Purifying polluted water through hemodialysis filters for poor villages without electricity: the easy water for everyone approach and experience
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ABSTRACT
Background: Given the need for treating polluted drinking water, our NGO Easy Water for Everyone has produced pure water in remote villages without power and achieved health benefits. With the goal of reaching more needy populations we report our experience and successful implementation in Ghana. Methods: In 20 villages polluted water is pumped every few days to an elevated water tank connected to a filtration device leading to a faucet. Repurposed hemodialyzers with polysulfone membranes, having a filter pore size of 0.003 micrometers, prevent passage of pathogens. Results: Gravity from a 3 m height pushes water through the membrane whenever the faucet is open. Backflushing of the hemodialyzer membrane 3 times daily removes built-up of organic material and maintains flow rates of 250 L/hour for at least 2 years. Filtered water has been culture negative. Management of problems and optimization are reported. The 5-year cost per village of <1,500 population averaged <2 US$ per day.

Key words | diarrhea from infected drinking water, hemodialyzers for removal of pathogens, low cost drinking water without electricity, polysulfone membrane, purification of polluted water, village health in Subsaharan Africa

HIGHLIGHTS
- Hemodialyzers filter polluted water into drinking water in 20 villages with no electricity.
- The polysulfone membrane’s pore size rejects pathogens including bacteria & viruses.
- The documented reduction in diarrhea is obvious to villagers.
- The cost per village (<1,000 people) for pathogen-free water is <$2/day.
- The simplicity of gravity-force and its benefits encourages self-sufficiency for sustainability.
GRAPHICAL ABSTRACT

INTRODUCTION

Surface water is often polluted with parasites, bacteria and/or viruses that can cause serious health issues (Piper et al. 2017). Diarrhea is a common result of drinking water polluted with pathogens and is associated with markedly elevated mortality risk, particularly in children (Levine et al. 2020). Pollution of drinking water is magnified near slow-flowing rivers and stagnant waters in villages where sanitation facilities are unavailable and when farm animals are nearby. Well water is also susceptible to such pathogens particularly when boreholes or wells are shallow or intermittently overcome by rising water tables. Purification of water from such contamination is feasible and highly effective when electricity or solar power is available (Peter-Varbanets et al. 2009). However, electricity is often not available in remote villages of developing countries, where a substantial proportion of their populations lives. Remote villages are also difficult to reach for distribution of sachet water derived from reverse osmosis treatment (Semey et al. 2020). In absence of power, alternative approaches currently used worldwide include biosands providing some decontamination, and the addition of antiseptic agents such as chlorine to kill remaining pathogens (Clasen et al. 2007). The monitoring of levels of toxic antiseptic agents may identify low levels thus indicating unsafe drinking water, while high levels may make the water unpalatable and lead individuals to choose unsafe water.

Our alternative approach particularly for areas without power is based on knowledge and experience from clinical hemodialysis for patients with kidney failure. Hemodialyzer membranes have been shown to be effective in producing sterile water that can be safely infused intravenously to patients during hemofiltration after addition of appropriate
electrolytes (Canaud et al. 2004). The chemical composition of the source water is not of interest here, since it is not modified by filtration as electrolytes and larger molecules pass freely through the hemodialyzer membrane. Having recently documented initial significant public health benefits in Ghana using our novel filtration system based on use of reprocessed once used polysulfone hemodialyzers (Raimann 2019), we report here further experience with this relatively simple technique for the preparation of drinking water from polluted river water in villages, where electrical power is lacking. With the goal of spreading this successful technique to many more needy populations in Ghana and elsewhere, we describe the practical technical design and improvements through refinements in our approach over recent years at twenty rural communities in Ghana. We also report on the magnitude of water production and cost estimates per village served.

METHODS

A particularly urgent need for uninfected drinking water was identified in Ghanaian rural villages in the estuarial region of the massive Volta River. For these villages the river has been the main source for drinking water even though it has been known to carry pathogens of fecal origin. Power has not been available in these villages, most of which are located on islands in the river. Based on the needs identified by a local physician/regional hospital director (Dr P. Narh) and driven by the interest within a given village, facilitated by a local radio station, our Non-Government Organization, Easy Water for Everyone (US based), has offered to install and maintain a hemodialyzer filtration device for water purification in many of these villages.

The dialyzer membrane filtration device (NUF500), developed by Yoram Lass (Lass 2017) and manufactured by NUFIltration (Caesarea, Israel) consists of a set of 8 hollow fiber hemodialyzers. The previously once-used medical hemodialyzer filters had been cleaned and sterilized according to the US standards of the Association for the Advancement of Medical Instrumentation (AAMI 2020) prior to being used for water filtration. Each hemodialyzer contains over 10,000 capillaries of polysulfone fibers with a resulting surface area close to 2 square meters. The membrane pore size is remarkably small, 0.0053 micrometer (Fresenius Medical Care 2020), thus preventing passage of bacteria, parasites and viruses, but nevertheless enables an output of 250 L pure water per hour when used in a setting where filtration is driven by gravitational force. Contaminated water from river, lake, borehole or well is pumped to a storage tank above the device and enters the inside of the hollow fibers or capillaries, while only clean water is forced to the outside of the capillaries. Organic matter that accumulates on the inside of the capillary fibers needs to be flushed away intermittently by short periods of opening the outflow of the hollow fiber compartments and pumping manually the source water through the open capillaries (‘backflushing’).

After approval by appropriate local committees, the device is set up within each village at a spot close to a source of the polluted water. During several months before and after initiation of the filtration system, monthly information is obtained (after written informed consent from each household) with particular emphasis on health issues including the occurrence of new diarrhea episodes among its members. Drinking water becomes available for everyone after bacteriological testing has verified the safety of the water. Data collection on diarrhea continues monthly over the next year. The results of the bacteriological testing are shared with village leaders, who are later informed on the improvement of public health in the partnering villages.

RESULTS

The water source is typically a lake or river that has been known to be persistently polluted with pathogens particularly coliform bacteria and fecal coliform bacteria, associated with lack of sanitation. When needed we have also purified water from wells or boreholes that have been chronically polluted. A large hose with its inlet protected by a coarse sieve is submerged in the water source, e.g. near the edge of the river. From there it is pumped to a large elevated tank using a gasoline pump. As shown in Figure 1, dirty brown river water, when pumped through the hemodialyzers, comes out as clear water that shows no bacterial growth on culture. Bacterial cultures of water at
The Ghana Standards Authority certified that the filtration system derived filtered water fulfilled the requirements of the Ghana Standard ‘Water Quality – Specifications for Drinking Water’. Bacterial cultures of water at the faucet of the device have been negative for pathogens. The Ghana Standards Authority certified that the filtered water fulfilled the requirements of the Ghana Standard ‘Water Quality – Specifications for Drinking Water’. These standards require testing by the Council for Scientific and Industrial Research of Ghana and zero counts (cfu) per 100 mL for fecal coliform and for other coliform bacteria, while allowing heterotrophic water bacteria at counts up to 500 cfu/mL.

**DESIGN OVERVIEW**

The flow pattern: The polluted water is stored in an elevated storage tank from where it is released on demand to flow by gravity to the hemodialyzer filtration device and from there to the faucet (Figure 2).

**FILTRATION DEVICE**

Eight hemodialyzers are set up in parallel by dividing the flow from the storage tank into connectors to the hemodialyzer inlet to the lumens of the capillaries. The corresponding hemodialyzer outlet remains closed during filtration. The compartment outside the capillary membranes collects the sterile filtrate. The tubing from each of the 8 filtrate outlets are joined into one tube that connects to the faucet. Filtration occurs only while the faucet is in the open position.

**BACKFLUSHING**

Since particulate matter in the polluted water will accumulate in the hollow fibers of the filtering membranes over time, it is necessary to flush the capillary membranes intermittently. This is achieved by opening the block in the outflow of the capillary compartment and manually pumping the polluted water through the dialyzers. Initially this back flush water has a very dirty appearance and its change to a clear appearance indicates the success of clearing the debris off the hollow fiber membranes. It takes typically about 5 minutes of manual pumping, which needs to be done 3–4 times daily to maintain long-term function of the
filters. After closing the capillary outlets again and bypassing the manual pump, success can also be verified by observing the improved flow rate for a goal of 250 L/hour by gravity flow.

DETAILS AND REFINEMENTS

Water storage

The water enters the large (1,000 or 4,500 liters) reservoir. The size of the tank is chosen according to the size of the population served. This tank is elevated by 10–14 feet (3–4.3 m) to provide the gravitational force for filtration. Since the filtration device is about 2 feet above the ground, the filtration pressure is based on a minimal height difference of 8–12 feet, i.e. when the tank reservoir is nearly empty. Since growth of algae in the polluted water is known to be facilitated by exposure to sunlight, the tank and all lines have a black color. Water flows from the storage tank through the filter device on demand, i.e. whenever the faucet is opened. Efficiency is improved by inserting two simple commercial pre-filters at the outlet of the elevated tank as these reusable filters remove leaves, dust and particulate matter. These pre-filters are cleaned or replaced every 2–4 weeks.

The hemodialyzer filtration device

This device contains the eight commercial hollow fiber hemodialyzers that had been reprocessed after one clinical use. The reprocessing procedure has been a standard procedure for reuse on the same patient in some hemodialysis facilities (ANSI-AAMI 2020). The NUF500 device has been designed and patented by Y. Lass (Lass 2017). It is shipped by NU Filtration from Israel with pre-assembled connections to the 8 hemodialyzers to the site for installation. It allows easy connection to the single inflow tubing and the single outflow tubing. The polluted water flows into the hollow fiber compartment (blood compartment for hemodialysis) and its outlet at the bottom remains closed. The tubings from each filtrate side are joined and lead to the faucet to provide pure drinking water at the faucet. Filtration and flow occurs only when the faucet is in the open position.

TECHNICAL REFINEMENTS

The elevation of the water reservoir is a potential variable that deserves discussion. A greater height differential to the hemodialyzer provides greater flow rates at the faucet, but requires a stronger construction for a higher elevation of the large tank on a concrete foundation for stability. An elevation for the tank of 3 m above ground has been typical although a greater height difference may be advantageous for larger communities. Flow rates of 250 L/hour have been common particularly after each back-flushing procedure even over longer terms.

As an alternative to this gravity driven design, this same device could be set up for manual pumping, which could achieve flowrates as high as 500 L/hour.

Assigning maintenance tasks to a village:

Since backflushing needs to be done 3–4 times daily, this task had to be assigned to 2 or 3 villagers after they had been trained by our staff. Initially our NGO paid for this service by the trained villagers. Some village elders felt that this task should be the responsibility of the village and thus not depend on donated money. We welcome such independence and are working with other villages to follow this example. Working through established village committees to provide initial and ongoing education has contributed the success of the project. Through these brief and periodic education sessions, the village population, including school children, has recognized the benefits of clean drinking water. This has brought about community empowerment, and contributed to the care, maintenance and sustenance of the devices.

Filling the water tank with the contaminated source water, e.g. river water, has been done typically 2–5 times weekly by our staff. A staff member of our NGO comes to the site by boat bringing a gasoline-driven pump to fill the tank and verify the flowrate for the drinking water. Recently some villages have indicated that they would like to perform this service themselves. Given the relatively low cost of the pump, we now provide a new pump to selected villages to allow them to become even more independent. Our plan is to maintain regular but less frequent (e.g. monthly) visits from our NGO staff member to assure that everything is working well.
Observed problems and solutions

Vandalism: Willful destruction to our devices has occurred at one of the sites. To prevent vandalism we have since enclosed the entire filtration device in a locked metal cage at all sites.

Growth of algae in the water tank: Knowing that light (sun) exposure enhances growth of algae, we switched to using all black tubings within the initial year of operations and have always utilized black water tanks. However, algal growth was observed in the polluted water in three villages. The sterility of the drinking water was not affected by this growth. However, algal accumulation needs to be treated and avoided. For treatment of an outbreak we placed bleach into the tank and tubings and let it temporarily bypass the filter device. After exposure, the entire system was thoroughly rinsed and then the inflow tubing was reconnected to the device. No recurrence of algae was observed in subsequent months.

Duration of hemodialyzer function: Hemodialyzers have continued to function well beyond one year. In fact, some have remained functioning for 4 years. Since the cost of 8 replacement hemodialyzers is very low ($8 each) we arbitrarily instituted a protocol to replace the hemodialyzers every other year.

Ability to increase clean water availability for a village: We aim to have ample water available for each village so that water generated is used not only for drinking but also for handwashing and other purposes. The amount of water available per day can potentially be very high since flow is ‘on demand’ whenever the faucet is opened day or night. Far greater water consumption can be easily supported by filling the water tank more often, up to seven times weekly. The added cost would be very small. We estimate that the current design could easily serve villages up to 1,500 population, even when handwashing becomes common practice. We recommend handwashing with soap as is also strongly supported by published work (Ejemot-Nwadiaro et al. 2013; Piper et al. 2017).

Contamination of the filtered water lines: In 2020 counts for heterotrophic bacteria were found to exceed the allowable levels in four villages. Since pathogenic coliform bacteria continued to be removed by the hemodialysis filters (zero cfu/100 mL), this finding would not indicate failure of the membrane but rather an upstream contamination of the lines from the faucet. This was treated by a procedure that temporarily blocks the hydrostatic pressure and installs a hypochlorite solution from the faucet upstream to the hemodialyzers for a 15-minute dwell. After subsequently discarding the bleach with newly filtered water for several minutes until the taste and odor of bleach could no longer be detected (verified by undetectable levels in analyses), the system was again functioning well and levels of heterotrophic bacteria were zero or in acceptable ranges. This procedure is scheduled to be repeated on a monthly basis until we are certain that the water meets all standards consistently.

Cost of providing clean water per village:

It is difficult to accurately estimate the cost/liter; however the cost per village can be estimated and should include clean water for handwashing. We recognize that costs for the initiation of this system are quite high, but we have experience in that the life span of the system already exceeds 4 years in Ghana. Therefore, Table 1 provides the overall

| Table 1 | Cost estimate for a village during the first 5 years |
|----------------|-----------------|-----------------|
| Initial costs: | per village (US$) | 5-year cost estimate |
| Foundation, tower, cage | 600 | 2,256 |
| Water tank | 256 |
| Hemodialyzer filtration device | 1,100 |
| Shipping, customs | 300 |
| Subtotal: | 2,256 |
| Maintenance costs: | (per year) per 5 years |
| Prefilters (reusable) (60) | 300 |
| Hemodialyzers (every 2 years) (32) | 160 |
| Spare parts, pump (shared) (100) | 500 |
| Subtotal: | 960 |
| Overall 5 Year Total: | 3,216 |
| Daily cost for clean water per village | 1.76 |

Note: personnel and indirect costs are not included here.
cost estimates per village of up to 1,500 population averaged over the first 5 years.

The overall estimate assumes that staffing and indirect cost are paid by the community. The averaged annual cost of $ 643 translates to $1.76 per day serving a village of up to 1,500 population. Thus, a daily cost of less than $ 2.00 on average can serve a village of <1,500 residents with unlimited clean water for the first 5 years (and beyond).

**Observed health benefits**

In a prospective study (Port et al. 2020; Raimann et al. 2020) we collected data monthly on the incidence of diarrhea in the households of 4 villages before and after implementation of our water treatment during February through November 2018. The incidence of diarrhea for the two 5 month periods before and after implementation of the hemodialyzer filtration device was recorded.

The monthly rate per 100 villagers averaged 8.1 before versus 3.0 after initiation of the hemodialyzer filtration device. This suggests a 63% reduction in diarrhea incidence (rate ratio = 0.37) when the drinking water source changed from polluted river water to hemodialyzer filtered water. In a control group of 5 villages in the same area that had not (yet) initiated our filtered water system during the same calendar months, the same analysis suggested only a non-significant reduction in diarrhea incidence during the second 5 months.

These analyses were based on 2,605 villagers who participated in the monthly data collection. The large reduction in diarrhea has been noticed right away andy praised by mothers and teachers.

**Current status**

As of February 2020 there were 20 villages with functioning devices in Ghana and one in Uganda. The population served with hemodialyzer-filtered clean water consisted of approximately 8,000 villagers. Additionally, about 2,000 schoolchildren have full access to pure water for drinking and handwashing while in school.

Expansion to four additional villages was already accomplished in early 2020 in Ghana with more units planned for this year. In collaboration with two other NGOs, the same system for clean water is being prepared for installation in villages in Uganda and Senegal.

**DISCUSSION**

During the past 4 years, the implementation and refinement of our gravity-driven hemodialyzer filtration device have allowed us to demonstrate the success of providing clean and pathogen-free drinking water to villages where sources of water have been consistently contaminated with fecal pathogens. Since this system works well even in remote areas without any available power, we have focused primarily on villages that previously have had no other opportunities for obtaining clean water. No restrictions on water use will need to be imposed even when our encouragement to also use clean water for frequent hand washing receives full acceptance in the villages. We agree with numerous publications that emphasize the additional health benefits from handwashing (Ejemot-Nwadiaro et al. 2015; Piper et al. 2017). When more water is desired, we are able to increase the frequency of filling of the main water tank to several times a week, or potentially even daily. We are currently developing a method to measure the actual consumption of pure water, but we are certain that it is far below maximum capacity of water provision with the device in all studied villages.

In remote villages, the use of solar panels might be a useful alternative to the gravity-driven design discussed here. However, it will substantially increase the cost and the complexity of its use and perhaps also its maintenance. Given the advantages of our gravity-driven system including simplicity and greater cost-effectiveness, we have not explored a solar energy driven alternative and have therefore not gained any experience with it. Of note, one village served by our NGO had solar panels installed two years prior to our arrival, however they had never been put to use at that village.

The polysulfone membrane used in our hemodialysis-based device is superior to a recently tested PES hollow
fiber membrane, as a recent report shows that E. coli is incompletely removed by this membrane (Carolyn et al. 2020). Alternative approaches to water purification in rural environments include reverse osmosis; however this requires power to produce sufficient pressures for filtration. Sachet water from reverse osmosis is available for sale in some areas in Ghana, however distributions are within small areas with a median radius of 10–14 miles (Semey et al. 2020). Another system uses low pressure filtration through organic filters such as biosands. These are not capable of eliminating all viruses. Most other approaches can remove larger pathogens and reduce counts of smaller pathogens. Therefore addition of antiseptics, such as chlorine or bleach to the drinking water is often recommended in order to kill remaining pathogens. Unless very closely monitored for maintaining optimal concentrations of the antiseptic throughout the system, potential problems arise related to inadequately low concentrations or excessively high concentrations that may lead villagers to drink unsafe water. In the absence of electrical or solar power our approach of filtering polluted water through repurposed hemodialyzers is unique and highly effective in the complete removal of all pathogens. The pore size of 0.0033 micrometer is unusually small and is sufficient to prevent passage of even small pathogenic viruses. It has been noted that close to one third of clinical diarrheas may be caused by viral infection (Wood 1988).

While we are not able to make prospective comparisons of different methods of removing pathogens from water in the field, our dialyzer filtration has several unique advantages: [1] It works well in the absence of power, [2] it requires only intermittent (typically twice weekly) pumping of the source water into a large holding tank using a gasoline-driven pump, [3] its hemodialyzer filters are inexpensive (repurposed) and have lasted for over 2 years, [4] the backflushing procedure can be managed by villagers after brief training, [5] villagers have embraced this approach, [6] the clinical benefit of substantial reduction in diarrheal incidence has been well documented (and is spontaneously reported by mothers and clinic staff) and [7] the overall cost of clean water for a population of up to 1,500 villagers when averaged over a 5 year period is estimated to be US$ 1.76 per day. Thus, a whole village can receive pathogen-free water for a price comparable to a couple of grocery-bought bottles of water per day.

CONCLUSIONS AND OUTLOOK

We have demonstrated the successful use in 20 remote villages of a filtration device that is based on hemodialyzers to convert polluted water to pathogen-free drinking water. It works well for entire villages (<1,500 population) in remote areas that have no power source. Despite a substantial initial expenditure the overall cost including maintenance is low over time with good sustainability of its use. Importantly, we have documented beneficial effects on public health in the studied villages with a clear reduction in the incidence of diarrhea after the initiation of the repurposed hemodialyzer filtration devices for drinking water. Since availability of clean water is unrestricted with our system, we are currently encouraging regular handwashing with filtered water. We conclude that the use of this device utilizing repurposed hemodialyzers in our gravity-driven system is a simple, highly effective and low-cost approach to serve remote communities in developing countries where water is exposed to fecal contamination.

We find it particularly encouraging to observe that some villages are working eagerly toward running our system independently. Considering that the dialysis industry produces millions of hemodialyzers annually, large-scale efforts to sterilize dialyzers rather than discarding them after a one time clinical use and using them for water purification could solve problems of polluted water more widely in Ghana and elsewhere. We hope to assist others in extending this useful approach for the benefit of villagers in poor regions with high incidences of waterborne disease especially in young children.

CONCLUSION

Our experience with disinfecting drinking water through gravity-fed hemodialyzer filtration shows longer-term success and acceptance in addition to our reported reductions in diarrhea. Simplicity, high effectiveness and low cost
makes this hemodialyzer system particularly useful wherever villages have infected drinking water.

CONFLICT OF INTEREST STATEMENT

The lead author, Dr Friedrich K. Port, affirms for all authors that they have reviewed and contributed to this manuscript. Jochen Raimann and Seth Johnson are employees of Renal Research Institute; all other authors declare no conflict of interest. This study has been supported solely by the non-government organization (NGO), Easy Water for Everyone.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


