Microbial risk assessment of local handling and use of human faeces

Caroline Schönning, Therese Westrell, Thor Axel Stenström, Karsten Arnbjerg-Nielsen, Arne Bernt Hasling, Linda Høibye and Anders Carlsen

ABSTRACT

Dry urine-diverting toilets may be used in order to collect excreta for the utilisation of nutrients. A quantitative microbial risk assessment was conducted in order to evaluate the risks of transmission of infectious disease related to the local use of faeces as a fertiliser. The human exposures evaluated included accidental ingestion of small amounts of faeces, or a mixture of faeces and soil, while emptying the storage container and applying the material in the garden, during recreational stays to the garden, and during gardening. A range of pathogens representing various groups of microorganisms was considered. Results showed that 12-months' storage before use was sufficient for the inactivation of most pathogens to acceptable levels. When working or spending time in the garden the annual risk of infection by *Ascaris* was still slightly above 10^{-4} in these scenarios, although the incidence rate for *Ascaris* is very low in the population in question. Measures to further reduce the hygienic risks include longer storage, or treatment, of the faeces. The results can easily be extended to other regions with different incidence rates.

Key words | excreta, faeces, microbial risk assessment, pathogens, sanitation

Caroline Schönning
Therese Westrell
Thor Axel Stenström
Department of Mycology, Parasitology and Environmental Microbiology,
Swedish Institute for Infectious Disease Control,
SE-171 82, Solna,
Sweden

Karsten Arnbjerg-Nielsen (corresponding author)
Arne Bernt Hasling
Linda Høibye
COWI A/S,
DK-2800, Lyngby,
Denmark
Ph.: +45 4597 1367
E-mail: *kar@cowi.dk*

Anders Carlsen
Embedslægeinstitutionen,
DK-8800, Viborg,
Denmark

INTRODUCTION

Transportation of human excreta in urban areas by means of water produces environmental problems in the aquatic environment. Often, the pollutants are harmless or even useful if handled in the terrestrial environment because they will become part of the nutrient cycle. One component of sustainable development is therefore to develop safe and efficient methods for handling of human excreta in a terrestrial environment. Faeces and urine, as well as mixed sewage products, need to be seen as resources rather than waste. In human excreta, urine contains the major part of essential plant nutrients (nitrogen, phosphorus and potassium). Faeces can, apart from nutrients, contribute humus-like substances, thus improving soil fertility. Hazards associated with the recycling of these products include pathogens and pharmaceuticals as well as other micropollutants and heavy metals. It is important to note, however, that pharmaceuticals and other micropollutants also constitute a problem in the aquatic environment. Therefore, the major concern when handling human excreta locally in the terrestrial environment is believed to be associated with possible threats to human health. This paper focuses on acute human health issues and, consequently, exposures to pathogens are dealt with.

From a hygienic risk perspective, faeces should always be considered to contain pathogens. There is a wide range of pathogens that may be excreted, mainly causing gastro-intestinal infections. When recycling other fractions such as urine or grey-water, the potential faecal cross-contamination and related pathogens may constitute the main risk (Höglund 2001; Ottoson & Stenström 2003). To evaluate and compare different sanitation systems, including (re)use of the 'waste products', microbial risk assessment is a valuable tool that allows human risks related to future scenarios to be quantified and compared in a structured manner (Shuval *et al.* 1997; Höglund *et al.* 2002; Ottosson 2003). Quantitative microbial risk assessment (QMRA) includes the following

doi: 10.2166/wh.2006.049

main components: hazard identification, exposure assessment, dose-response assessment and a risk characterisation (Haas *et al.* 1999). These are further described below. Epidemiological investigations often require larger study populations, and are generally applicable only when the practices are already in place.

When using fertiliser products containing human or animal excreta, the reduction of excreted pathogens is a critical step in minimising the risk of further spreading of the pathogens. Transmission of disease may occur if humans or animals come in contact with the excreta and accidentally ingest the pathogen-containing material before the pathogens have been inactivated. Subsequent exposure is possible if pathogens are transported to watercourses, for example by run-off, and the water is used for recreational activities or the production of potable water. Another potential route for transmission is consumption of excreta-fertilised crops. By treating the excreta early in the handling chain, exposure to pathogens and consequent risks could be significantly decreased. Treatments often rely on an increase in temperature (e.g. composting or anaerobic digestion) or an increase in pH (e.g. addition of lime).

Prolonged storage will also lead to a reduction. However, long survival times have been reported for some pathogens and indicator organisms in materials such as sludge, manure and faeces (Pesaro *et al.* 1995; Gantzer *et al.* 2001; Moe & Izurieta 2003). The inactivation occurring after application of the fertiliser will further decrease the risks of disease transmission by exposure to the soil or through the consumption of crops. Current regulations in Denmark and other European countries focus on products such as sewage sludge, and generally do not include excreta as such. There are, however, guidelines established by WHO, which encourage treatment of excreta by storage, digestion or composting before use (WHO 1989). Use of untreated excreta is, however, allowed if the excreta is covered with a layer (>25 cm) of soil. These guidelines are currently being amended and extended.

The current study was aimed at, on a theoretical level and utilising QMRA, assessing the risks of transmission of infectious diseases to humans associated with the use of faeces as a fertiliser within private households in Denmark. The risks evaluated focused on direct contact with the faecal material during handling and use in the garden. The evaluation is based on studies of how human excreta are handled in special settlements where each household is responsible for the handling of its own excreta.

METHODS

The case scenarios

The faeces were collected from dry, urine-diverting toilets in single-family households (consisting of two adults, one older child and one younger child <6 years) and used in their own gardens as a fertiliser. The toilet paper was thrown in the same collection bin and additives such as sawdust were sometimes added to facilitate composting, corresponding to up to 10–15% of the total weight. Theoretical scenarios were evaluated by using data collected from previous studies of this type of toilet. Even if a thermophilic (high-temperature) composting process was aimed for in the previously investigated systems, temperatures never rose above 20°C and were at a maximum 7°C higher than the ambient temperature. The faeces could thus be said only to be treated by means of storage prior to the application in the garden. The pH of the faeces varied from 6.7 to 8.4 and the dry substance content was 22–39% (J. Møller, Royal Veterinary and Agricultural University, Denmark, personal communication). The following scenarios were evaluated:

1. Application of the material after storage for 0 months
2. Application of the material after storage for 6 months
3. Application of the material after storage for 12 months
4. Application and incorporation of the material after storage for 6 months
5. Application and incorporation of the material after storage for 12 months

Application was defined as spreading the faeces evenly on top of the soil (i.e. mixed with the upper 1 cm of soil), while incorporation was defined as spreading the faeces evenly on top of the soil and then working it into the upper layer of the soil, resulting in a faeces to soil ratio of around 1:100, compared with a ratio of 1:10 when the faeces were just applied on top of the soil. Storage of up to 12 months was evaluated because toilets with this

storage capacity are commercially available. The scenarios are based on the studies of the settlements and are in fact rather conservative. None of the persons in the settlements in question knew about or used the guidelines provided by WHO (1989).

Microbial risks associated with urine were not specifically evaluated, but comparative evaluations have previously been performed (Höglund *et al.* 2002; Hald and Andersen, in press).

Hazard identification

Representatives from the various groups of pathogenic microorganisms that can be transmitted through faeces to humans by the faecal-oral route were chosen based on the following criteria:

- The organisms should be relatively common in Denmark
- The most persistent microorganisms should be included
- Organisms having low infectious doses should be included
- Some organisms giving severe sequelae should be included
- Reasonable background information about the organism should be available

As representatives for the bacterial group *Salmonella* and enterohaemorrhagic *E. coli* (EHEC) were chosen, and among the viruses, rotavirus and hepatitis A. Rotavirus were chosen mainly because data for survival in the environment exist; these should be regarded mainly as an indicator of the risk of infection by common gastro-intestinal viruses. To model parasites the protozoa *Giardia* and *Cryptosporidium* as well as the helminth *Ascaris* were included, the latter being uncommon in Denmark, but recognised as a persistent organism with long survival in the environment. With the exception of hepatitis A each of these organisms causes gastro-intestinal infections, but further severe symptoms involving other organs may also occur. Viruses and protozoa generally have lower infectious doses than bacteria, the lowest being attributable to *Ascaris* where, in theory, one egg is enough to cause an infection. Infectious doses (dose-response models) and incidences are given in Table 1.

Exposure assessment

Each organism was modelled by means of distributions (i.e. probability density functions (PDFs)) for incidence in the population, excretion and duration of infection as well as die-off in the storage container and die-off in the soil after application of the material in the garden.

Incidence data was mainly collected from Danish statistics, where *Salmonella*, EHEC, hepatitis A and *Giardia* are officially reported. Surveillance systems are, however, considered to underestimate the actual number of cases occurring in the population (Wheeler *et al.* 1999) and the reported numbers were therefore corrected, assuming higher underestimations for infections with less severe symptoms. Estimates of rotavirus and *Ascaris* infections in the population were made from extrapolation of the number of positive samples registered at SSI (Statens Serum Institut, Denmark) whereas the incidence of *Cryptosporidium* was based on estimations by Hald and Andersen (in press). Using the incidences assessed for the selected pathogens, the probability that the faeces in the storage container from a typical household contained at least one type of pathogen was calculated to be 11.6%. A total of 0.5% of the containers would contain at least two types of pathogen. Rotavirus and *Giardia* would be the most frequently occurring pathogens, present in 4.7% and 4.3% of the containers, respectively. The level of infections was not assumed to depend on the age, gender or other characteristics of the family in question; only the number of occupants was assumed to be of importance. The annual variations in infections are small compared with the general level of infections.

The number of excreted pathogens is assessed by means of literature data on the duration and concentration of pathogens in faeces during infection (see Table 1). Since available studies on the survival of pathogens in human faeces are limited, results from studies involving other materials such as animal manure and sewage sludge were also evaluated in order to establish PDFs for inactivation in the collection and storage container (the container in which the faeces are collected is stored without addition of new material). The collection and storage was assumed to take place indoors at a temperature of around 20°C. The calculations resulted in median (50th-percentile)

Table 1 | Input data used in the QMRA modelling. N (*m*, *s*) denotes a normally distributed PDF with mean *m* and standard deviation *s*. Some of the input variables are highly skewed to the right, meaning that there are higher probabilities of high numbers than of low numbers. This property of variable *Y* may be modelled by means of a log-normal distribution, i.e. ln(*Y*) is a normally distributed PDF. Incidence data are described in the text and original references to the other input data are found in Arnbjerg-Nielsen *et al.* (2005)

Microorganism	Incidence [per 100,000]	Excretion no. (ln [per g wet weight])	Excretion time (ln [days])	Inactivation in faeces, T_{90} [days]	Inactivation in soil, T_{90} [days]	Dose-response model
Bacteria						
Salmonella	N (500; 100)	N (13.8; 2.3) median $= 9.9 \times 10^5$	N (3.6; 0.2) median $= 37$	N (30; 8)	N (35; 6)	Beta-Poisson $\ln(N_{50}) \sim$ N(10; 0.7) $\alpha = 0.3126$
EHEC	N (30; 5)	N (5.8; 1.2) median $= 3.3 \times 10^2$	N (2.1; 0.25) median $= 8$	N (20; 4)	N (25; 6)	Exponential k $\sim$ N(300; 50)
Viruses						
Rotavirus	N (1200; 200)	N (20.7; 2.3) median $= 9.8 \times 10^8$	N (1.6; 1.25) median $= 5$	N (60; 16)	N (30; 8)	Beta-Poisson $\ln(N_{50}) \sim$ N(1.7; 1.2) $\alpha = 0.265$
Hepatitis A	N (6; 1)	N (11.5; 1.2) median $= 9.9 \times 10^4$	N (3.0; 0.25) median $= 20$	N (55; 18)	N (75; 10)	Beta-Poisson $\ln(N_{50}) \sim$ N(3.4; 1.2) $\alpha = 0.2$
Parasites						
Giardia	N (1100; 100)	N (15.0; 1.7) median $= 3.3 \times 10^6$	N (4.5; 0.7) median $= 90$	N (27.5; 9)	N (30; 4)	Exponential ln(k) $\sim$ N(3.9; 0.7)
Cryptosporidium	N (200; 25)	N (17.3; 0.6) median $= 3.3 \times 10^7$	N (2.0; 0.85) median $= 7$	N (70; 20)	N (495; 182)	Exponential ln(k) $\sim$ N(5.5; 0.4)
Ascaris	N (20; 3)	N (9.2; 0.6) median $= 9.9 \times 10^3$	N (5.5; 0.5) median $= 245$	N (125; 30)	N (625; 150)	Exponential k $= 1$

T_{90} = time for a 90% reduction; N_{50}, α, and k are parameters in Equation (2.b).

concentrations of 2×10^{-12} – 4 organisms per mg faeces (0 months' storage), 2×10^{-21} – 7×10^{-2} organisms per mg faeces (6 months' storage) and 2×10^{-30} – 2×10^{-3} organisms per mg faeces (12 months' storage) depending on pathogen type, and given that a pathogen was excreted by a family member within the previous year. After storage for 6 and 12 months the highest concentration was attributable to *Ascaris* owing to a long excretion time and slow inactivation, whereas EHEC occurred in the lowest concentrations owing to a short excretion time and its short survival in faeces. Calculations for EHEC showed a total inactivation after 6 months' storage; that is, there was less than one active bacterium left in the container after this time. The survival of microorganisms in soil is dependent on local conditions: for example, soil type, moisture, UV-light and naturally occurring microflora. To describe the inactivation in soil at an average ambient temperature of approximately 11°C, results from studies conducted in various types of soil were consolidated to create the PDFs. The PDFs representing the input data are summarised in Table 1. The underlying references are given in Arnbjerg-Nielsen *et al.* (2005).

By combining the data, the concentrations of pathogens in the faeces after the different storage periods were calculated. Similarly, the concentrations in the soil after application and incorporation were calculated taking into

Table 2 | Modelled intake of faeces when exposed to the stored material mixed with soil

	Ingestion of faeces, $Intake_{faeces}$ [mg/exposure]		
Type of exposure	**Typical (50th-percentile)**	**Range**	**Distribution used to model the intake***
Children, raw material	67	9–500	ln (4.2; 1.0)
Adults, raw material	33	8–134	ln (3.5; 0.7)
Exposure in area with applied material	3	0.01–164	ln (1.1; 2.0)
Exposure in area with applied and incorporated material	0.4	0.004–37	ln (−1.0; 2.3)

*$Intake_{faeces}$ is modelled by a log-normal distribution as described in Table 1.

account the continuous inactivation that will occur after the application, which was assumed to take place in April (spring in the Northern hemisphere). Possible re-growth of bacteria was accounted for by making slightly conservative estimates for the decay of the bacteria.

The actual human exposure was assumed to take place during one of three events, when accidental ingestion of small amounts of faeces, or faeces and soil mixture, may occur:

- Emptying of the container and distribution of the material
- Recreational activities in the garden
- Gardening

The faeces-soil intake was based on a literature study by Larsen (1998), where children are estimated to ingest around 200 mg of soil per day on average with an absolute maximum of 5–10 g per day occurring once every ten years by exposure each day. It was further assumed that adults ingest 15–50% of this amount, with a maximum of 100 mg per day (Table 2). The container was emptied once a year, assuming that only adults were performing this task and thus exposed. Modelling of the number of exposures through recreation in the garden resulted in a median value (50th-percentile) of 3.5 times per week (during June–August), whereas 50% of the persons were exposed through gardening once a week (during May–September) (Table 3). An exposed 'standard member' of the family was assumed to correspond to 25% child and 75% adult or older child (>6 years). The faeces to soil ratios mentioned above, which are approximately equal to the 50th-percentile, were used to create distributions for the composition of the faeces and soil mixture, with the worst-case scenario corresponding to ingestion of 'pure' faeces. It was further assumed that one exposure corresponded to two hours of gardening, occurring a maximum of two times per day.

The dose-response relationships

For some pathogens dose-response relationships are relatively well defined with respect to the expected infectivity in the population (Haas *et al.* 1993; Teunis *et al.* 1996; Haas *et al.* 1999). Variations due to differences between different persons are largely unavailable and are virtually missing for

Table 3 | Estimated number of weekly garden exposures due to recreation and gardening

	Exposures per week, *n*		
	Typical (50th-percentile)	**Range**	**Distribution used to model the annual number of exposures***
Recreation (June – August)	3	1–13	ln (1.2; 0.7)
Gardening (May – September)	1	0.1–11	ln (0.0; 1.2)

*n is modelled by a log-normal distribution as described in Table 1.

the more susceptible parts of the population, such as children, the elderly or the immuno-compromised. They cannot, therefore, be accounted for separately in the models. On the other hand, parts of the population are less susceptible, as, for example, previously infected persons. In order to take this inherent variation into consideration the uncertainty of the parameters in the dose-response relationships must be included as shown in Table 1. The resulting relationship between dose and response is then itself a probability density function as indicated in Figure 1.

Risk calculations

The risk of infection in the QMRA was calculated using @RISK version 4.5 (Palisade Corporation, Newfield, New York, USA), applying 5,000 iterations in the Monte Carlo simulations. Since many variables are described by means of distributions, calculations of both the 'realistic' impact and worst-case scenarios were possible. These are translated here to the 50th-percentile and 95th-percentile of the resulting distributions, respectively. Calculations were made for two different situations: (i) applying the incidence of each infection in the population (unconditional); and (ii) assuming that one member of the family actually had an infection during the period of faeces collection (conditional). The interpretation of the risks in the evaluated scenarios will be based on the unconditional situation because those risks reflect the actual risk to the exposed people in the Danish setting. However, reporting the conditional risks enables easy calculation of risks in areas where the incidence rates are substantially different.

Results are presented as probability of infection (P_{inf}) per exposure or per year and compared with an acceptable risk level of 10^{-4} infections per year, as suggested by Regli *et al.* (1991). It was assumed that only one person could be infected from exposure to the faecal material per year per family because the prevalence of the infections is quite low.

The quantification of the risk must be done in several steps. First, the amount of infectious microorganisms available in the container may be calculated under the assumption that a person in the family has been infected and that the faeces from this person contain infective microorganisms. This is calculated in Equation 1. Second, the exposure of healthy individuals to this infected material is calculated in Equation 2. Finally, in Equation 3, the unconditional risk is calculated; that is, the risk of a person being infected when exposed to a random container.

The formulae for calculating the amount of infectious material at day i after the individual begins to excrete

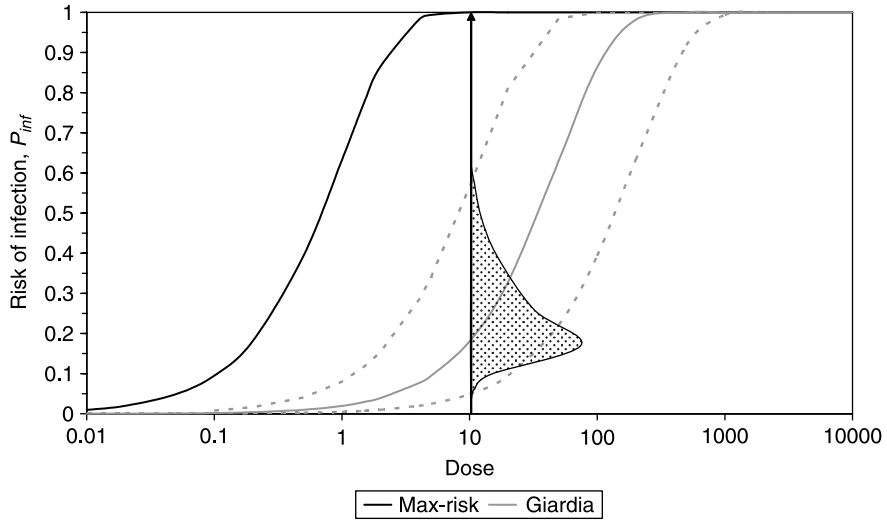

Figure 1 | Probability of the risk of infection. When ingesting a dose of 10 *Giardia* cysts it is most likely that 18% of a large group of exposed persons will be infected. Based on the uncertainty of the dose-response model a specific person will have 95% probability of having a risk of infection between 5% and 56%.

infected material are as follows:

$$M_i = M_{i-1} + U_i - H_i \quad (1.a)$$

$$U_i = \begin{cases} C_u V_u & ; \text{ infected individuals} \\ 0 & ; \text{ no infected individuals} \end{cases} \quad (1.b)$$

$$H_i = M_{i-1}\left[1 - \exp\left(-\frac{\ln(10)}{T_{90}}\right)\right] \quad (1.c)$$

$$M_0 = H_0 = 0 \quad (1.d)$$

where

M_i is the number of infectious pathogens at day i
U_i is the number of excreted pathogens from the infected person at day i
H_i is the decay of pathogens at day i
C_u is the number of pathogens excreted per g wet weight faeces
V_u is the wet weight of faeces excreted per day and per person in g
T_{90} is the rate of inactivation in days for a $\log_{10}$ reduction

The duration and time of year of the infection varies randomly between different iterations. At the time of exposure the risk of infection may be calculated as:

$$Dose_i = \frac{Intake_{faeces} M_i}{Total_{faeces}} \quad (2.a)$$

$$P_{inf,i|infection} = \begin{cases} 1 - \exp\left(-\frac{Dose_i}{k}\right) & ; \text{ Exponential} \\ 1 - \left[1 + \frac{Dose_i}{N_{50}}\left(2^{\frac{1}{\alpha}} - 1\right)\right]^{-\alpha} & ; \text{ Beta-Poisson} \end{cases} \quad (2.b)$$

where

$Total_{faeces}$ is the amount of faeces excreted into the container per year in g
$Intake_{faeces}$ is the (small) amount of faeces ingested per exposure in g
$Dose_i$ is the ingested number of pathogens at day i
k is the parameter in the exponential model for the dose-response relationship
N_{50} is the parameter in the Beta-Poisson model for the dose-response relationship corresponding to the median infective dose
α is the shape parameter in the Beta-Poisson model for the dose-response relationship
$P_{inf,i|infection}$ is the risk of infection at day i given that infectious material was excreted during filling of the container

Equations 1 and 2 are valid if one person in the family has been infected and excretes infectious material into the family container and non-resistant people are exposed to the infectious faecal material. However, not all of the containers will contain infectious material. Therefore the risk incurred when being exposed to a random container depends on the incidence of infections in the population in question. This risk can be calculated as follows:

$$R \approx 1 - (1 - I)^4 \quad (3.a)$$

$$P_{inf,i} = R P_{inf,i|infection} \quad (3.b)$$

$$P_{inf,year} \approx \sum_n P_{inf,j} \quad (3.c)$$

where:

R is the proportion of infected containers given that no correlation exists between the four family members
I is the incidence of infection in the population of the pathogen in question
$P_{inf,i}$ is the risk of infection by exposure to a container at day i
n is the annual number of exposures
$P_{inf,year}$ is the risk that at least one person will be infected per container installed and used as suggested

Equation 3 is an approximation that holds if the calculated risks are below 10^{-2}. If the calculated risk is higher, there is a risk that exposure to one infected container may lead to several infections (Table 4).

RESULTS AND DISCUSSION

In approximately nine out of ten gardens, the use of stored faeces as a fertiliser will not result in a risk of infection in Denmark. This is because none of the family members was infected, and thus no pathogens were excreted into the container. In the remaining 11.6% of the gardens there is a

Table 4 | Risk of infection when emptying an infected storage container (conditional situation), which is done once per year per household, after storage for 0 months (as in scenario 1, giving the highest risk) and after storage for 12 months (as in scenarios 3 and 5, giving the lowest risk). The actual risks can be calculated for any region using Equation 3 and using actual incidence rates. Typical risk equals the 50th-percentile and worst case equals the 95th-percentile

		Salmonella	EHEC	Rotavirus	Hepatitis A	*Giardia*	*Cryptosporidium*	*Ascaris*
0 months' storage	Typical	8×10^{-7}	3×10^{-13}	8×10^{-1}	9×10^{-3}	6×10^{-2}	6×10^{-2}	1
	Worst case	2×10^{-1}	9×10^{-5}	1	6×10^{-1}	1	1	1
12 months' storage	Typical	nr	nr	4×10^{-5}	2×10^{-9}	nr	4×10^{-7}	7×10^{-2}
	Worst case	6×10^{-11}	nr	7×10^{-1}	2×10^{-4}	8×10^{-5}	2×10^{-3}	1

nr = negligible risk ($< 10^{-14}$; calculation accuracy of MS Excel).

risk of infection; however, most of the exposures will not lead to infection as too few pathogenic organisms will be ingested. For each scenario (1–5) the following results are presented:

- The typical risk from a random container (50th-percentile)
- The worst-case risk from a random container (95th-percentile)

The differences between the results are exemplified for *Salmonella* in Figure 2 and for *Ascaris* in Figure 3, and the risk of infection (P_{inf}) is summarised in Tables 5 and 6. The variations in the risk of infection depend on the pathogen in question and were up to 12 orders of magnitude in a specific scenario. If the material was stored for 12 months the typical risk (50th-percentile) in general decreased with 3–7 orders of magnitude when compared with 0 months of storage. The risk from EHEC is eliminated if the material is stored for 12 months and the typical risk of being infected by *Salmonella* is also very low. Viruses and parasites generally survive longer in the environment, and have

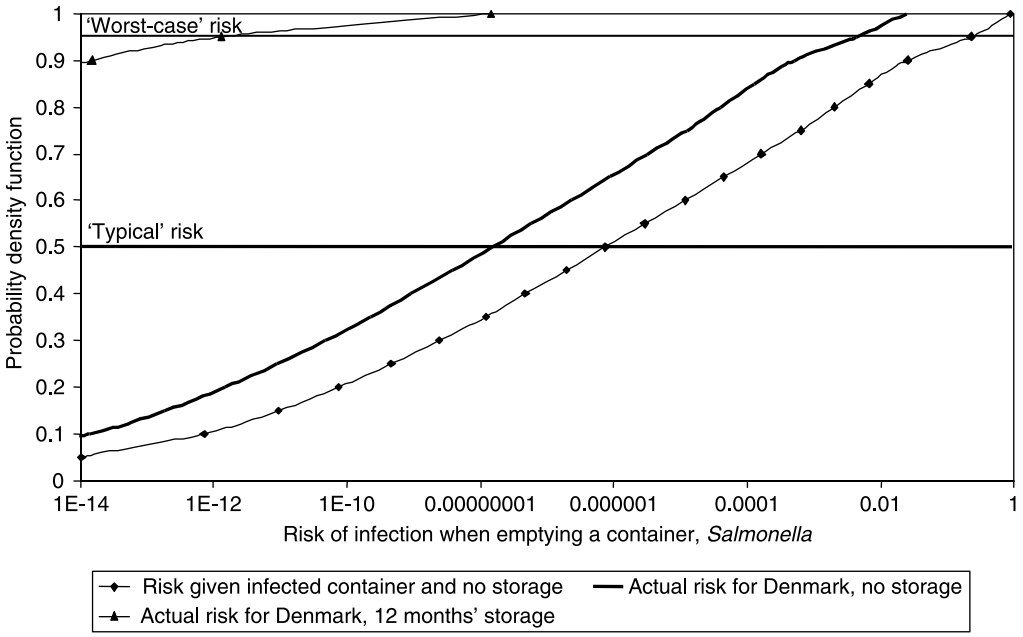

Figure 2 | Example of calculated risks. Storage is quite important for *Salmonella* as shown by the difference in risk by several orders of magnitude depending on storage time. For *Salmonella*, the risk depends more on storage than on incidence rates. For other pathogens (e.g. *Ascaris*) the storage has limited importance because of their higher persistence; therefore the risks are mainly dominated by the prevalence in the population in question. Typical risk equals the 50th-percentile and worst case equals the 95th-percentile.

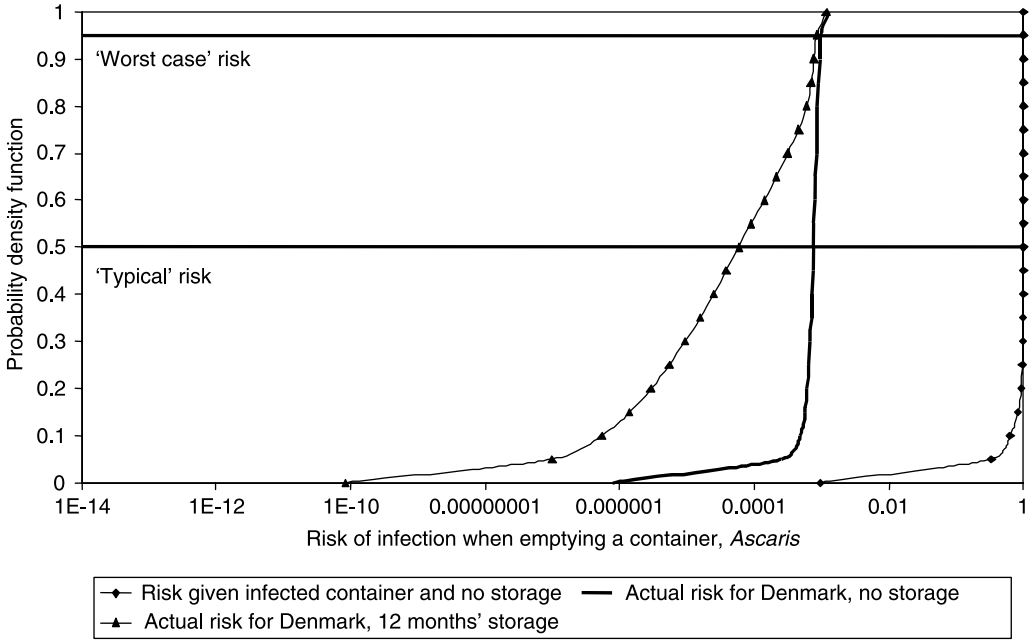

Figure 3 | Example of calculated risks for *Ascaris*. Storage is less important for *Ascaris* as shown by the limited amount of reduction of risk due to storage. The major reason for a relatively low risk of infection of *Ascaris* is the low incidence rate.

lower infectious doses, which result in higher risks for rotavirus, the protozoa and *Ascaris*. Without storage, the material in the containers was, with the exception of bacteria, highly infectious.

After 12 months of storage the typical risk associated with emptying the container was less than 10^{-4} for all of the pathogens, as presented in Table 5. When considering typical risks associated with gardening and recreational activities in the garden, the yearly risk of infection was only higher than 10^{-4} for *Ascaris* (Table 6). As such, the risks were just below the acceptable level suggested by Regli *et al.* (1991). However, the large differences between the typical risk and the worst-case risk indicate that, in general, viruses, protozoa and helminths may constitute a problem because of a substantial level of uncertainty. Furthermore, in general, the risks increased significantly if the material was stored for less than 12 months.

The importance of the estimated incidence rates differs greatly between the different pathogens. The incidence rate of the region is less important when the decay of the pathogen is rapid, whereas the overall risk is dominated by the initial incidence rate of the pathogen when the decay

Table 5 | Risk of infection when emptying a random storage container (unconditional situation), which is done once per year per household, after storage for 0 months (as in scenario 1, giving the highest risk) and after storage for 12 months (as in scenarios 3 and 5, giving the lowest risk). The risks are calculated using Danish incidence rates. Typical risk equals the 50th-percentile and worst case equals the 95th-percentile

		Salmonella	EHEC	Rotavirus	Hepatitis A	*Giardia*	*Cryptosporidium*	*Ascaris*
0 months' storage	Typical	2×10^{-8}	nr	3×10^{-2}	2×10^{-6}	2×10^{-3}	5×10^{-4}	8×10^{-4}
	Worst case	5×10^{-3}	1×10^{-7}	5×10^{-2}	2×10^{-4}	5×10^{-2}	9×10^{-3}	1×10^{-3}
12 months' storage	Typical	nr	nr	2×10^{-6}	4×10^{-13}	nr	3×10^{-9}	6×10^{-5}
	Worst case	1×10^{-12}	nr	3×10^{-2}	5×10^{-8}	4×10^{-6}	2×10^{-5}	9×10^{-4}

nr = negligible risk ($< 10^{-14}$; calculation accuracy of MS Excel).

Table 6 | Yearly risk of infection (50th-percentile, representing the typical risk) during gardening and recreational activities in the garden. The numbers indicate the different scenarios for storage and usage of the faeces; 1, 2 and 3 correspond to application of the material after storage for 0, 6 and 12 months, respectively, 4 and 5 correspond to application and incorporation after 6 and 12 months, respectively. The risks are calculated using the Danish incidence rates

	Gardening					Recreational activities in the garden				
Scenario	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Salmonella	2×10^{-9}	nr	nr	nr	nr	7×10^{-10}	nr	nr	nr	nr
EHEC	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
Rotavirus	4×10^{-2}	2×10^{-4}	2×10^{-7}	2×10^{-5}	2×10^{-8}	3×10^{-2}	4×10^{-5}	3×10^{-8}	4×10^{-6}	4×10^{-9}
Hepatitis A	1×10^{-6}	6×10^{-10}	3×10^{-13}	7×10^{-11}	4×10^{-14}	1×10^{-6}	4×10^{-10}	2×10^{-13}	5×10^{-11}	2×10^{-14}
Giardia	2×10^{-4}	7×10^{-11}	nr	8×10^{-12}	nr	5×10^{-5}	1×10^{-11}	nr	2×10^{-12}	nr
Cryptosporidium	1×10^{-3}	3×10^{-6}	8×10^{-9}	3×10^{-7}	9×10^{-10}	1×10^{-3}	3×10^{-6}	7×10^{-9}	4×10^{-7}	9×10^{-10}
Ascaris	8×10^{-4}	7×10^{-4}	2×10^{-4}	5×10^{-4}	2×10^{-5}	2×10^{-3}	2×10^{-3}	2×10^{-4}	5×10^{-4}	2×10^{-5}

nr = negligible risk ($< 10^{-14}$; calculation accuracy of MS Excel).

rate is low. This finding is emphasised when comparing risks for *Salmonella* and *Ascaris* in Figure 2 and Figure 3, respectively. Based on the information in Table 4 it seems that the risk of infection is low for bacteria regardless of the incidence rate in the population in question. The typical risks for viruses and protozoa are also below the acceptable level suggested by Regli *et al.* (1991).

Rotavirus constituted the highest risk if the material was un-stored, which illustrates that viruses can be highly infectious. Even if rotavirus is recognised mainly as a pathogen of concern for small children, its importance as a pathogen in adults has been underestimated (Andersen & Weber 2004). Other viruses, such as norovirus, are more common in all age groups and could be of greater concern. The main reason for not including norovirus in this study is that there are only limited data available.

Many additional excreta treatment alternatives exist that could improve the situation and significantly reduce the risks from pathogens by promoting a more rapid die-off. Sufficiently high temperatures in small-scale composting/dehydrating/storage systems may be difficult to guarantee even if other material such as straw or wood chips are added for structure. Co-composting, mixing the faeces with organic household waste, in a well-insulated composting vessel could improve the composting process, although temperature monitoring is desirable to ensure that the composting process takes place. Another possibility is to elevate the pH in the material through the addition of lime (or ash), which enhances the pathogen inactivation.

A minimum time period of one year is necessary in order to reduce the risk of infection by *Ascaris* to acceptable levels if relying solely on storage. The risk of transmission of disease when emptying the container after one year's storage may still be high, particularly for other pathogens such as viruses; however, other measures such as wearing personal protection equipment such as gloves and mouth protection could lower the risk extensively. The greatest overall risk may be accidental ingestion of faeces by children playing on the soil. The application and incorporation of faeces will not result in a homogeneous faeces–soil mixture, and small but significant amounts of faeces may be ingested, as was partly accounted for in the modelling.

Animals as secondary transmitters were not accounted for, but may also need consideration. House pets, such as dogs and cats, will imply a risk as they often dig in the soil and could transport pathogens to fomites or surfaces indoors, resulting in human exposure. Vectors could also transport pathogens from one garden to another.

Risks related to the consumption of crops fertilised with the material were not specifically evaluated, but this is

another route of transmission that may be important. Regulations and guidelines may be based on the combination of treatment and restrictions on what crops can be fertilised. Crop restrictions may be utilised as another barrier to exposure and pathogen transmission. One example is to discourage the use of faeces on crops that are to be consumed raw (Schönning & Stenström 2004).

Recommendations that allow for a period to pass between fertilisation and harvest, as have been suggested for use of urine (Höglund 2001), could also be proposed for the faecal fraction. Such regulations are probably easier to apply in larger systems, since, on a household level, the personal decisions are still of prime importance. This also implies that it will be difficult to ensure that the material is actually stored sufficiently and without exposure to humans.

It is questionable whether human faeces should be recommended for use as a fertiliser in gardens and other green areas to which people have easy access. How beneficial the material is depends on the status of the soil and how efficiently the risks can be communicated to the users of the areas. In less developed regions the soil may be poorer and the supply of fertilisers not as good as in Western countries. Treated faeces could here result in great improvements in soil fertility; on the other hand, pathogens are often more prevalent. These issues are quite complex but can be handled if awareness of risks is raised, and treatment and handling of faeces is adapted to the specific system and setting.

CONCLUSIONS

If strictly comparing the risks with previously identified acceptable levels (10^{-4} per year), the practice of using one-year stored but otherwise untreated faeces should be regarded as unacceptable. The risk of infection is mainly dominated by the helminth *Ascaris*. Further, the risk is very sensitive to changes in the incidence rate, indicating that local handling of faeces is an important route of exposure. The risk of infection will be greatest when emptying the container of collected faeces as the material at this stage has not then been mixed with soil and no further reduction of pathogens has occurred. Emptying the container will result in potential exposure to pure faeces that have been stored for 0–12 months. The highest risk resulting from exposure to un-stored material was attributable to rotavirus (3×10^{-2}), whereas *Ascaris* constituted the highest risk after 6 or 12 months' storage, even if this infection is quite uncommon in the Danish population. The study suggests that local handling of faeces may open a new route of infection for *Ascaris* in a population where this helminth is rare.

There is a high level of uncertainty regarding inactivation of pathogens in faecal material, and further studies are recommended. The risks of infection can be reduced by measures such as longer storage, treatment with a pH-elevating substance, or heating.

ACKNOWLEDGEMENTS

The Danish EPA as part of the Ecological Wastewater Handling Program financed the major part of this project.

REFERENCES

Andersen, E. J. & Weber, S. G. 2004 Rotavirus infection in adults. *Lancet Infect. Dis.* **4**, 91–99.

Arnbjerg-Nielsen, K., Hansen, L., Kjølholt, J., Stuer-Lauridsen, F., Hasling, A. B., Hansen, N. J., Stenström, T. A., Schönning, C., Westrell, T., Carlsen, A. & Halling-Sørensen, B. 2005 *Risk Assessment of Locally Collected Faeces for Use in Private Gardens* (Risikovurdering af anvendelse af lokalt opsamlet fæces i private havebrug.) Danish EPA report, Copenhagen, Denmark (in Danish, English summary), www.mst.dk/udgiv/Publikationer/2005/87-7614-693-6/pdf/87-7614-694-4.PDF.

Gantzer, C., Gaspard, P., Galvez, L., Huyard, A., Dumouthier, N. & Schwartzbrod, J. 2001 Monitoring of bacterial and parasitological contamination during various treatment of sludge. *Wat. Res.* **35**, 3763–3770.

Haas, C. N., Rose, J. B., Gerba, C. P. & Regli, S. 1993 Risk assessment of virus in drinking water. *Risk Anal.* **13**(5), 545–552.

Haas, C. N., Rose, J. B. & Gerba, C. P. 1999 *Quantitative Microbial Risk Assessment*. John Wiley and Sons, New York.

Hald, T. & Andersen, J. S. *Microbial Risk Assessment on Using Human Urine as Fertilizer* (Risikovurdering vedrørende eksponering for smitstoffer i forbindelse med anvendelse af human urin som gødning). Danish EPA, Copenhagen, Denmark in press (in Danish, English summary).

Höglund, C. 2001 *Evaluation of Microbial Health Risks Associated with the Reuse of Source Separated Human Urine*. Doctoral thesis. Department of Biotechnology, Royal Institute of Technology Stockholm, Sweden.

Höglund, C., Ashbolt, N. & Stenström, T. A. 2002 Microbial risk assessment of source-separated urine used in agriculture. *Waste Manag. Res.* **20**, 162–171.

Larsen, P. B. 1998 *Afskæringskriterier for forurenet jord (Allowable Pollution Loads for Contaminated Soil). Miljøprojekt 425*. Danish EPA, Copenhagen, Denmark (in Danish).

Moe, C. & Izurieta, R. 2003 Longitudinal study of double vault urine diverting toilets and solar toilets in El Salvador. *Proceedings from the 2nd International Symposium on Ecological Sanitation*, Lübeck, Germany, 7–11 April 2003.

Ottosson, J. 2003 *Hygiene Aspects of Greywater and Greywater Reuse*. Licentiate thesis. Department of Land and Water Resources Engineering, Royal Institute of Technology Stockholm, Sweden.

Ottoson, J. & Stenström, T. A. 2003 Faecal contamination of greywater and associated microbial risks. *Wat. Res.* **37**, 645–655.

Pesaro, F., Sorg, I. & Metzler, A. 1995 In situ inactivation of animal viruses and a coliphage in nonaerated liquid and semiliquid animal wastes. *Appl. Environ. Microbiol.* **61**(1), 92–97.

Regli, S., Rose, J. B., Haas, C. N. & Gerba, C. P. 1991 Modeling the risk from *Giardia* and viruses in drinking water. *J. Am. Wat. Wks Assoc.* **83**, 76–84.

Schönning, C. & Stenström, T. A. 2004 *Guidelines for the Safe Use of Urine and Faeces in Ecological Sanitation Systems*. *EcoSanRes Report 2004-1*. SEI, Stockholm, Sweden.

Shuval, H., Lampert, Y. & Fattal, B. 1997 Development of a risk assessment approach for evaluating wastewater reuse standards for agriculture. *Wat. Sci. Technol.* **35**(11–12), 15–20.

Teunis, P. F. M., van der Heijden, O. G., van der Giessen, J. W. B. & Havelaar, A. H. 1996 *The Dose-Response Relation in Human Volunteers for Gastro-intestinal Pathogens*. *Report 284550 002*. National Institute of Public Health and the Environment, Bilthoven, the Netherlands.

Wheeler, J. G., Sethi, D., Cowden, J. M., Wall, P. G., Rodrigues, L. C., Tompkins, D. S., Hudson, M. J. & Roderick, P. J. 1999 Study of infectious intestinal disease in England: Rates in the community, presenting to general practice, and reported to national surveillance. *BMJ* **318**, 1046–1050.

WHO 1989 *Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture*. WHO, Genéva, Switzerland.

Available online September 2006