Ronco C, La Greca G (eds): Hemodialysis Technology.
Contrib Nephrol. Basel, Karger, 2002, vol 137, pp 227–232

The Ideal Hemodialysis Machine

Hans-Dietrich Polaschegg

Medical Devices Consultant, Köstenberg, Austria

The ideal dialysis machine does not exist and will never exist, simply because the term 'ideal' is not well defined. The 'medical ideal' machine would automatically adjust treatment parameters according to the need of the patient. This, however, would require a clear understanding of the dialysis physiology and clear goals for control parameters. Although sensors have been developed allowing balancing of electrolytes and energy and measuring blood volume changes, appropriate control algorithms are missing, possibly with the exception of thermal energy balancing. I therefore abstain from defining the 'medical ideal' machine that would require too many 'may' and 'might'.

For this investigation I define 'ideal' as realization of the utilitarian philosophers' *ideal* of 'the greatest good for the greatest number'.

Even so, I am unable to define a single 'ideal' machine good for all purposes. Rather the definition must be adapted to the environment in which the dialysis machine is used.

The 'greatest good for the greatest number' must include confirmed medical requirements, e.g., minimum dialysis doses, accuracy of controlled values, but also costs because the cost of dialysis prevents treatment of most of the world's population.

Systems Approach

The dialysis machine cannot be discussed isolated from the rest. It is part of an assembly consisting of the water treatment system, the dialysate concentrate supply, the dialysis machine, the extracorporeal circuit, the dialyzer and the data network. Its operation is related to processes. The most important ones being control of treatment, disinfection, waste management and maintenance.

A dialysis machine can only be optimized for a given environment. While dialysis machines are well standardized, water treatment and concentrate supply is not. A dialysis machine adaptable for every possible environment is not 'ideal' because it is too costly to manufacture and to operate because of many redundant components. In this paper I will therefore attempt to sketch the ideal dialysis system rather than the 'ideal machine'.

The GENIUS™ System

For medium-sized dialysis units, the GENIUS™ developed by the late Dr. Tersteegen appears close to ideal. It has the lowest number of components of any dialysis system on the marked, does not require elaborate water and electrical installation of the treatment rooms and can run on batteries for hours. It is a simple batch type dialysis machine. Some features that are regarded as drawbacks, e.g. fixed ratios of dialysate to blood flow, maximum blood flows of 300 ml/min were specifically chosen by Dr. Tersteegen and can easily be changed without changing the principle of operation. With Dr. Tersteegen's patents expiring in ~3 years competition may reduce the market prices for the system and make it more popular. For a description of the machine and the clinical applications see Kleophas et al. [1]. The batch system does not allow 'sodium profiles' which need not be regarded as drawback anyway but it allows individualization of the dialysate composition in a way not possible with conventional systems, e.g. addition of amino acids or vitamins.

Conventional Dialysis Units

Conventional dialysis units may still be preferable for the existing organizational structures. In the past such units were often operated with central dialysate delivery machines and bed side monitors. Criticisms of such systems were the lack of individual dialysate adjustment, bacterial contamination and the hazard of catastrophic failure in case of a chemical disinfection malfunction. Despite the lack of individualization of dialysate excellent and even superior patient survival rates have been reported from clinics using such systems as, e.g. Tassin in France [2]. Also, central delivery systems have been used widely in Japan and are still in use there. Today's technology makes it possible to design such systems without the drawbacks mentioned above.

State-of-the-art individual dialysis delivery systems reduce water pressure of the RO water to a level that can be handled by the hydraulic components of the machine. The machines heat and degas water, mix dialysate from two solid

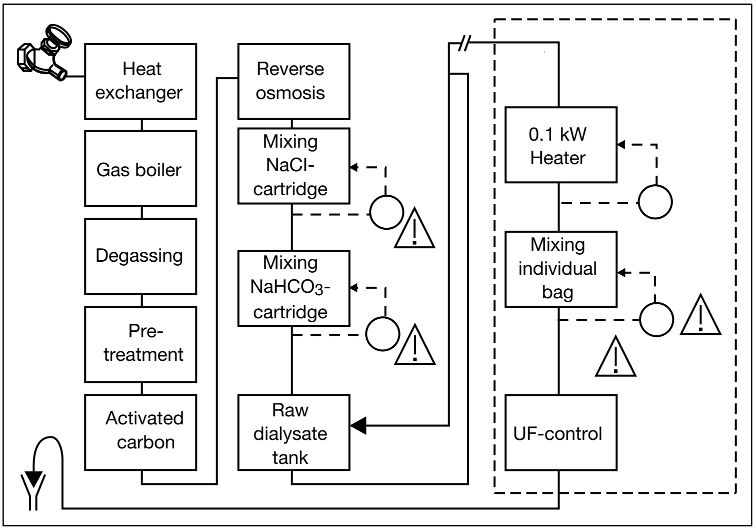

Fig. 1. Dialysis system with centralized heating, degassing and mixing of basic dialysate. Individual adjustment of dialysate composition and temperature is done at the bedside station.

and one liquid concentrate and provide for disinfection of the dialysate fluid path. Functional drawbacks of such systems are: separate disinfection of water treatment and dialysis machines with the connection between water distribution and individual machines often not disinfected at all; handling of concentrates and disinfectants, and waste of concentrates.

Technical drawbacks are an enormous waste of energy, complicated machine hydraulics and increased maintenance costs.

It is obvious that some functions as, e.g. degassing of water, can be done centrally without affecting the clinical usefulness of the dialysis machine. But also heating up to 35°C and mixing of a base dialysate containing, e.g. 134 mmol/l of Na and 30 mmol/l of bicarbonate can be done centrally. Also, automatic heat disinfection of the complete system can be easily carried out. Such a system is sketched in figure 1.

The following components of a dialysis machine would become redundant: The pressure reduction valve, heat exchanger, head tank, high-power heater, NaCl mixing, $NaHCO_3$ mixing and the disinfection system. The high-power heater would be replaced by a low-power heater allowing the machine to be designed as class II equipment.

Centrally, a high efficiency heat exchanger made from copper or a copper alloy can be used for heat recovery. Heat exchangers from copper are by far more cost efficient compared with stainless steal heat exchangers and would reduce fouling by bacteria. Next, heating can be done by a gas boiler alternatively hot water from a central boiler can be used. Effective degassing can be done by a combination of heat and reduced pressure. The quality of the material of all components upstream of the RO unit is uncritical which means that mostly conventional components used for hot water piping can be used.

Estimate of Potential Cost Savings from Heating Energy

Mean electrical heating power can be calculated by equation 1:

$$P_{heater}[kW] = (T_d - T_{in}) * Q_D * c_p * (1 - R) \qquad (1)$$

with T_d and T_{in} the dialysate and water input temperatures, respectively, [K] or [°C], Q_D. Dialysate flow [liters/s], c_p…specific heat of water [kJ/kg·K] and R … recovery rate of the heat exchanger.

For $T_d = 37°C$, $T_{in} = 10°C$, $Q_D = 500$ ml/min, $c_p = 4.18$ and $R = 0$ (no heat exchanger) we get:

$P_{heater} = 0.94$ kW.

A dialysis machine running two 4- to 5-hour shifts a day will run ~4,000 h per year that means that each machine consumes ~3,760 kWh of electricity per year for heating. Heat exchangers as used in some dialysis machines recover approx. 30–50% of this energy.

The following example uses oil and electricity prices for an Austrian household 2001:

Electricity cost per kWh ~0.13 €.

Oil heating cost per kWh are ~0.039 € (heat of combustion for 1 liter of oil extra light ~10.2 kWh, 90% boiler efficiency).

We can now calculate the cost for dialysate heating per year (per dialysis station). With central heating, the individual temperature adjustment, an increase of 2°C maximal will still be done by electrical heating.

Depending on the comparison used (with/without heat exchanger) the cost saving ranges from ~97 to 411 € per machine and year (table 1). In the USA, where the price difference between electricity and natural gas is higher, the cost savings may be more. Also, the savings do not take potential cost savings by using environmental sources, e.g. solar collectors into account.

Most suppliers of electricity charge a basic fee depending on installed power in addition to the delivered electricity. This basic fee will be considerably reduced because the installed electrical power will be reduced by ~80%.

Table 1. Cost of dialysate heating (EURO) per dialysis machine and year

	Conventional	Central (oil, gas)	Bedside (electricity)	Central (sum)
Without heat exchanger	488.80	135.78	36.21	171.99
With optimized heat exchanger	268.84	40.73	36.21	76.94

Reduced Complexity of Bedside Stations

As an example, the flow diagram of the Fresenius 4008 from 1998 was checked. From 83 hydraulic components listed (pumps, valves, chambers, connectors) 43 could be eliminated if degassing, dialysate mixing, heating and disinfection is centralized as described above.

Reduction of the complexity of the dialysis machine will not only reduce the initial cost of the hydraulic system but also the cost and power consumption of the electronics required for operation of the hydraulic components. The machine described as example dissipates approx. 500 W to the environment. In countries where air conditioning is required this energy loss must be removed by air conditioning, usually with an efficiency of 50% or less. This means that savings of 200 W in the dialysis machine will result in reduced energy consumption for air conditioning of 400 W or power savings of 600 W total per machine. These savings are in the same order of magnitude as the savings for dialysate heating.

Reduced Concentrate Consumption

Powder cartridges are usually designed for 6 h of dialysis operation. The residues remaining after shorter treatments are usually discarded. The residues in a central supply system are much lower. Also, the volume of solid waste will be reduced.

Discussion

The basic idea of the system proposed has been described by Murisasco et al. [3]. With today's technology and knowledge this system can be further simplified. Technical development of such a system is comparably simple. Any change of the infrastructure of dialysis units, however, involves many people who must be educated and trained, and the necessary modifications can only be introduced gradually. It requires long-term thinking for introducing such a system. A country or an organization intending to develop a dialysis program for 10,000 people will require ~2,500 dialysis machines. With estimated cost savings for system investment of 25% or 5,000 € per dialysis station the initial cost savings would be 12.5 Mio €, enough for covering the costs of development. For existing systems, step-wise adaption is possible by, e.g. starting with central heating.

References

1 Kleophas W, Haastert B, Backus G, Hilgers P, Westhoff A, van Endert G: Long-term experience with an ultrapure individual dialysis fluid with a batch type machine. Nephrol Dial Transplant 1998;13:3118–25.

2 Charra B, Calemard E, Laurent G: Importance of treatment time and blood pressure control in achieving long-term survival on dialysis. Am J Nephrol 1996;16:35–44.

3 Ragon A, Reynier JP, Murisasco A, Elsen R, Leblond G: Dialysate sodium control during modeling in hemodialysis. Artif Organs 1985;9:63–65.

Dr. Hans-Dietrich Polaschegg
Oberdorf 92, A–9231 Köstenberg (Austria)
Tel. +43 4274 4045, Fax +43 4274 4096, E-Mail pg@compuserve.com