Tracing enteric viruses in the European berry fruit supply chain

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A B S T R A C T

In recent years, numerous foodborne outbreaks due to consumption of berry fruit contaminated by human enteric viruses have been reported. This European multinational study investigated possible contamination routes by monitoring the entire food chain for a panel of human and animal enteric viruses.

A total of 785 samples were collected throughout the food production chain of four European countries (Czech Republic, Finland, Poland and Serbia) during two growing seasons. Samples were taken during the production phase, the processing phase, and at point-of-sale. Samples included irrigation water, animal faeces, food handlers’ hand swabs, swabs from toilets on farms, from conveyor belts at processing plants, and of raspberries or strawberries at points-of-sale; all were subjected to virus analysis. The samples were analysed by real-time (reverse transcription, RT)-PCR, primarily for human adenoviruses (hAdV) to demonstrate that a route of contamination existed from infected persons to the food supply chain. The analyses also included testing for the presence of selected human (norovirus, NoV GI, NoV GII and hepatitis A virus, HAV), animal (porcine adenovirus, pAdV and bovine polyomavirus, bPyV) and zoonotic (hepatitis E virus, HEV) viruses.

At berry production, hAdV was found in 9.5%, 5.8% and 9.1% of samples of irrigation water, food handlers’ hands and toilets, respectively. At the processing phase, hAdV was found in 1.7% of hand swabs, 0.6% of toilet swabs and 3.8% of raspberries or strawberries; at point-of-sale, the prevalence of hAdV in fresh raspberries, frozen raspberries and fresh strawberries was 0.7%, 3.2% and 2.0%, respectively. Of the human pathogenic viruses, NoV GII was detected in two (3.6%) water samples at berry production, but no HAV was detected in any of the samples. HAV-contaminated frozen raspberries were found once (2.6%). Animal faecal contamination was evidenced by positive pAdV and bPyV assay results. At berry production, one water sample contained both viruses, and at point-of-sale 5.7% and 1.3% of fresh and frozen berries tested positive for pAdV.

At berry production hAdV was found both in irrigation water and on food handler’s hands, which indicated that these may be important vehicles by which human pathogenic viruses enter the berry fruit chain. Moreover, both zoonotic and animal enteric viruses could be detected on the end products. This study gives insight into viral sources and transmission routes and emphasizes the necessity for thorough compliance with good agricultural and hygienic practice at the farms to help protect the public from viral infections.

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1. Introduction

Consumption of berry fruit contaminated with norovirus (NoV) or hepatitis A virus (HAV) has been recognized as a cause of gastroenteritis and hepatitis, respectively, in humans (Fiore, 2004; Glass et al., 2009). In addition to their transmission through food, most enteric viruses are transmitted through water, through fomites, and directly from person to person (Carter, 2005). The important role of food handlers has been established in the contamination of food with human enteric viruses (Todd et al., 2008).

Infected humans can excrete large quantities of enteric viruses in their faeces (i.e. 10^9–10^11 virus particles per g of faeces) and shedding may continue for several weeks (Atmar et al., 2008; Rodríguez-Lázaro et al., 2012). Untreated sewage of human origin usually has a high viral load. These viruses are neither completely removed nor totally inactivated by conventional wastewater treatment processes. For example, the reduction of only 1 to 2 log_10 infectious units of culturable human adenoviruses (hAdV) has been reported by Hewitt et al. (2011). Thus, viruses can be discharged into natural water sources. Non-enveloped RNA or DNA enteric viruses are persistent in water and in the environment (Glass et al., 2009). Ineffectively treated water used for drinking or irrigation may thus be contaminated with viruses. Since hAdV can be found at consistently high levels in sewage all year round, it has been proposed as an indicator virus for the presence of human faecal contamination in water (Wyn-Jones et al., 2011).

Although most enteric viruses are generally considered to be species specific, hepatitis E virus (HEV) is known to be zoonotic (Meng, 2011). HEV infections in Europe are often travel-related in humans, but infections caused by genotype 3 swine HEV are endemic (Di Bartolo et al., 2008; Vasicikova et al., 2011). Porcine adenoviruses (pAdV; Hundesa et al., 2009) and bovine polyomaviruses (bPyV; Hundesa et al., 2010) have been proposed as indicator viruses for the source-tracking of animal faecal contamination in the environment.

Several NoV outbreaks related to raspberries have been reported (Poronka et al., 1999; Sarvikivi et al., 2012), but there is still a lack of data about how berries become contaminated by viruses. The present study was designed to elucidate the most significant sources of virus contamination in the raspberry (Rubus idaeus) and strawberry (Fragaria vesca) supply chains, in four European countries, namely the Czech Republic, Finland, Poland and Serbia. In this study, as in the studies of Berto et al. (2012), Di Bartolo et al. (2012), Diez-Valcarce et al. (2012), and Kokkinos et al. (2012), the presence of hAdV, pAdV and bPyV in samples (water, swabs, faeces and berries) was investigated. The presence of these viruses demonstrates that routes of contamination exist from the gastrointestinal tracts of humans or animals to those points in the food supply chain from where the samples were taken. Other enteric viruses such as NoV, HAV or HEV will be able to follow these routes, to contaminate the food supply chain. hAdV, pAdV and bPyV are referred to in this study as index viruses, to emphasize that their use was to reveal the existence of contamination routes and points of vulnerability to virus contamination, and not to indicate per se the presence of pathogenic virus types. Selected samples were also tested for NoV, HAV and HEV. The elucidation of points of vulnerability in the berry supply chain should assist food safety management practices to reduce the potential for enteric viral contamination.

2. Materials and methods

2.1. Outline of berry fruit supply chain

In berry production on-farm, food handlers picked berries with their bare hands (Poland, Serbia), with gloved hands (Finland, the Czech Republic) or mechanically (Serbia). The green parts of the fresh strawberries were kept attached until sold at retail. The berries were packed into disposable cartons or plastic boxes (variable sizes depending on the farms). After harvesting they were transported (pre-chilled at 10 °C, the Czech Republic only) to a processing plant or directly distributed to retail or point-of-sale.

At each processing plant, those berries selected to be frozen were cooled down to temperatures between 0 to +2 °C for 4–8 h and subsequently frozen in freezing tunnels. Once frozen (−25 °C), they went through a bulking and sorting process on conveyor belts. Frozen berries were stored below −20 °C at the plant until they were delivered on demand via a cold chain. No water was used in the handling of the berries during the processing.

2.2. Sampling strategy

In this EU project (“Integrated monitoring and control of foodborne viruses in European food supply chains [VITAL]”) samples were taken at perceived critical points for virus contamination monitoring. These critical points were identified according to the procedure described in Kokkinos et al. (2012). Briefly, the berry producing farms, processing plants and point-of-sale premises in the Czech Republic, Finland, Poland and Serbia from which samples were to be taken provided background information by completing questionnaires based on HACCP (hazard analysis and critical control points) audit principles. The critical control points in the premises were identified and then a sampling strategy was planned and followed.

Samples were tested initially for the index viruses hAdV, pAdV and bPyV. If positive for hAdV, then samples were considered to be contaminated with human faeces and further tested for NoV and HAV. If positive for pAdV, then samples were considered to be contaminated with pig faeces and further tested for HEV. Depending on the remaining resources per laboratory after this screening, a selection of samples that tested negatively for the index viruses was also tested for NoV, HAV and/or HEV.

2.3. Sampling

Of the total of 785 samples, 396 samples were taken from the production phase: irrigation water (n = 95), swabs from food handlers’ hands (n = 243), toilets/latrines (n = 22), toilet door handles (n = 22), and animal faeces (n = 14). The 106 samples that represented the processing phase included swabs from food conveyor belts (n = 55) and food handlers’ hands (n = 51). At point-of-sale phase, the 283 berry samples consisted of raspberries (n = 232) and strawberries (n = 51). These samples were collected at supermarkets and at a farmers’ market. Berries were not sampled at berry production and processing, since the total number of samples to be taken was limited in each country (n = 230) and the likelihood for finding viruses on the berries was expected to be lower than on other sample matrices.

In the Czech Republic, Finland, Poland and Serbia, the 785 samples were collected (212, 166, 215 and 192 samples per country, respectively) according to the sampling guidelines tailored for each country (see sampling strategy 2.2). The sampling occurred during summers and autumns of 2009 and 2010 with several subsequent visits to each site, which included a total of 6 farms, 3 processing plants and 6 markets. At berry production, samples were taken on 6 occasions in the Czech Republic, Finland and Poland, (161, 65 and 94 samples, respectively), and on 7 occasions in Serbia (76 samples from two farms). Samples were taken from on 6 occasions from processing plants in both Finland and Poland (16 and 24 samples, respectively) and on 5 occasions in Serbia (66 samples). Point-of-sale samples were taken on 23 occasions in the Czech Republic (51 samples), on 19 occasions in Finland (85 samples), on 18 occasions in Poland (97 samples) and on 10 occasions in Serbia (50 samples).

In this study, the berry chain was followed at generic level from supplier to processing to point-of-sale. Thus, specific berry harvests were not followed directly. Production farms and processing plants with 4 to 150 food handlers were included in the study. Irrigation was used for growing berries in the Czech Republic, Serbia and Poland; no
irrigation was needed in Finland. Cattle and pigs were bred on one berry farm in Serbia.

2.4. Outline of sample analysis

From the total of 785 samples taken in the study (Table 1), 771 were analysed for hADV (excluding 14 animal faecal samples); these samples included 382 samples from berry fruit growing farms, 106 samples from berry processing plants and 283 samples from points-of-sale. 333 of the 785 samples (326 water, environmental swab or berry samples, 7 porcine and 7 bovine faecal samples) in berry fruit chains were monitored for pADV and bPyVs in 3 countries in order to investigate whether there were routes of viral contamination originating from animals. Of these, 96 were obtained from the production phase, 39 during processing and 198 from the point-of-sale. HEV, HAV and NoV were analysed from 186, 333 and 333 samples, respectively. Fig. 1 describes the outline of the methods used for analyses of the samples.

2.5. Sample process control virus (SPCV)

The term SPCV denotes murine norovirus 1 (MNV-1) (Diez-Valcarce et al., 2011b), which had been propagated in RAW264.7 cells. MNV-1 stocks (10⁷ pfu/ml) were kindly provided by the group led by Dr. Franco Ruggeri at the Istituto Superiore de Sanità, Rome, Italy by agreement with Washington University, USA.

2.6. Sample treatment

2.6.1. Faeces

A 250 mg quantity of faecal sample was suspended in 2.25 ml PBS containing 10 mg/ml gentamycin and 10 μl (10⁵ genomic copies) of the SPCV. The suspension was centrifuged at 3000 × g for 15 min, and the supernatant was transferred into a clean microcentrifuge tube. The supernatant was then immediately used for nucleic acid extraction or stored at −20 °C.

2.6.2. Swabs

Food handlers’ hands, toilets, toilet door handles and conveyor belts were sampled using a 10 cm × 10 cm sterile gauze swab (several manufacturers) moistened in 20 ml of PBS containing 10 mg/ml gentamycin, and in a sterile plastic bag. Sampling was performed before handwashing at a pre-determined time of the day, e.g. immediately before lunch or coffee break. One food handler’s hand (the dominant hand) was swabbed by rubbing the swab firmly four or five times on the back, the palm and the spaces between the fingers and all the fingertips.

After swabbing hands, the swabs of environmental surfaces (toilets and conveyor belts) were taken by wiping the relevant surface area rubbing the swab firmly four or five times before being directly transported to the laboratory. Subsequently, the gauze was squeezed to release the contents. The liquid in the bag was decanted into a clean centrifuge tube and 10 μl of SPCV was added. The suspension was vortex-mixed at full speed for 20 s, centrifuged at 3000 × g for 5 min and the supernatant was transferred into a clean centrifuge tube. The supernatant was immediately used for nucleic acid extraction or stored at −20 °C.

2.6.3. Irrigation water

A sample of 10 L of irrigation water was collected into an aseptic container and directly transported to the laboratory. The water sample pH was lowered to 3.5 with 1 M HCl, a final adjustment was made with 0.1 M HCl, and 10 μl of SPCV was added. Then the sample was processed by the method described by Vilaginès et al. (1993), as modified by Wyn-Jones et al. (2011). Briefly, glass wool filters were prepared by compressing 10 g of glass wool (type 725; Rantigny, Saint-Gobain, France) into a 30 × 3 cm polystyrene column to obtain a filter height of 6 to 8 cm. The filter was washed by passing a volume of 50 ml of 1 M HCl, tap water, 1 M NaOH, and finally tap water through it until the filtrate pH was neutral. The sample was drawn through the filter by a vacuum at a rate not exceeding 1.5 L/min. Subsequently, the viruses were eluted by a slow (20–30 min) passage of 200 ml 3% (w/v) beef extract (pH 9.5) in glycine buffer (0.05 M) through the filter. The eluate was flocculated by the addition of 1 M NaOH until the pH reached 3.5 to 3.0 and a visible floc was formed. The resultant protein floc was deposited by centrifugation at 7500 × g for 30 min, dissolved in PBS and adjusted to a final volume of 10 ml. This suspension was then filtered through a 0.45 μm filter (Sartorius Minisart) to remove the remaining particulates. The filter had been pre-treated by passing 5–10 ml 1.5% w/v beef extract at pH 7.4 through it to saturate the filter with proteins. The filtered suspension was stored at −20 °C prior to analysis for nucleic acids.

2.6.4. Berry fruit

A sample of berry fruit was collected into a sterile plastic bag or other appropriate sterile container and transported to a chilled or frozen state (frozen berries were kept frozen) to the laboratory. The sample was processed using the method of Dubois et al. (2006) and according to ISO technical specifications (Norovirus and hepatitis A virus analyses from food and animal feed; ISO/TS 15216-1: 2013; ISO/TS 15216-2: 2013) with small modifications. First, 25 g of whole berries was placed into a sterile beaker, 10 μl of SPCV was pipetted onto the fruit and 40 ml of Tris glycine buffer (pH 9.5) containing 1% beef extract (TGBE), and 6500 U pectinase (Pectinex™ Ultra SPL solution, Sigma) were added to the sample. The pH of the sample was maintained at 9.0 while rocking at 60 rpm for 20 min at room temperature; if necessary, an adjustment by 1 N NaOH was performed with extension of the agitation period by 10 min after each adjustment. Subsequently, the liquid was decanted through a strainer (mesh size of 1.0 mm), and centrifuged at 10,000 × g for 30 min at 4 °C. The supernatant was transferred into a clean tube and its pH was adjusted to 7.2 and 0.25 volumes of 50% (w/v) polyethylene glycol (PEG) 8000/1.5 M NaCl solution were added. The suspension was mixed by shaking for 1 min, incubated with gentle rocking at 4 °C for 60 min and then centrifuged at 10,000 × g for 30 min at 4 °C. The obtained pellet was compacted by centrifugation at 10,000 × g for 5 min at 4 °C then resuspended in 500 μl of PBS and mixed with 500 μl chloroform:butanol (1:1). The sample was incubated for 5 min at room temperature, centrifuged at 10,000 × g for 15 min at 4 °C. The aqueous phase was transferred to a clean tube and immediately used for nucleic acid extraction or stored at −20 °C or −70 °C.

2.7. Nucleic acids extraction

Nucleic acids were extracted from animal faeces using QIAamp Viral RNA Mini kit (QIAGEN) according to the manufacturer’s instructions. The final elution step was performed twice with 150 μl of elution buffer,
which resulted in 300 μl of nucleic acid extract. Nucleic acids were isolated from 5 ml of irrigation water concentrate, 5 ml of swab washes and 500 μl of berry fruit extracts by NucliSens miniMAG (bioMerieux) system with a final repeated elution resulting in 300 μl of nucleic acid extract. The procedure was performed according to the manufacturer’s instructions. The samples of isolated nucleic acids were assayed immediately or stored at −70 °C.

2.8. Real-time PCR

Primers used for real-time PCR (qPCR), for hAdV, pAdV, bPyV, or reverse transcription real-time PCR assays (RT-qPCR), for MNV-1, NoV GI and GII, HAV and HEV, are shown in Table 2.

The detection of DNA viruses (hAdV, pAdV and bPyV) was performed using TaqMan Universal PCR Master Mix (Applied Biosystems) in a total volume of 25 μl per reaction. The qPCR protocol specific for adenoviruses contained 1× TaqMan Universal PCR Master Mix, 0.9 μM (final concentration) forward and reverse primers, 0.225 μM adenovirus specific probe, 50 nM internal amplification control (IAC) probe, approximately 100 copies of IAC DNA and 10 μl of template nucleic acid. The qPCR protocol specific for hAdV was initiated by UNG treatment at 50 °C for 2 min, followed by activation of AmpliTaq Gold polymerase (Applied Biosystems) at 95 °C for 10 min and 45 cycles of 95 °C for 15 s and 60 °C for 1 min. To the contrary pAdV assay was carried out under the following conditions: UNG treatment at 50 °C for 2 min, followed by activation of AmpliTaq Gold polymerase at 95 °C for 10 min and 45 cycles of 95 °C for 15 s, 55 °C for 20 s and 60 °C for 20 s.

The bPyV specific qPCR included 1× TaqMan Universal PCR Master Mix (Applied Biosystems), 0.4 μM each primer, 0.12 μM bPyV specific probe, 50 nM IAC probe, 300 copies of IAC DNA and 10 μl of template nucleic acid. Amplification was accomplished by the following protocol: UNG treatment at 50 °C for 2 min, activation of AmpliTaq Gold polymerase at 95 °C for 10 min, followed by 45 cycles of 95 °C for 15 s and 60 °C for 1 min.

RNA viruses (NoV GI, NoV GII, HAV, HEV and MNV-1) were detected using RNA UltraSense™ One-Step Quantitative RT-PCR System (Invitrogen) in total volume of 20 μl. The reaction mixture specific for NoV GI, NoV GII, HAV and MNV-1 contained 1× RNA UltraSense reaction mix, 1× ROX reference dye, 1 μl of RNA Ultrase sensor enzyme mix and 10 μl of tested nucleic acid. RT-qPCR reaction specific for NoV GI, NoV GII and HAV also included 0.25 μM virus specific probe, 50 nM IAC probe, 0.5 μM forward, 0.9 μM reverse primer and 300 copies of IAC RNA, whereas the MNV-1 assay contained 50 nM IAC probe, 0.2 μM each MNV-1 primer and probe and 600 copies of IAC RNA. Reverse transcription reaction and amplification were performed according to the generic protocol: reverse transcription at 50 °C for 15 min, preheating at 95 °C for 2 min, followed by 45 cycles of denaturation at 95 °C for 15 s and annealing at 60 °C for 1 min.

The presence of HEV genome was tested according to Jothikumar et al. (2006) with slight modifications; the reaction contained 1× RNA Ultrase reaction mix, 0.25 μM primers, 0.1 μM HEV probe, 50 nM IAC probe, 1× ROX reference dye, 1 μl of RNA Ultrase sensor enzyme mix, 300 copies of IAC RNA and 10 μl of isolated nucleic acids. RT-qPCR was performed at 50 °C for 30 min, preheating at 95 °C for 2 min and 45 cycles of amplification by 95 °C for 10 s, 55 °C for 20 s and 72 °C for 15 s. Amplification and fluorescence detection was performed using the LightCycler 480 Instrument (Roche) using 96-well PCR plates (Czech Republic), the Rotorgene RG-3000 (Corbett/Qiagen) in Finland, and the 7500 Real-Time PCR System (Applied Biosystems) in Poland and in Serbia. Each sample was tested by qPCR or RT-qPCR in duplicates as neat samples and 1:10 diluted samples. Uracil DNA Glycosylase was used in each qPCR or RT-qPCR reaction to avoid possible carry-over contamination. Proficiency testing for the detection of adenoviruses from berry fruit was performed by participating laboratories in a pre-trial study (D’Agostino et al., 2012). Samples with a Ct value >37 in a single replicate were considered doubtful positives and the respective amplification curves were judged by both the testing laboratory and RIVM (National Institute for Public Health and the Environment, the Netherlands), not involved in the laboratory testing, to conclude on the final result. Discordant interpretations were discussed between the two laboratories.

2.9. Quality controls

Positive and negative controls were included in the entire virus detection method at all times to guarantee that the procedure was performed...
Table 2

<table>
<thead>
<tr>
<th>Name</th>
<th>Primer sequence</th>
<th>Reference</th>
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<tr>
<td>hAdV</td>
<td>5′-CTTACATGCAATCGACATGCTGCGG-3′</td>
<td>Herneth et al. (2002)</td>
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<td>AdFR</td>
<td>5′-CGCGACCTCTGTGAGATACAG-3′</td>
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<td>AdFr</td>
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<td></td>
</tr>
<tr>
<td>HAV</td>
<td>5′-CTTATGTCCTGAGATACAG-3′</td>
<td></td>
</tr>
<tr>
<td>HAV8</td>
<td>5′-CTTATGTCCTGAGATACAG-3′</td>
<td></td>
</tr>
<tr>
<td>HAV100</td>
<td>5′-AGGATTTCTCTGAGATACAG-3′</td>
<td></td>
</tr>
<tr>
<td>HAV150</td>
<td>5′-AGGATTTCTCTGAGATACAG-3′</td>
<td></td>
</tr>
<tr>
<td>HEV</td>
<td>5′-CTTATGTCCTGAGATACAG-3′</td>
<td></td>
</tr>
<tr>
<td>HEV-F</td>
<td>5′-CTTATGTCCTGAGATACAG-3′</td>
<td></td>
</tr>
<tr>
<td>HEV-R</td>
<td>5′-CTTATGTCCTGAGATACAG-3′</td>
<td></td>
</tr>
<tr>
<td>HEV-P</td>
<td>5′-CTTATGTCCTGAGATACAG-3′</td>
<td></td>
</tr>
<tr>
<td>mNoV</td>
<td>5′-CTTATGTCCTGAGATACAG-3′</td>
<td></td>
</tr>
</tbody>
</table>

2.10. Estimation of the virus concentration

The concentration of viruses per sample was estimated as the number of PCR detectable units (PDU) using a most probable number-like approach, based on the detection probabilities given the actual portion of the samples examined. The presence or absence of target viruses was determined by RT-qPCR in neat nucleic acids solutions and sufficient serial 10-fold dilutions thereof to determine the end-point dilution, in duplicate. The higher the virus concentration, the greater the probability of multiple positive RT-qPCR results per dilution series. In contrast, the lower the concentration, the greater the probability of multiple or all negative test results. The presence/absence pattern for the j examined dilutions per sample was combined according to the following:

$$
\ell = \prod_{i=1}^{j} \left( 1 - \exp\left( -c \cdot V_i \right) \right) \times \exp\left( -c \cdot V_i \right)^{1-p_i}
$$

where \( V_i \) is the recorded actual amount of sample examined per reaction and \( p_i \) denotes the presence (\( p_i = 1 \)) or absence (\( p_i = 0 \)) of \( \geq 1 \) PDU in dilution \( i \). The most likely PDU concentration \( c \) is the concentration that gives the largest value for \( \ell \). It was assumed that when viruses were present, they were distributed homogeneously in throughout the samples.

The number of target genomes per PDU for each assay and matrix cannot be determined. Furthermore, this number is likely variable, because it depends on the efficiency of amplification. Under ideal amplification circumstances, with an exact doubling of targets per cycle, and a perfect test, 1 PDU would represent a single virus genome. The number of PDUs required for a 95% probability of detection (assuming homogeneously mixed samples) were estimated by solving the above equation for \( c \) using \( p = 1 \) and \( V \) being the total amount of sample tested. The estimate numbers for faeces, swabs, water and berries were 587 PDU/g, 27 PDU/L, 2.7 PDU/L and 1.6 PDU/g, respectively. All estimates were made by the same institute, RIVM.

3. Results

3.1. Presence of hAdV in the berry supply chain

Results obtained after 771 samples were analysed for hAdV are shown in Table 3. There were more hAdV-positive samples (27/382) in the berry production phase than in the processing (1/106) and point-of-sale (5/283) phases.

hAdV was detected in 9.5% of the irrigation water samples, followed by toilets and door handles (9.1%) and food handlers’ hands (5.8%, Table 3A). On some farms, several of the samples taken were contaminated by hAdV. For example 8/18 (44%) samples of irrigation water were contaminated by hAdV, in one strawberry-growing farm. The estimated average hAdV concentration for positive samples was 1.2 × 10^3 (95% interval: 760–1.9 × 10^3) PDU/L water for the strawberry growing farm and 5 (0.3–23) PDU/L water for one raspberry growing farm. In toilets, an average of 96 (28–260) PDU of hAdV per toilet swab were present. hAdV was identified on the hands of seasonal workers/harvesters in 3 out of 4 countries with a hAdV concentration of 320 (220–460) PDU per food handler’s hand.

Samples were analysed for hAdV contamination occurring during the raspberry processing phase in three countries. hAdV was identified once in a sample collected from a food handler’s hand (Table 3B).
hADV was found in samples taken from the conveyor belts at the processing plants.

Both raspberries and strawberries were shown to contain hADV (Table 3C) at point-of-sale. The prevalence of hADV was 1.7% (4/232) in raspberries and 2.0% (1/51) in strawberries. In farmers’ markets 1.7% (1/60; versus 0/77 in supermarkets) and 2.1% (1/47; versus 0/4 in supermarkets) of fresh raspberry and strawberry samples were hADV positive. Frozen berries contaminated by hADV were sampled twice in supermarkets, with positives of 3.4% (2/58) in supermarket samples, and once (2.7%, 1/37) in a storehouse at point-of-sale. hADV was detected more frequently in frozen raspberries (3.2%) than in fresh raspberries (0.7%; Fisher’s exact test, \( p = 0.02 \)). The estimated average hADV concentration on the frozen raspberries was 0.2 (0.06–0.6) PDU per g and on the fresh raspberry 0.7 (0.04–3.4) PDU per g. The estimated concentration on the positive strawberries was 54 (15–200) PDU per g.

3.2. Animal, zoonotic and human pathogenic viruses in the berry fruit supply chain

Table 4 shows that faecal contamination of animal origin was found in one (1.1%) out of 89 irrigation water samples, but it was not found in processing or point-of-sale samples. PAdV was detected more often: in 4.5% of irrigation water samples, in 5.7% of fresh raspberries and in 1.3% of frozen raspberries. All PAdV-positive raspberries were collected from supermarkets: 40% (4/10; versus 0/60 in farmers’ markets) of fresh raspberries and 2.5% (1/40; versus 0/47 in farmers’ markets) of frozen raspberries were positive.

The presence of zoonotic and human pathogenic viruses other than hADV in the berry fruit supply chain was analysed in 186 and 333 samples (Table 4). Although no HEV contamination was detected in the berry production phase, HEV was found once in a pack of frozen raspberries taken from a cold room at point-of-sale. The estimated PDU concentration of HEV per 1 g of raspberries was 1.1 (0.2–3.5) PDU. HAV was not detected in any of tested samples. Berries at point-of-sale did not test positive for NoV (0/120). NoV GII was detected twice in the irrigation water of a strawberry-growing farm. The average estimated NoV GII concentration was 1.1 × 10^3 (500–2 × 10^3) PDU per 1 L of water.

### Table 3

<table>
<thead>
<tr>
<th>Point-of-interest</th>
<th>Finland</th>
<th>Poland</th>
<th>Serbia</th>
<th>Czech Rep.</th>
<th>Total hADV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Production</strong> (n = 96)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigation water</td>
<td>0/6a</td>
<td>0/19</td>
<td>1/34</td>
<td>8/36</td>
<td>9/95</td>
</tr>
<tr>
<td>Toilets</td>
<td>1/6</td>
<td>0.6</td>
<td>1/4</td>
<td>0/6</td>
<td>2/22</td>
</tr>
<tr>
<td>Toilet door handles</td>
<td>0/8</td>
<td>0.5</td>
<td>2/3</td>
<td>0/6</td>
<td>2/22</td>
</tr>
<tr>
<td>Food handlers’ hands</td>
<td>0/45</td>
<td>4.64</td>
<td>9.21</td>
<td>1.13</td>
<td>14.243 (5.8%)</td>
</tr>
<tr>
<td><strong>B. Processing</strong> (n = 106)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conveyor belt</td>
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<td>0/24</td>
<td>0/15</td>
<td>n.d.</td>
<td>0.55</td>
</tr>
<tr>
<td>Food handlers’ hands</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1/2</td>
<td>n.d.</td>
<td>1.51</td>
</tr>
<tr>
<td><strong>C. Point-of-sale</strong> (n = 283)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Fresh raspberries</td>
<td>1/5</td>
<td>1.60</td>
<td>0/10</td>
<td>n.d.</td>
<td>1/137</td>
</tr>
<tr>
<td>Frozen raspberries</td>
<td>0/18</td>
<td>1.37</td>
<td>2/40</td>
<td>n.d.</td>
<td>1/35</td>
</tr>
<tr>
<td>Fresh strawberries</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1/51</td>
<td>n.d.</td>
<td>1.51</td>
</tr>
</tbody>
</table>

* a Number of positives/number of tested; n.d. no data.

### Table 4

<table>
<thead>
<tr>
<th>Point-of-interest</th>
<th>Animal viruses</th>
<th>Zoonotic virus</th>
<th>Human pathogenic viruses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Production</strong> (n = 96)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigation water</td>
<td>4.89 (4.5%)</td>
<td>1.89 (1.3%)</td>
<td>0.56 (0.56)</td>
</tr>
<tr>
<td>Toilets</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.9 (0.9)</td>
</tr>
<tr>
<td>Food handlers’ hands</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0/10 (0.10)</td>
</tr>
<tr>
<td>Pig faeces</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8 (0.8)</td>
</tr>
<tr>
<td>Cattle faeces</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td><strong>B. Processing</strong> (n = 319)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conveyor belt</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.24 (0.24)</td>
</tr>
<tr>
<td>Food handlers’ hands</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0/1 (0.1)</td>
</tr>
<tr>
<td><strong>C. Point-of-sale</strong> (n = 198)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh raspberries</td>
<td>1.77 (1.3%)</td>
<td>0.77 (2.6%)</td>
<td>0.8 (0.8)</td>
</tr>
<tr>
<td>Fresh strawberries</td>
<td>0.51</td>
<td>0.51</td>
<td>0.21 (0.21)</td>
</tr>
</tbody>
</table>

* a n.d. no data.

### 4. Discussion

Berry fruit is a known vehicle for foodborne viruses. However, to our knowledge this type of large multinational study on the contamination of the berry fruit supply chain by viruses has not been carried out before. The sampling plan of the study was developed to derive optimal benefit from the number of samples determined to be taken. The strategy included increasing the probability of detecting a virus obtained from a sampling point when low virus concentrations were expected, or obtaining the most accurate estimates of prevalences given the total number of samples. The monitoring of berry producing farms, processing plants and points-of-sale for the presence of hADV revealed that...
there are possibilities for berries to become contaminated by viruses especially at production. Zoonotic and animal viruses were also detected along the berry fruit supply chain.

4.1. Water (at berry production)

The significance of water as an efficient route of disseminating human enteric viruses has been known for a long time. Although natural waters have been shown to become contaminated by sewage or treated wastewater (Wyn-Jones et al., 2011), and drinking water containing viruses have been published. In South Korea, Cheong et al. (2009) found adenoviruses in 4/29 and 3/30 irrigation water and vegetable water have been published. In South Korea, Cheong et al. (2009) found adenoviruses in 4/29 and 3/30 irrigation water and vegetable samples, respectively. Our study also revealed that raspberries and strawberries were irrigated with water that contained human and animal viruses.

According to the recommendations of Codex Alimentarius (FAO/WHO, 2012), water of suitable quality should be used for irrigation. In Europe, regulations (Regulation (Ec) No 852/2004 of The European Parliament and of the Council on the Hygiene of Foodstuffs, and Article 5 (c) of Annex 1 of the General Hygiene Provisions for Primary Production and Associated Operations) state that potable water, or clean water be used whenever necessary to prevent contamination. However, it is not practical for all berry production farms to use potable water for irrigation. Moreover, since bacterial indicators may not be suitable for predicting some potential viral contamination and water is not regularly monitored for viruses, water that has passed the indicator test may still contain viruses. There is also a general perception that the hygienic quality of irrigation water is less important than that of drinking water. Viruses persist in water for a long time, e.g. it has been shown that NoV can persist for at least 60 days in groundwater (Seitz et al., 2011). Although drip irrigation prevents direct contact of irrigation water with berry fruit, spraying berries with pesticides shortly before harvesting might lead to the contamination of berries, since it has also been shown that viruses may persist in pesticides reconstituted in virus containing water (Verhaelen et al., 2012a).

4.2. Food handlers’ hands

Our study showed that berry handlers at berry production may contaminate berries, since viruses were found in several swab samples taken from harvesters’ hands. The presence of hAdV on the harvesters’ hands and then also on berries at point-of-sale suggest that this is one possible route of virus transmission. The sanitary condition of water closets and handwashing facilities in the fields and in food handlers’ living accommodation may not always meet the necessary standards of hygiene. This, coupled with poor hand hygiene practices, increases the risk that enteric viruses may be transferred via hands to the picked berries. It has also been experimentally shown that viruses are efficiently transferred from contaminated hands to surfaces (Barker et al., 2004; Bidawid et al., 2004). In previous studies, NoV was detected in swabs taken from food handler’s hands in a gastroenteritis outbreak setting (Boxman et al., 2009). In an outbreak caused by HAV-contaminated blueberries (Calder et al., 2003), harvesters’ hands were speculated to be a likely vehicle of virus transmission, although the source of contamination could not be traced.

4.3. Processing

In this study the processing site was not found to be a likely place where viruses enter the berry fruit supply chain. This finding is in agreement with previously published results that disease outbreaks caused by berry fruit had not often been traced back to processing. One reported case occurred in a tourist resort in Egypt where HAV was linked to the processing of orange juice (Frank et al., 2007). During processing, berries are not usually manually handled but instead are processed automatically, which may diminish the likelihood of viral contamination of berries by food handlers. In the processing of lettuce and other vegetables, water is used for washing, which thereby increases the risk for viral contamination of the lettuce (Kokkinos et al., 2012). However, little or no water is used in the processing of berries, which may also be another reason why berries are not as easily contaminated during processing. Enteric viruses survive well in a cold environment, so when berries are contaminated at berry production, viruses are likely to remain infectious during processing and at point-of-sale. Experimental studies have shown that the reduction for MNV as a surrogate of human NoV during pasteurization of raspberry puree was less than 3 log-units (Baert et al., 2008a).

However, the fact that frozen berries were more often contaminated than fresh berries may suggest that freezing is in some way preferred by viruses, perhaps since it preserves the viruses on berries better than storage at higher temperatures. Future studies that focus on the processing phase and analyses of a larger number of samples may further clarify the impact of processing in viral contamination of berries.

4.4. Berries at point-of-sale

A recent publication (Tuladhar et al., 2012) found that in some circumstances hAdV may be less stable than MNV-1, a surrogate for NoV. On the other hand, Verhaelen et al. (2012b) reported that both hAdV and NoV persist for the duration of the shelf life of raspberries on contaminated berries at room temperature, which suggests that the presence of hAdV would be useful in indicating faecal contamination of berries. In our study, the prevalence of hAdV in frozen raspberries at point-of-sale was 3.2%, which was lower than those (34.5% and 6.7%, for Belgium and France, respectively) reported for NoV in the review of Baert et al. (2012). In addition to the analysis of different enteric viruses, the higher prevalence of virus in berries in Belgium may be as a result of a random selection due to a relatively low number of samples. The high prevalence may also have been influenced by place and time of the sampling. As an example, in Finland, in 2009, exceptionally high numbers of NoV outbreaks linked to berries were detected (Sarvikivi et al., 2012), but had not been detected before or since that year. Differences in the methods used for testing berries for viruses may also partially explain the differences in the prevalence values.

In the present study, the inclusion of IACs in the (RT)-qPCRs ruled out false negative interpretations of results due to the presence of RT or PCR inhibitors that are frequently found in food samples. The presence of PCR inhibitors in the samples usually leads to high ct values, the verification of which is challenging, since real-time PCR is highly sensitive as compared to confirmation tests. Inclusion of adequate controls is also necessary to exclude nucleic acid contamination in the laboratory. Furthermore, the NIC and NTC values obtained showed that positive results were not false positives due e.g. to amplicon contamination in the laboratory.

At the beginning of the study the first samples were collected before the development of the analytical methodology was complete. All these initial samples were stored frozen for several months before analysis, which may have slightly decreased the number of positive results we obtained (e.g. if viral RNA had degraded during storage). It was considered worthwhile however to ensure that the analytical methods were fully fit for purpose, and demonstrated as robust in collaborative trial (D’Agostino et al., 2012).

4.5. Zoonotic viruses

In this study the presence of human enteric viruses other than hAdV had not been confirmed either in fresh or in frozen fruits, but unexpectedly HEV was found. The insufficient amount of viral RNA did not allow us to perform further molecular analysis of this virus isolate. The potential sources of produce contamination on berry producing farms are...
irrigation water, animal-based fertiliser, soil and produce handling (Beuchat, 1996; Rodríguez-Lázaro et al., 2012). In a previous study, Brassard et al. (2012) detected HEV on strawberries grown in a field irrigated with polluted river water. In our study it was not possible to definitively establish a traceable link between polluted irrigation water and HEV-contaminated produce, but it is highly likely that HEV could have originated from contaminated soil or water used for plant irrigation as some of the tested irrigation water samples were positive for the animal index viruses. Currently, for most of the raspberry farms direct water contact with growing plants and fruits is rare due to the common use of drip irrigation systems. Natural water sources, including well water, can be exposed to enteric viruses abundantly present in agricultural run-off, leakage from sewage tanks or animal farms adjacent to the production fields. The high frequency of pAdV (57%) obtained in our study in pig faeces in a berry-growing farm and the occurrence of pAdV or bPV in water samples supports the previous assumption that animal-based fertiliser could be considered as a vehicle for virus contamination. The significance of pig manure in the dissemination of HEV needs further investigation.

Occasional cases of hepatitis E in humans that originate from the consumption of food of animal origin have been reported (Bouwknegt et al., 2007; Colson et al., 2010). Although HEV has been found on fresh produce (Kokkinos et al., 2012) including berry fruit (Brassard et al., 2012) on other occasions, the role of this kind of food in HEV transmission to humans has not been unequivocally confirmed.

5. Conclusion

This study has demonstrated the potential for viruses to enter the berry fruit supply chain via contaminated food handlers’ hands and water during the production phase. In addition, it has provided evidence for the potential for contamination of the berry fruit supply chain by HEV. Data obtained in this study will be used to estimate the prevalence of viruses in irrigation water, on food handlers’ hands or berry fruit into human health risks, as has previously been performed for lettuce crops (Hamilton et al., 2006; Petterson et al., 2001).

In the future, more focused studies that intensively examine berry fruit virus contamination routes should be carried out. Now that significant sources have been identified, virus-aware revisions of existing food safety management systems should be implemented. The VITAL project found more non-compliance with prerequisite food safety and hygiene requirements when handling produce and juice with an HEV index virus than when handling produce and juice with a surrogates for human noroviruses, during the production process of green- and red-onion and spinach. J. Food Prot. 71 (8), 1590–1597.


