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# Viral pathogens in water: occurrence, public health impact, and available control strategies

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The public health impact of the transmission of viruses in water is significant worldwide. Waterborne viruses can be introduced into our recreational and finished drinking water sources through a variety of pathways ultimately resulting in the onset of illness in a portion of the exposed population. Although there have been advances in both drinking water treatment technologies and source water protection strategies, waterborne disease outbreaks (WBDOs) due to viral pathogens still occur each year worldwide. By highlighting the prevalence of viral pathogens in water as well as (1) the dominant viruses of concern, (2) WBDOs due to viruses, and (3) available water treatment technologies, the goal of this review is to provide insight into the public health impact of viruses in water.

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## Introduction

Waterborne viruses are frequently implicated as the cause of water-related gastrointestinal illness. Waterborne disease outbreaks (WBDOs) are reported each year and are associated with recreational water (RW), treated drinking water (DW), and ground water (treated and untreated). Depending on the water source, the actual source of contamination can vary; however, the two common threads are (1) the introduction of fecal material into the water source and (2) inadequate or interrupted treatment of water intended for drinking [1–4]. In 2003, the World Health Organization estimated that worldwide 3.4 million deaths each year can be attributed to the water-related (water, sanitation, hygiene) transmission of pathogens (all pathogens, not just enteric viruses) [5]. For the European Union (EU), the European Environment and Health Information System estimated the annual burden of disease due to water-related pathogens at 13,548 deaths for children 0–14 years old. For the United States, Reynolds (2008) estimated 7 million illnesses and more than 1000 deaths

each year were due to waterborne pathogens though these are based on model simulations and not actual values. Unfortunately, the number of illnesses and deaths due specifically to waterborne viruses is difficult to determine and thus basically unknown.

The current review (Figure 1) focuses on (1) the occurrence of viral pathogens of primary concern in various water sources; (2) virus-related WBDOs by water type reported worldwide over the past decade (from approximately 2000 to 2012); and (3) DW treatment options for the inactivation or removal of viruses. Finally, this review briefly discusses how we may better understand the public health impact of waterborne viruses as well as potential measures that can be taken to reduce the impact of viral pathogens in water.

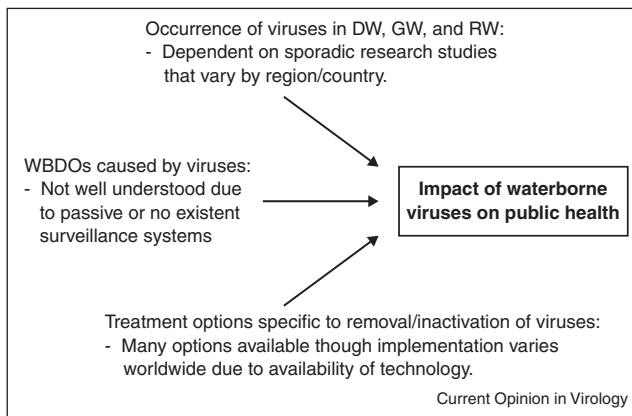
## Waterborne viruses of primary concern

Viruses most often implicated in WBDOs include (but are not restricted to) noroviruses (NoV), Hepatitis A virus (HAV), Hepatitis E virus (HEV), adenovirus (AdV), astrovirus, enteroviruses (EV), and rotavirus (RV) (Table 1). Although viruses implicated in WBDOs are capable of causing a variety of acute illnesses (Table 1), acute gastrointestinal illness (AGI) is most commonly reported. Enteric viruses are host-specific (i.e. in this instance, specific to humans) and are not capable of replicating in the environment outside of its host. In addition, enteric viruses have a presumed low infectious dose (i.e.  $<10-10^3$  virus particles) [6–9]; prolonged (3–4 weeks), asymptomatic periods of shedding; and enhanced environmental stability due to their non-enveloped capsid structure [10]. These characteristics allow enteric viruses to play a significant role in water-related outbreaks. Noroviruses have been the largest cause of virus-related WBDOs in the U.S. since 2003, and data indicate a similar trend in selected countries (France, Japan, Sweden, Switzerland, The Netherlands, UK) [11,12,13]. Aside from NoVs, HAV, HEV, and RV are still of significant concern in low-income countries without adequate water and sanitation. Additional viruses of lesser epidemiologic importance though still capable of waterborne transmission include human reovirus, parvovirus, parechovirus, polyomavirus, coronavirus, and torovirus [14,15].

## Occurrence of viral pathogens in water

Human enteric viruses may be introduced into the water environment through various routes. One obvious route of transmission is through the discharge of sewage-contaminated water into RW and/or DW sources. Viruses may also

Figure 1



Summary of key factors effecting the impact of waterborne viruses on public health. DW: drinking water; RW: recreational water; GW: groundwater; WBDO: waterborne disease outbreak.

be introduced by land application of municipal biosolids [16,17]; groundwater impacted by surface water or in proximity to faulty septic systems and leaking sewers [18–21]; and discharge of untreated wastewater [22] or inadequately treated wastewater effluent [23,24\*,25]. The occurrence of human enteric viruses in water

remains largely unknown unless an outbreak is reported and samples are collected since water sources are not routinely tested for viruses. Moreover, there are challenges related to sampling studies to determine virus presence due to both differences and limitations in recovery and concentration methods for the detection of viruses in water [26\*]. Regardless of these challenges, a snapshot of the occurrence of enteric viruses in water sources over the past decade is provided below.

### Treated drinking water

In this section, there is a specific focus on DW derived from treated surface water as opposed to treated ground water that is used as DW. Keswick *et al.* (1984) — one of the seminal publications on the prevalence of viruses in DW in the U.S. — reported 83% of the samples to be positive for either RV or EVs [27]. Shortly thereafter, Bitton *et al.* (1986) followed up with a review on viruses in DW both in the U.S. and internationally [28]. Aside from these earlier studies, few studies on virus occurrence in DW in the U.S. have been reported since, and of those, such as Gibson and Schwab (2011), no viruses were detected [29]. This paucity of available data for viruses in DW can most likely be attributed to the need for very large volumes (>100 to 6000 L) of water to be concentrated followed by subsequent recovery and detection of virus targets — a process that is challenging often

Table 1

#### Viruses of primary concern for waterborne disease outbreaks.

Family	Virus group	Properties	Associated illnesses	Public health impact
<i>Adenoviridae</i>	Adenoviruses	90–100 nm, dsDNA	Conjunctivitis, gastroenteritis, respiratory disease	Outbreaks not common in the U.S. though sporadic illnesses do occur; respiratory disease most common
<i>Astroviridae</i>	Astroviruses	28–30 nm, ssRNA	Gastroenteritis	Predominantly impacts children ≤2 years of age; possibly higher prevalence in settings outside of U.S. (i.e. China, India, Egypt)
<i>Picornaviridae</i>	Enteroviruses <sup>a</sup>	24–30 nm, ssRNA	Gastroenteritis, HFMD, encephalitis, meningitis, conjunctivitis	10–15 million infections in the U.S. each year (all routes of transmission, not just water) <sup>b</sup>
<i>Picornaviridae</i>	HAV	25–30 nm, ssRNA	Hepatitis	17,000 new cases in the U.S. in 2010 (person-to-person, food and water) <sup>c</sup> ; in developing countries nearly all children are infect with HAV by 9 years of age <sup>d</sup>
<i>Picornaviridae</i>	HEV	25–30 nm, ssRNA	Acute viral hepatitis	Rare in the U.S. though it is very common in many parts of the world due to inadequate sanitation; 20 million cases globally each year <sup>e</sup>
<i>Caliciviridae</i>	Noroviruses	27–38 nm, ssRNA	Gastroenteritis	Leading cause of reported outbreaks of gastroenteritis in the U.S. and primary cause of viral gastroenteritis and foodborne outbreaks worldwide
<i>Reoviridae</i>	Rotaviruses	70–75 nm, dsRNA	Gastroenteritis	Before introduction of vaccine in 2006, resulted in hospitalization 55,000 children each year in the U.S. and caused 527,000 deaths in children each year worldwide <sup>f</sup>

ds: double stranded; ss: single stranded; HFMD: hand, foot, and mouth disease.

<sup>a</sup> Non-polio enteroviruses: Coxsackievirus A and B, Echoviruses.

<sup>b</sup> CDC: <http://www.cdc.gov/non-polio-enterovirus/about/overview.html>.

<sup>c</sup> CDC: [http://www.cdc.gov/hepatitis/Resources/Professionals/PDFs/ABCTable\\_BW.pdf](http://www.cdc.gov/hepatitis/Resources/Professionals/PDFs/ABCTable_BW.pdf).

<sup>d</sup> WHO: [http://www.who.int/csr/disease/hepatitis/HepatitisA\\_whocondscsredc2000\\_7.pdf](http://www.who.int/csr/disease/hepatitis/HepatitisA_whocondscsredc2000_7.pdf).

<sup>e</sup> WHO: <http://www.who.int/mediacentre/factsheets/fs280/en/>.

<sup>f</sup> CDC: <http://www.cdc.gov/rotavirus/clinical.html>.

resulting in low recovery efficiency and detection sensitivity [26<sup>\*</sup>].

In international settings, there is more research related to determining the occurrence of viral pathogens in DW. Again, Bitton *et al.* (1986) highlighted several studies out of the E.U. In particular, research from 1965 in Paris, France was the driving force for the investigation of the occurrence of viruses in DW worldwide for the next 20 years and beyond. As this review is primarily focused on the past decade, data published no later than 2002 have been included. Lee and Kim (2002) reported 4 and 7% of tested DW samples positive for NoV GI and GII, respectively, in South Korea [30]. Studies on viruses in DWTPs in Egypt [31] reported no viruses positive samples. Conversely, in South Africa [32], 11–16% of DWTP samples were positive for enteric viruses (predominantly coxsackievirus B). In 2009, Albinana-Gimenez *et al.* reported 11% of DW samples collected in Spain positive for AdV [33]. Additionally, a study by Dong *et al.* (2010) on viruses in New Zealand DW found 18–36% of samples positive for AdV depending on the method of analysis [34]. Last, Ye *et al.* (2012) reported the presence of human enteric viruses in DW from Wuhan, China with 100% of the 48 samples positive for RVs and AdVs and 21% of samples positive for EVs [35]. Overall, depending on the type of DW treatment process, source water quality, and sampling and detection methods, there is a wide range of viral pathogen occurrence in DW from around the world.

#### Ground water-treated and untreated

One of the greatest fallacies regarding groundwater (GW) as drinking water is that GW is more likely to be free of pathogenic microorganisms due in part to the presumed natural filtering abilities of subsurface environments [19]. Pathogen contaminated GW can often be attributed to failing or poorly sited septic systems in karst settings that do not allow for proper attenuation of pathogens, especially viruses, due to their rapid movement from surface to aquifer [36<sup>\*</sup>,37]. Several studies over the past decade have demonstrated widespread occurrence of human enteric viruses in both individual and municipal wells in the U.S. In 2003, Abbaszadegan *et al.* reported 4.8% and 32% of 448 GW samples to be virus positive by infectivity assay and PCR, respectively [20]. Additional U.S. centric studies have reported 8–49% virus positive GW sites [38–42]. A more recent study by Borchardt *et al.* (2012) reported 24% of the samples ( $n = 1200$ ) positive for human enteric viruses (AdV, EV, and NoV GI) and also estimated 6–22% of the AGI in the study communities ( $n = 14$ ) to be attributable to exposure to viruses in nondisinfected tap water [43<sup>\*\*</sup>]. One reason for this vulnerability — aside from the complexity of pathogen–subsurface interactions — is that before the Ground Water Rule (GWR) of 2006 [44], public utilities with a GW source were not required to disinfect their water supply; moreover, many individual wells are still used untreated. As reported in

Fout *et al.* (2003), untreated GW was responsible for approximately 50% of WBDOs in the U.S. and this trend continues today [38].

For an international perspective, a study on NoV occurrence in GW sources in South Korea reported 17–22% NoV positive out of 300 samples collected and analyzed [45<sup>\*</sup>]. Another study out of South Korea [46] reported similar levels of GW contamination with 18%, 5.1%, and 7.7% of samples positive for NoV, EV, and AdV, respectively.

#### Recreational water

Most data available on the occurrence of enteric viruses in RW sources is related to untreated venues such as lakes, rivers, marine beaches, among others as opposed to treated venues (i.e. waterparks, pools); however, virus-related WBDOs can occur in both venues as outlined in the next section. Moreover, the quantity of data available on human enteric virus occurrence in RW sources is quite significant; therefore, a portion of these data has been compiled in Table 2. Overall, RW have a high occurrence of human enteric viruses depending on the water type and virus; however, when considering these studies in Table 2, one should take into account the differences in sampling and detection methodologies which are beyond the scope of this review.

#### Waterborne disease outbreaks due to viruses — United States

Table 3 details the reported WBDOs due to viral pathogens from 2003 to 2010 — the most recent reporting period for WBDOs related to DW available from the Centers for Disease Control and Prevention (CDC). For 2011 to 2013, there are no official numbers available aside from sporadic peer-reviewed publications and news media reports as detailed below. The relatively low number of WBDOs may be misleading as a result of voluntary reporting of WBDOs to the CDC [47]. Therefore, in general, outbreak data — such as what is presented here — may not be as comprehensive [11<sup>\*</sup>]. Additionally, total morbidity and mortality are uncertain as virus-related illnesses and outbreaks are often unrecognized, unreported, or not even monitored.

#### Drinking water sources

From 2003 to 2010, 12 virus-related WBDOs were caused by contaminated DW — all from GW sources (Table 3). Reported outbreaks were caused predominantly by NoVs with two outbreaks caused by HAV. The dominance of NoV in DW related WBDOs may be strictly due to its status as the primary cause of AGI in the population or there may be other intrinsic factors involved such as the environmental stability of NoV and related viral ecology.

#### Recreational water sources

Of the 26 virus-related WBDOs reported from 2003 to 2008, more than half (16 of 26; 62%) were due to

Table 2

## Occurrence of human enteric viruses in recreational water sources — U.S. and international combined.

Water type	Sampling year	Description of results	Reference
Urban Rivers	2000	52, 62, and 76% of samples (total of 21) positive for AdV, EVs, and HAV, respectively	[66]
River	2002	57 and 37% of samples (total of 30) positive for HEV and AdV, respectively	[67]
Lake/River	2002–2003	0 to 76% positive samples depending on sampling site and virus (AdV, astroviruses, EVs, HAV, NoVs, RVs)	[68]
Fresh	2004	24% samples (14 of 58) virus positive for AdVs	[69]
River	2007–2008	90 and 40% positive for AdV and human polyomaviruses, respectively	[33]
Marine	2007	No virus positive samples (total of 12) for NoV and HAV	[70]
Lake	2007	50% of samples (25 of 58) virus positive (AdV, EV, RV)	[71]
Coastal/Stream	2002–2007	53% of samples (8 of 15) positive for AdV by integrated cell culture — nested PCR	[34]
River	2008–2009	18 to 96% positive depending on the virus with AdV being most prevalent followed by polyomaviruses, RV, NoV, and EVs	[72]
River	2008–2009	20 and 36% of samples (total of 85) positive for AdV and EVs, respectively	[73]
Urban Rivers	2006–2009	83% of samples (70 of 84) were positive for at least one enteric virus (AdV, astrovirus, EV, NoV, HAV)	[74]
Fresh/Marine	2006	Nearly 40% of samples virus positive; AdVs were more prevalent than NoVs in both marine and fresh waters	[75*]
River	2009–2010	54, 63, and 44% of samples (total of 52) positive for NoV GI, NoV GII, and AdV, respectively	[76]
River	2007–2008	Nearly 31% of samples (20 of 65) positive for NoV	[25]
River	2010–2011	100% of samples (total of 12) were positive for AdV and RV while 50% were positive for EVs	[35]

AdV: adenovirus; EV: enteroviruses; HAV: Hepatitis A virus; NoV: norovirus; RV: rotaviruses.

contaminated RW sources — both treated and untreated (Table 3). The dominant viral etiologic agents were human NoVs followed by one outbreak due to an EV, Echovirus 9. As highlighted by Sinclair *et al.* (2009), the apparent increase in virus etiologies accounting for recreational WBDOs is most likely the result of improved detection methods, but may also represent a true increase in incidence related to shifts in viral ecology or changes in population behavior patterns [48]. Other outbreaks that have not yet been reported by the U.S. WBDOSS include a NoV GI outbreak at Lake Wazee in Jackson County Wisconsin that sickened at least 200 people [49]. Interestingly, Matthews *et al.* (2012) determined that NoV GI outbreaks were significantly more likely to be associated with waterborne transmission (worldwide) compared to GII NoVs — the dominant circulating NoV genogroup (i.e. NoV GII.4) worldwide [11\*].

### Waterborne disease outbreaks due to viruses — international (not U.S.)

Determining the occurrence of virus-related WBDOs outside of the U.S. is somewhat challenging with more data available for high-income as opposed to low-income countries — most likely related to the capacity of surveillance systems within each country. Data available through the European Environment and Health Information System [50] states that from 2000 to 2007 there were 148 WBDOs caused by enteric viruses — 136 and 12 due to contaminated DW and RW sources, respectively — accounting for 42% of all reported WBDOs. However, these data only represent 14 countries, and within these countries, the efficiency of surveillance systems, as well as the reporting period, is variable. More recent, official data on WBDOs could not be ascertained

though some peer-reviewed publications on outbreaks are highlighted here.

#### High-income countries

In 2005, Fretz *et al.* reported on NoV outbreaks in Switzerland caused by NoV from 2001 to 2003 [13]. The authors identified 2 outbreaks caused by the waterborne transmission of NoV out of 73 total outbreaks. Hoebe *et al.* (2004) described another NoV WBDO in The Netherlands in 2002 in which a recreational fountain was determined to be the common source of exposure for approximately 100 children with AGI [51]. In 2008, a massive WBDO due to contaminated municipal DW was investigated in Podgorica, Montenegro where nearly 1700 people fell ill with NoV [52]. Last, Koh *et al.* (2011) describe a WBDO at a waterpark where at least 67 cases of AGI were caused by GW contaminated with NoV [53].

#### Low-income countries

As one might expect, estimates on virus-related WBDOs in low-income, developing countries are difficult to determine due to the lack of surveillance systems and complexity of pathogen transmission when both adequate drinking water and sanitation are lacking. Ashbolt *et al.* (2004) provides a comprehensive review of the microbial contamination of DW in developing countries and highlights RV as one of the primary etiologic agents in children while HAV, HEV, and EVs are more common in adults [54].

#### Treatment options for virus removal and inactivation

The options available to treat water for the removal and/or inactivation of enteric viruses range from low-tech (i.e. household water treatment) to high-tech (i.e. DWTPs

Table 3

Waterborne disease outbreaks due to viral pathogens in the United States – 2003–2010.<sup>a</sup>

Location	Year	Water type	Virus	No. of cases	Reference
Connecticut	2003	RW-T	Echovirus 9	36	[77]
Florida	2004	RW-T	NoV	42	[77]
Idaho	2004	RW-T	NoV	140	[77]
Minnesota	2004	RW-U	NoV	9	[77]
Oregon	2004	RW-U	NoV	39	[77]
Pennsylvania	2004	DW, pond	NoV	70	[78]
Vermont	2004	RW-T	NoV	70	[78]
Minnesota	2005	RW-U	NoV	8	[80]
Florida	2006	RW-U	NoV GII	50	[80]
Maryland	2006	DW, well	NoV GI	148	[79]
Minnesota	2006	RW-U	NoV GI	10	[80]
North Carolina	2006	DW, spring	HAV	16	[79]
Oregon	2006	DW, well	NoV GI	48	[79]
Wisconsin	2006	RW-T	NoV	18	[80]
California	2007	RW-T	NoV GII	6	[81]
Colorado	2007	DW, well	NoV GII	77	[82]
Idaho	2007	RW-T	NoV GII	50	[81]
Maryland	2007	DW, well	NoV GII	94	[82]
Washington	2007	DW, well	NoV	32	[82]
Wisconsin	2007	DW, well	NoV GI	229	[82]
Connecticut	2008	RW-U	NoV GI	16	[81]
Minnesota	2008	RW-U	NoV	26	[81]
Ohio	2008	RW-U	NoV GI	54	[81]
Oklahoma	2008	DW, well	NoV GI.4	62	[82]
Tennessee	2008	DW, well	HAV	9	[82]
Wisconsin	2008	RW-U	NoV GI	23	[81]
Maine	2009	DW, well	HAV	2	[83]
California	2010	DW, well	NoV	47	[83]

RW-T: treated recreational water; RW-U: untreated recreational water; DW: drinking water; NoV: human norovirus; HAV: Hepatitis A virus.

<sup>a</sup> Includes only outbreaks reported by the CDC in official surveillance summaries.

utilizing advanced membrane filtration processes). Treatment options tend to focus solely on removal of bacteria therefore, some of the technologies described below were never initially designed for the removal of viruses.

#### Point-of-use

Point-of-use (POU), or household water, treatment options are primarily implemented in low-income countries that (1) do not have a centralized DW treatment and distribution system or (2) do have a centralized DW distribution system, but one that may inadequately treat water and is unreliable. One of the most recent, comprehensive reviews on POU water treatment options is by Sobsey *et al.* (2008). Sobsey and others systematically evaluated five separate POU options including chlorination with safe storage, coagulant — chlorine disinfection systems (i.e. Watermaker and PuR packets), SODIS (transparent PET bottles filled with water and exposed to sunlight), ceramic filters, and biosand filters [55]. Point-of-use technologies involving the use of chlorine were determined to be the most effective for virus reduction (2 to  $\geq 6$  logs) while the available filtration methods were the least effective (0.5–4 log removal). Additional research on the efficacy of these various POU water treatment technologies to remove human enteric viruses has been published in the past 5 years [56–59] which further support the conclusions of Sobsey *et al.* (2008).

#### Community-based

Community-based water treatment systems have also been implemented in rural and peri-urban areas of low-income countries over the past decade and are designed to target rural communities with limited opportunity to hook up to a centralized DWTP. Opryszko *et al.* (2012) investigated the impact of water-vending kiosks in rural Ghana. The water-vending kiosks were designed as ‘mini’ DWTPs including surface water treatment using multi-stage filtration and ultraviolet light disinfection [60]. A companion study by Gibson *et al.* (2011) evaluated the efficacy of the water-vending kiosks in Ghana to remove human enteric viruses and reported the presence of NoV GII and human polyomavirus in 1 of 6 of DW samples analyzed [61<sup>\*</sup>]. Additional studies on the efficacy of community-based water treatment systems for the reduction of human enteric viruses are non-existent — most likely due to the methods needed for viral recovery and detection in water.

#### Full-scale DWTPs

Conventional DWTPs are designed for reliable physico-chemical removal (5–7-log<sub>10</sub>) of microorganisms — bacteria, protozoa, viruses — from public DW supplies during optimal operation [62]. However, in the past decade, more advanced processes for DW treatment have been implemented including alternative disinfectants (combined chlorine, ozone, UV radiation) and membrane

filtration (low-pressure microfiltration and ultrafiltration) technologies. However, enteric viruses are more resistant to inactivation by both UV and combined chlorine (monochloramine) when compared to chlorine [62]. On the other hand, advanced membrane filtration technologies, especially ultrafiltration, allow for the simultaneous removal of all classes of microorganisms from DW sources [63]. Numerous studies highlighted in recent review articles [62,64] have reported on the efficacy of advanced membrane technologies and select alternative disinfectants for the removal and inactivation of enteric viruses in DW sources.

### Concluding remarks

Viral pathogens in the water environment will continue to adversely impact public health. Even though viruses are not the only pathogens present in water that can cause disease, the risk of illness is 10–10,000 times greater for viruses than bacteria at a similar level of exposure [65]. Because of this increased risk and in consideration of the data presented herein, there are a few points of discussion that can be made. First, human enteric viruses are clearly a concern for both DW and RW microbial water quality; however, we still rely on a bacterial indicator system to alert us if there is a potential contamination issue. The use of bacterial indicators has been debated for decades, and we are still at a stalemate when it comes to actually predicting the presence of human viral pathogens in water. For the protection of public health, a true viral indicator should continue to be pursued. Second, in order to move toward an indicator for viruses, we need to harmonize the concentration, recovery, and detection methods employed for the analysis of waterborne viruses. Harmonizing steps have been taken by the U.S. Environmental Protection Agency with the introduction of Method 1615 though this method is specific to EVs and NoVs. Last, countries should start investing in both aging DW distribution systems and wastewater infrastructure, especially in large cities, as this would likely decrease a portion of the WBDOs that are reported each year, at least in high income countries.

### Acknowledgements

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