CRYPTOSPORIDIUM SURROGATE REMOVAL IN PILOT-SCALE RAPID SAND FILTERS AND HOUSEHOLD FILTERS

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ABSTRACT

Drinking-water contamination by pathogenic *Cryptosporidium parvum* and *Cryptosporidium hominis* poses a serious health risk. Insufficient oocyst removal in drinking-water has caused numerous cryptosporidiosis outbreaks worldwide. As *Cryptosporidium* oocysts are extremely resistant to traditional disinfection, filtration through porous media plays a very important role in the removal of *Cryptosporidium* oocysts during drinking-water treatment. To ensure safe drinking-water supplies, the filtration efficiencies of treatment systems need to be assessed to optimise filter operations and better plan disinfection steps.

Using pilot-scale experimental facilities, we assessed protozoan filtration efficiencies in 3 different rapid sand filters and 5 different point-of-use household filters commonly used in New Zealand. Glycoprotein-coated polystyrene microspheres were used as a *Cryptosporidium* surrogate. The modified microspheres mimic the size, density, shape, surface charge and surface macromolecules of *Cryptosporidium* oocysts, and have been satisfactorily validated alongside *Cryptosporidium* in New Zealand and overseas in laboratory and pilot-scale coagulation-filtration studies.

The pilot filtration plant was located at the Branxholme Water Treatment Plant (WTP), which treats water sourced from the Oreti River. The pilot plant's feedwater came from the WTP's clarifiers post-coagulation with polyaluminium chloride (PACL) or alum. The sand filters comprised anthracite, pumice or Macrolite engineered ceramic sand, and simulated a typical water treatment plant's operational condition. The filter (15 cm diameter) contained 1 m of granular media (70 cm filter media: 20 cm silica sand: 10 cm pea gravel) and it had a 40 cm water column head. The surrogate's $\log_{10}$ reduction values (LRVs) based on the peak concentrations were >3 in 100%, 70% and 41% of the trials with the ceramic sand, pumice sand and anthracite filters, respectively. The LRVs achieved in the ceramic sand filter trials (4.44 ± 0.38) were significantly greater than those in the pumice sand (3.21 ± 0.30) and anthracite (3.01 ± 0.70) filter trials ($P<0.00001$).

The data describing the media filtration efficiencies could help WTP operators improve their practices for ensuring drinking-water safety. This could be achieved, for example, by using more effective filter media, allowing sufficient time for the water to run to waste after backwashing before the filter is brought back on-line and incorporating additional post-filtration treatments.

A full-scale filter test rig was custom-built to simulate typical household-use conditions (40 psi, 21.6 L water/day treated, intermittent operation). The data from 120 test runs (duplicate filters, 24 replicate runs per filter type) indicated that the surrogate particles' LRVs were 3.93–4.54 in the 1 μm nominal activated carbon filters, 1.95–2.94 in the 2 μm nominal silver-impregnated activated carbon filters, and < 1.0 in the 1 μm nominal polypropylene, 1 μm nominal polyester and 1 μm absolute pleated-paper filters. To achieve an LRV>3, which is a requirement of domestic drinking-water treatment units for protozoan reduction, 1 μm activated carbon filters are recommended. To satisfy protozoan removal requirements when using the other four filter types tested, additional treatment, for example, water boiling or ultraviolet disinfection, is necessary.

KEYWORDS

Cryptosporidium, surrogate, filtration, $\log_{10}$ reduction value, rapid sand filter, household filter

PRESENTER PROFILE

Liping Pang is a science leader at ESR with a PhD in civil engineering. Her expertise is in the experimental investigations and modelling of contaminant transport in porous media, in particular subsurface microbial transport. Her recent research involves developing synthetic pathogen surrogates and DNA tracers for water applications.

INTRODUCTION

Drinking-water contamination by *Cryptosporidium parvum* and *Cryptosporidium hominis* protozoa poses a serious health risk. *Cryptosporidium* oocysts, which are shed in the faeces of infected humans and animals, are often found in the source waters of water supplies. Insufficient oocyst removal during drinking-water treatment has caused numerous cryptosporidiosis outbreaks worldwide. New Zealand has a higher incidence of drinking-waterborne cryptosporidiosis than other developed countries (Efstratiou et al., 2017) due to high livestock densities and the widespread use of surface water for drinking-water sources.

Filtration through porous media plays a very important role in the removal of *Cryptosporidium* oocysts during conventional drinking-water treatment and point-of-use household water treatment. To ensure safe drinking-water supplies, the filtration efficiencies of treatment systems need to be determined to optimise filter operations and better plan disinfection steps. The current practices used to assess *Cryptosporidium* removal during conventional water treatment rely largely on the use of turbidity as a performance measure. However, the endpoint turbidity level does not measure the filtration efficiency directly nor does it indicate the oocyst removal level that may be achieved (Monis et al., 2017).

For point-of-use household drinking water treatment, it is essential to use filter cartridges that have effective pore sizes that are smaller than the oocysts, which are 3.9–5.9 µm in diameter. However, many commercial suppliers do not provide information that describes the cartridges' absolute pore sizes and only nominal pore sizes are given. Thus, the actual effectiveness of filter cartridges that are rated using nominal pore sizes for oocyst removal is unknown.

Working with *Cryptosporidium* oocysts poses health risks and their detection is expensive. We have developed a new *Cryptosporidium* surrogate by coating glycoprotein onto carboxylated polystyrene microspheres (Pang et al., 2012). The microspheres have the size, density and shape similar to oocysts, while glycoprotein and *C. parvum* share very similar isoelectric points, and glycoprotein is the predominant macromolecule on the oocysts' surfaces. The surrogate's mimicry of *Cryptosporidium* has been satisfactorily validated in different porous media (Liu et al., 2019; Zhang et al., 2017; Stevenson et al., 2015; Pang et al., 2012) and a pilot-scale study involving conventional coagulation and filtration through sand-anthracite dual-media (Monis et al., 2017).

We have recently conducted research in assessing some sand filter media (Pang et al., 2022) and household filter media (Pang et al., 2021) that are used in New Zealand for their relative efficiencies at removing the *Cryptosporidium* surrogate.

CRYPTOSPORIDIUM SURROGATE REMOVAL IN PILOT-SCALE RAPID SAND FILTERS

Most WTPs in New Zealand use imported anthracite filter media, but some plants also use imported Macrolite engineered ceramic sand filter media or New Zealand pumice sand. Thus, these filter media were evaluated for their efficacies in removing protozoa.

A pilot-scale filter was installed at Invercargill's Branxholme water treatment plant (WTP) and operated by council's water treatment staff. The pilot filter (15-cm diameter) contained 1 m of porous media (70 cm filter media: 20 cm silica sand: 10 cm gravel). The filter had 40-cm water column head fed by a header tank. It received water from the main WTP's clarifiers post coagulation. Like the processes at the main WTP, backwashes with air scouring were conducted regularly to clean the filter media.

For each filter medium, three types of trials were performed at constant flow rates with spiking solutions (5 L) of the *Cryptosporidium* oocyst surrogate, including:

- single-spiking trials, conducted mostly at 0.5 h after backwashes to evaluate surrogate removal efficiencies at the filter's vulnerable stage for protozoan breakthrough;
- multiple-spiking time-series trials, at 0.5, 1, 2, 3 and 4 h after backwashes to examine filter performance during maturing;
- spiking after excessive backwashing trials, conducted at 0.5 h after two consecutive backwashes at the end of multiple-spiking time-series trials to examine filter performance under excessive backwash conditions.

For the anthracite filter, additional trials were conducted at high and low flow rates (8 m/h, 2 m/h), high and low surrogate concentrations, and with and without additional coagulant to examine the effects of flow rate, surrogate concentration and the coagulant concentration on filtration removal, respectively. However, the results were not statistically different from using high/low flow rates or high/low surrogate concentrations. Thus, all the trials with pumice sand and ceramic sand were conducted at high filtration rates and low surrogate concentrations. Adding extra coagulant to the injection solutions removed too much of the surrogate to enable the acquisition of any quantitative results, and this was not tested further.

A total of 85 pilot trials were performed, including 49, 18 and 18 trials in anthracite, pumice sand and ceramic sand, respectively, and about 30 samples per trial. As the samples contained low surrogate concentrations, the surrogate particles were captured by filtering, imaged by fluorescence microscopy, and enumerated using the ImageJ programme.

Key findings from single injection trials (Table 1):

- Macrolite engineered ceramic sand showed the highest surrogate removal efficacy, with average log removal value (LRV)=4.40±0.38, and LRV> 3 in 100% trials. The LRVs achieved in the ceramic sand filter trials were significantly greater ($P < 0.00001$) than those achieved in the anthracite and pumice sand filter trials.
- The LRV (3.21±0.30) from the pumice sand filter trials did not differ significantly ($P > 0.32$) from those in the anthracite filter trials (LRV=3.01±0.70). However, the pumice sand filter trials yielded higher frequencies of LRVs >3 (70%) than the anthracite filter trials (41%).
- Variations in filter performance were greater in the anthracite trials than in the pumice sand and ceramic sand trials.

Key findings from multiple injection time-series and excessive backwashed trials:

- Anthracite and pumice sand filters demonstrated clear increases (in power functions) in filter efficacies of at least 1 log over 2.5 h during filter maturing.
- In contrast, the LRVs determined from the ceramic sand filter remained relatively constant over 0.5–2 h, and only increased at 3 h after backwashing.
- Excessive backwashing reduced the filtration efficiency significantly, with LRV reductions of 0.7–2.3.

The oocyst surrogate's LRVs (mean 3.01±0.70, range 1.65–4.61) for the sand-anthracite dual-media filter are very similar to the *Cryptosporidium* oocyst LRVs summarised in the review by Emelko et al. (2005) from pilot-scale studies involving conventional rapid filtration through sand-anthracite dual-media (LRVs=1.6–5.0).

The results from our experiments showed that the average LRV for the ceramic media filter (4.40±0.38) was 1.4 $\log_{10}$ greater than that for the sand-anthracite dual-media filter (3.02±0.28) under the similar experimental conditions, namely, PACl coagulation and a flow rate of 8 m/h. This is consistent with others' findings. Compared with conventional sand-anthracite dual-media filter, LRVs derived from Macrolite engineered ceramic media were 1.5 $\log_{10}$ greater for trials using oocyst-sized microspheres (Emelko et al. (2007) and 1.3 time greater for trials using *Cryptosporidium* oocysts (Scott 2008).

The observed differences in surrogate removal in the different filters can be explained by the properties of the filter media. The superior performance of the Macrolite engineered ceramic sand could be attributed to its high surface roughness and high surface area. Pumice sand also has a high porosity and high surface area. The ceramic and pumice sand filter media comprised smaller effective grain sizes (d_{10}=0.60 and d_{10}=0.61 mm, respectively) than the anthracite filter media (d_{10}=0.81 mm); thus, they contained smaller pore sizes and achieved greater filtration removal of the particles. The surface charges of the filter media are another important factor that influence particle removal. However, accurately determining the zeta potentials of granular porous media requires the use of a streaming potential analyser or a zetaprobe analyser, which were unavailable for this study.

CRYPTOSPORIDIUM SURROGATE REMOVAL IN FULL-SCALE HOUSEHOLD FILTERS

A full-scale PoU filter rig was installed with the operational parameters closely mimicking actual household use conditions. The filter rig was pressurised to a level under 40 psi, and was used to treat 20 L water/day per filter, which is the minimal daily water usage per household estimated by WHO (2011). Water was supplied intermittently to simulate household use. The test rig pumped water 12 times for 1 min at a flow rate of 1.8 L/min at 30-min intervals during the day. The test rig incorporated two identical filter cartridges in parallel to provide replicated experimental results.

We examined efficacies of *Cryptosporidium* surrogate removal in five commonly used low-cost household filter cartridges, namely, 1 μm nominal activated carbon, 1 μm nominal polypropylene, 1 μm nominal polyester, 1 μm absolute pleated-paper and 2 μm nominal silver-impregnated carbon. These filter cartridges were manufactured in overseas and were 25.4 cm (10 inches) long and 7 cm in diameter. A total of 120 test runs (duplicate filters, 24 replicate runs per filter type) spiking the surrogate microparticles were conducted.

These experiments simulated instantaneous contamination events when new PoU filters are in use, which is the most vulnerable stage in the filter product life for pathogen breakthrough.

Key findings on *Cryptosporidium* surrogate removal in household filters (Table 2):

- The 1 μm nominal activated carbon filters removed the surrogate effectively. Their LRVs were significantly higher ($p<0.00001$) than those of the other filters, and their LRVs were consistently >3 (LRV=3.93–4.54).
- The 2 μm nominal silver-impregnated activated carbon filters removed the surrogate less effectively (LRVs=1.95–2.94) than the 1 μm activated carbon filters because of their larger nominal pore size.
- LRVs were less than 1 in the 1 μm absolute pleated-paper (LRVs=0.39–0.90), polypropylene (LRVs=0.04–0.66) and polyester (LRVs= 0.00–0.35) filters.

CONCLUSIONS/RECOMMENDATIONS

Our study's findings on rapid sand filters demonstrated that the engineered ceramic sand filter was significantly more effective at removing the *Cryptosporidium* oocyst surrogate than the anthracite and pumice sand filters, and that the anthracite filter showed the greatest variation regarding surrogate removal efficiency. Excessive backwashing reduced the filtration efficiency significantly. The data describing the media filtration efficiencies could help WTP operators improve their practices for ensuring drinking-water safety. This could be achieved, for example, by using more effective filter media, allowing sufficient time for the water to run to waste after backwashing before the filter is brought back on-line and incorporating additional post-filtration treatments.

Our experimental results on the household filters suggest that of the 5 different filters tested, only the 1 μm nominal activated carbon filters achieved LRV>3 (99.9% reduction), which was required for protozoan reduction in domestic water treatment units (AS/NZS 4348:1995). The 1 μm nominal polypropylene, 1 μm nominal polyester, 1 μm absolute pleated-paper and 2 μm nominal silver-impregnated activated carbon filters were ineffective at removing the oocyst surrogate to a satisfactory level. If a filter other than the 1 μm activated carbon filter is used, boiling the water or ultraviolet irradiation should be implemented to achieve the necessary LRV. This information provides guidance for selecting the most efficacious PoU filters for *Cryptosporidium* removal, thereby contributing to the improved safety of non-reticulated water supplies.

Table 1
***Cryptosporidium* surrogate reductions derived from the single-spiking trials in the pilot-scale rapid sand filters**

					Log$_{10}$ reduction value (LRV)				
Filter media	Trial	No. of trials	Main plant	Filtration rate (m/h)	Mean	Std	Min	Max	% LRV>3
Anthracite	A3-6	4	Alum	8	3.30	0.84	2.60	4.35	50
Anthracite	A7-10, A18-20	7	PACl	8	2.98	0.95	1.65	4.61	43
Anthracite	A11-16	6	PACl	2	2.86	0.62	2.31	3.94	33
Anthracite	A21-25	5	PACl	8	3.02	0.28	2.67	3.43	40
Pumice sand	P3-6	4	Alum	8	3.25	0.41	2.68	3.60	75
Pumice sand	P1-2, P7-10	6	PACl	8	3.19	0.25	2.89	3.52	67
Anthracite	all A trials	22	Alum, PACl	2, 8	3.01	0.70	1.65	4.61	41
Pumice sand	all P trials	10	Alum, PACl	8	3.21	0.30	2.68	3.60	70
Ceramic sand	all M trials	10	PACl	8	4.40	0.38	3.93	5.03	100

Table 2
Log$_{10}$ reduction values of *Cryptosporidium* surrogate derived from the point-of-use household filters

Filter media	Pore size	No. of trails	Mean	Std	Min	Max
Activated carbon	1 μm nominal	16*	4.28	0.25	3.93	4.54
Silver impregnated activated carbon	2 μm nominal	24	2.53	0.25	1.95	2.94
Pleated paper	1 mm absolute	24	0.64	0.13	0.39	0.90
Polypropylene	1 mm nominal	24	0.36	0.12	0.04	0.66
Polyester	1 mm nominal	24	0.15	0.10	0.00	0.35

*24 runs were conducted, but the surrogate was not detected in the filter effluent in 8 runs.

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