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A probabilistic model of norovirus disease burden associated with greywater irrigation of home-produced lettuce in Melbourne, Australia

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ABSTRACT

The reuse of domestic greywater has become common in Australia, especially during periods of extreme drought. Greywater is typically used in a raw, untreated form, primarily for landscape irrigation, but more than a quarter of greywater users irrigate vegetable gardens with the water, despite government advice against this practice. Greywater can be contaminated with enteric pathogens and may therefore pose a health risk if irrigated produce is consumed raw. A quantitative microbial risk assessment (QMRA) model was constructed to estimate the norovirus disease burden associated with consumption of greywater-irrigated lettuce. The annual disease burdens (95th percentile; DALYs per person) attributed to greywater irrigation ranged from 2×10^{-8} to 5×10^{-4}, depending on the source of greywater and the existence of produce washing within households. Accounting for the prevalence of produce-washing behaviours across Melbourne, the model predicted annual disease burdens ranging from 4×10^{-9} for bathroom water use only to 3×10^{-6} for laundry water use only, and accounting for the proportionate use of each greywater type, the annual disease burden was 2×10^{-6}. We recommend the preferential use of bathroom water over laundry water where possible as this would reduce the annual burden of disease to align with the current Australian recycled water guidelines, which recommend a threshold of 10^{-6} DALYs per person. It is also important to consider other exposure pathways, particularly considering the high secondary attack rate of norovirus, as it is highly likely that the estimated norovirus disease burden associated with greywater irrigation of vegetables is negligible relative to household contact with an infected individual.

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1. Introduction

Views about greywater have shifted in recent years, with developed countries such as Australia, the USA and Japan leading the way with reuse (Domènech and Saurí, 2010). Predominantly used for landscape irrigation (Casanova et al., 2001), the practice is becoming more common, particularly in arid and semi-arid regions (Roesner et al., 2006; Wiel-Shafran et al., 2006) and has undergone a resurgence of use in Australian households. With recent extended drought conditions and water restrictions severely limiting outdoor tap water use, many Melbourne households turned to greywater (up to 71% in 2007; ABS, 2007), including water bucketed from showers and washing machines (ATA, 2005; Pinto and Maheshwari, 2010).

Greywater is often perceived as relatively harmless and is typically used untreated, either immediately after generation or after some period of storage, yet it has been well established that it can be contaminated with a wide range of chemicals and microorganisms (Eriksson et al., 2002; Maimon et al., 2010). Viruses are assumed to be present in greywater, simply as a function of human excreta including faeces and vomit (Lopman et al., 2012), although only a few studies have tested for viruses (Birks and Hills, 2007; O'Toole et al., 2012) (Birks and Hills, 2007; O'Toole et al., 2012). Viruses can be shed during bathing and can also be transferred on fomites, such as clothing and towels (Boone and Gerba, 2007) resulting in contamination of laundry water. Rose et al. (1991) demonstrated that viruses could survive in greywater with no change in seeded virus numbers over 2 days at 17 °C.

Enteric viruses are a major concern because they typically have a low ID50, high shedding rate and high persistence in the environment. Norovirus is a major cause of gastroenteritis worldwide (Boone and Gerba, 2007; Matthews et al., 2012). It is transmitted faecal-orally, can survive in water, and is highly resistant to treatment (Lodder and De Roda Husman, 2005; Ueki et al., 2005). Previous studies have demonstrated potential waterborne transmission of norovirus via drinking water (Ãstrom et al., 2007; Masago et al., 2006) and recreational waters (Viau et al., 2011), but there are no published studies measuring norovirus concentrations in greywater.

Several quantitative microbial risk assessment (QMRA) studies have investigated risks associated with greywater irrigation (Jackson et al., 2006; Surinkul and Koottatep, 2009) although only two have attempted to estimate viral risks. Ottoson and Stenström (2003) used rotavirus as a model viral pathogen (determined from estimates of faecal contamination, based on coprostanol values and epidemiological data) and predicted risks associated with direct exposure due to irrigation, while Barker-Reid et al. (2010) used published thermotolerant coliform concentrations for source-separated greywater and estimated annual probability of enteric virus infection. The scale of reuse is an important consideration in terms of the overall context of risk. At small scales of reuse (such as a household), person-to-person contact may be the predominant exposure pathway given the high secondary attack rates for norovirus (Alfano-Sobsey et al., 2012). As well, only a few assessments of norovirus risks (Ashbolt et al., 2010; Mara and Sleigh, 2010; Schoen et al., 2011; Soller et al., 2010; Viau et al., 2011; Yang et al., 2011) have been published since the development of the norovirus dose-response model (Teunis et al., 2008). In an effort to contribute to this gap in knowledge, we used QMRA to estimate the disease burden from norovirus associated with greywater reuse behaviours in Melbourne households.

2. Model construction

2.1. Hazard assessment and exposure model

Lettuce was chosen as the representative food crop because it is a common plant for home production. About 15% (20,982 tons) of all lettuce consumed by Australians is grown in backyards (ABS, 2000) and, of those who eat home grown produce, nearly 20% rank lettuce among the top five vegetables grown (Langley et al., 1998). Lettuce is predominantly eaten raw (i.e. no pathogen reduction from cooking) and it retains a relatively large volume of water on the surface of the plant, thus conferring greater potential for transfer of pathogens from irrigation water. Norovirus was chosen as the microbial hazard to model because it is the most common cause of community gastroenteritis in Melbourne (Sinclair et al., 2005). The model was constructed as a sub-component of a larger project on greywater reuse in Melbourne, and data on *Escherichia coli* counts (O'Toole et al., 2012) and reuse behaviours and practices (Sinclair et al., in press) have been drawn from the broader project. Given that two studies have shown that less than 5% of greywater users in Melbourne use any form of greywater treatment (ATA, 2005; Sinclair et al., in press), the model assumed that greywater was not treated prior to use. Kitchen greywater may be heavily contaminated with food particles, detergents and oils and grease (EPAV, 2006; Travis et al., 2008) and may have high faecal indicator counts (Friedler, 2004). Kitchen greywater was excluded from the model because (i) it accounts for a very small proportion of total use (∼8% by volume (Sinclair et al., in press)), (ii) its reuse, especially for purposes where human exposure is likely, is strongly advised against by various authorities (EPAV, 2006), and (iii) human excreta inputs to kitchen greywater are less likely than for bathroom and laundry greywater. Bathroom water and laundry water, the predominant greywater sources, were considered in the model as well as average greywater – a representation of the proportionate use of individual greywater sources across the broader Melbourne population.

The dose of norovirus (λ; no. ingested person^{-1} d^{-1}) resulting from the consumption of greywater-irrigated home grown lettuce that an individual is exposed to was modelled as

$$\lambda = VIce^{-kt}, \quad (1)$$

where V is the volume of greywater caught on the surface of a lettuce plant following irrigation (mL g^{-1}), I is the mean per capita intake of lettuce (g person^{-1} d^{-1}), c is the concentration of norovirus in the greywater (no. mL^{-1}), k is the in-field virus kinetic decay constant (d^{-1}), and t is the withholding period (d), i.e. time between last greywater irrigation event and harvest. This exposure model considered overhead irrigation only because Sinclair et al. (in press) found that the majority

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