear and therefore it is imperative to adopt some disinfection protocols to hold contamination at acceptable levels. Most disinfectants are chemicals (chlorine, chlorine dioxide, formaldehyde, glutaraldehyde, ozone, peracetic acid),[17] but experiences have also been reported with hot water (70°C or more), vapor or ultraviolet irradiation. The efficacy of this last process has been questioned as in killing bacteria it delivers bacterial fragments into the fluids. The ideal disinfectant should kill all strains of bacteria and inactivate the bacterial fractions, it should be easily removed from the system and monitored and it should also have no deleterious effect on the piping material or osmosis membrane. Recently, biofilm formation has been incriminated in the resistance to disinfectants and as a consequence the selection of the chemical and/or process used in disinfection procedure must be based on careful evaluation and testing of this aspect too.[18] As biofilms are very difficult to destroy, their formation should be prevented, using not only adequate material and a design avoiding low shear rates associated with slow water flow, but also using a disinfectant with detergent activity on a regular basis.[19,20]

Water quality controls and assurance

Whatever the water system in use, the only way to assure proper quality of water is to have a maintenance and quality control program.[21] Some parameters may be checked continuously with an automatic device while for most of them there should be periodical monitoring of which the frequency is regulated on manufacturer recommendations and on suggestions from the same reference standards authorities, even though, the monitoring process has not been clearly defined for each contaminant yet.[1,7] Recently a governmental document in France has laid technical details for "on-line" treatments and could represent a model for standard hemodialysis.[14] It suggests that, following validation, conductivity should be measured daily, chemical contaminants included in the standards of the European Pharmacopoeia should be checked at least every three months, while bacteria and endotoxins have to be checked monthly. Moreover, it recommends performing microbiological controls after maintenance check-ups. Guidelines of the Renal Association in UK suggested some years ago monitoring tap water monthly for total chlorine and nitrates and every three months for all chemicals. Furthermore, they suggested checking the bacteria and endotoxins in the finally produced water from the plant weekly, total chlorine and nitrates monthly, and all chemical contaminants in the tap water every three months.[8] The control program in a specific dialysis unit should be based not only on these suggestions but also on the knowledge of the specific local contaminants that require more frequent intervals, and on the balance with costs.[21]

Final remarks

In search of adequate dialysis,[22] many clinical and technical improvements have been achieved in the last decade, from exact dose quantification to better toxins removal as well as to an increased biocompatibility of the whole dialytic system. In this regard the use of ultrapure dialysis fluid represents an increasing tendency.[23] This high level quality water should not only be reserved to high-flux or on-line treatments but should be adopted in all treatments due to the awareness of the extent of microbiological contamination. With the exception of some centers, recent reports show that there is still a high percentage of centers that do not comply with the set-up standards either microbiologically (from 8% to 49%) or chemically (14%), in the United States, [24] Canada[12] or Europe.[25-28] Furthermore, there is still a controversy on the methods of microbiological analysis. Bacterial counts increase on all types of media if incubation time is prolonged from the standard 48 hours to seven days, while low nutrient media gives better results.[29] The presence of a quality assurance program is the cornerstone for obtaining high quality water. It is hoped that in the future, ultrapure water philosophy will spread among nephrologists to improve the quality of dialysis. Whatever the modality of treatment in use, quality controls should include the whole production chain.[3,14] As with any other quality system it will only work if the standards laid down are adhered to, and the methods of analysis are correctly implemented.

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