WATER RESEARCH 55 (2014) 256–271

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/watres

Review

Application of microfluidics in waterborne pathogen monitoring: A review

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ARTICLE INFO

Article history:
Received 31 October 2013
Received in revised form
23 January 2014
Accepted 24 January 2014
Available online 12 February 2014

Keywords:
Microfluidics
Waterborne pathogens
Monitoring techniques
Sample processing
Detection methods

ABSTRACT

A review of the recent advances in microfluidics based systems for the monitoring of waterborne pathogens is provided in this article. Emphasis has been made on existing, commercial and state-of-the-art systems and research activities in laboratories worldwide. The review separates sample processing systems and monitoring systems, highlighting the slow progress made in automated sample processing for monitoring of pathogens in waterworks and in the field. Future potential directions of research are also highlighted in the conclusions.

Contents

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0043-1354/$ – see front matter
http://dx.doi.org/10.1016/j.watres.2014.01.061

1. Introduction

Inadequate access to clean water is hugely detrimental both to economic development and human health. In the developing world 2200 children die daily from diseases transmitted through unsafe water and, despite the Millennium Development Goal of halving the proportion of people without access to an improved water source being met, 780 million people still lack access to safe water (www.cdc.gov/healthywater/global/wash_statistics.html). Far from being a solely developing world problem, waterborne disease is a threat to citizens in the developed world. For example, one of the largest recent outbreaks affected Milwaukee in 1993 in which approximately 400,000 people were infected by cryptosporidiosis (Corso et al., 2003). Moreover, it has been estimated that 10% of total hospital patients in the USA contract diseases due to poor water sanitation, significantly increasing morbidity, mortality and financial burden. Overall, lost productivity in the USA due to waterborne diseases is estimated at $20 billion per year (Straub and Chandler, 2003). According to the World Health Organisation (WHO), microbial hazards remain the primary concern in both developing and developed countries (WHO, 2011).

Waterborne pathogens include viruses, bacteria and parasites, several of which are highly infectious, robust and long-lived in the environment as well as being resistant to standard methods of water treatment. Viruses are the smallest of these pathogens, typically around 20–300 nm in diameter, which makes them difficult both to detect and to remove. Additionally, viruses are highly infectious and often long-lived in the aqueous environment, with norovirus for example being shown to remain infectious after over 2 months in groundwater (Seitz et al., 2011). Furthermore, many viruses are resistant to disinfection, particularly norovirus, which has demonstrated resistance to chlorination, and adenovirus, which has remained viable even after UV treatment (WHO, 2011). Bacteria, with sizes on the order of a few micrometers, are often less infectious, with some notable exceptions (e.g. *Escherichia coli O157:H7* and *Shigella*). Bacteria are more susceptible to chlorine disinfection. Parasites are the largest of the waterborne pathogens, of around 5 μm and larger, and comprise protozoa and helminths. Helminth infections have decreased significantly over recent years as the causative agents (e.g. the host within the water environment) are easily removed by filtration. Protozoa however, remain a problem due to a low infectious dose, longevity in the environment and resistance to water treatment methods (Baldersson and Karanis, 2011; Chen et al., 2007).

In recent years there have been numerous research advances in methods for monitoring waterborne pathogens (Bridle, 2013). Monitoring plays several key roles in the design and implementation of water safety plans and can be applied for surveillance, operational or investigative means (WHO, 2011). This review focuses on the role that miniaturisation, in particular using microfluidic systems, can play in the delivery of "lab-on-a-chip" devices to perform monitoring procedures.

Microfluidic systems, *i.e.* fluid handling systems with channel dimensions on the micrometer scale, have developed rapidly during the past decade and have found many applications, especially within chemical analysis and biological assays. This is unsurprising considering their numerous advantages which include reduced sample consumption, increased speed of analysis, improved efficiency and process parallelisation as well as access to phenomena and mechanisms that are not accessible on the macroscopic scale (Beebe et al., 2002). For example, there have been developments in using microfluidics to obtain better environmental control over cells or bacteria during culture, even now to the level of creating organs on-chip (Huh et al., 2011), which could lead to improvement in traditional culture based pathogen monitoring approaches. Microfluidics might also allow the design of environments to promote culture of microorganisms, which have not yet been cultured in the lab. Yoon and Kim, however, are not positive about this approach for foodborne (or waterborne) pathogens with the justification that lab-on-a-chip has focussed on rapid methods of detection while culturing is time-consuming (Yoon and Kim, 2012). Their review from 2012 is an excellent overview of microfluidic detection methods and the latest application to foodborne pathogens (Yoon and Kim, 2012), many of which are identical to waterborne pathogens. Another review of microfluidics for pathogens in general is that by Mairhofer et al. (2009). The Nature review by Yager discusses application of microfluidics for developing world settings (Yager et al., 2006).

This review differs from the above by focussing specifically on waterborne pathogens. To the best of the authors' knowledge, no previous review exists, which concentrates specifically upon microfluidic approaches to waterborne pathogen monitoring systems, despite many developments in this field in recent years. Particular areas of focus in this article have been on sample processing applications, a key part of any waterborne pathogen monitoring strategy, as well as on significant developments in optical detection technologies in the last few years. This paper is organised into two main sections. The first will discuss how microfluidics has been applied to the challenge of sample processing within waterborne pathogen monitoring. The second will provide an overview of research advances in the use of microfluidics for waterborne pathogen detection. Finally, the paper concludes by summarising the