A novel genetic marker for the rapid detection of *Bacteroides fragilis* in recreational water as a human-specific faecal indicator
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**ABSTRACT**

*Bacteroides* spp. has gained substantial interest among the suggested potential candidates for alternative faecal indicators for untreated recreational waters by the US EPA. Interest in *Bacteroides* as a faecal indicator is based upon the relative abundance of selected members of the *Bacteroides* genus in the human colon and human faeces. In this study, we developed a real-time PCR detection system based on gyrase B subunit genes (*gyrB*) specific to *Bacteroides fragilis*. The *gyrB*-based method was compared with previously described 16S rRNA-based real-time qPCR methods and evaluated for specificity, sensitivity and robustness in detecting *B. fragilis* from untreated recreational water impacted by human and non-human faecal sources. The new *gyrB*-based system only detected *B. fragilis*, whereas the 16S rRNA-based methods generated cross-amplifications with other *Bacteroides* and *Prevotella* species. We used a procedure of prefiltration, filtration, sonication and DNA concentration in order to improve the DNA extraction efficiency and the sensitivity of the real-time PCR while removing interference. The amplification and sequencing of PCR products generated by the *gyrB*-based method confirmed that *gyrB*-amplified sequences only contained *B. fragilis*. This rapid method is useful for quantifying faecal contamination and may assist beach and watershed managers in elucidating possible contamination sources.

**Key words** | *Bacteroides*, *gyrB* gene marker, human-specific, rapid method, recreational water

**INTRODUCTION**

The association between illness and recreational contact with surface waters has been well documented since the 1950s (Stevenson 1953). Associations between faecal indicators and illness have also been established for these water users (Cabelli *et al.* 1979, 1982; Prüss 1998; Wade *et al.* 2003, 2006; Colford *et al.* 2007), which includes EPA studies establishing *Escherichia coli* as a criteria indicator in freshwater (Dufour 1984). Despite associations between exposure and water quality, the minimum time to obtain an *E. coli* colony count result is 18–24 h post-sample (US Environmental Protection Agency 2006) which is inadequate for communicating same-day water quality risks to the public to prevent exposure. This warrants rapid methods to improve risk reporting. Additionally, current US recreational water quality criteria for pathogens and pathogen indicators are scheduled for revision by 15 October 2012 (Natural Resources Defense Council v. Johnson and U.S. EPA 2008). Emerging from this consent decree is a mandate for US EPA to consider alternative rapid indicators of recreational water quality to ensure improved protection of US recreational water users (e.g. swimmers and bathers).

With the advent of rapid molecular techniques, recent exploratory research has suggested *Clostridium*, *Bacteroides*, *Bifidobacterium* and bacteriophages as potential candidates for alternative faecal indicators in recreational waters (US EPA 2007). Among the suggested potential
candidates for alternative indicators by US EPA, the *Bacteroides* genus has gained substantial interest, particularly because of the relative abundance of certain genera in human faeces and human-impacted waters (Holdeman *et al.* 1976; Layton *et al.* 2006; Converse *et al.* 2009), where they may outnumber faecal coliforms 1,000-fold (Fiksdal *et al.* 1985). Another advantage of the *Bacteroides* genus as an indicator of recent faecal contamination is their inability to persist or grow in the aerobic foreshore sediments or freshwater environment since they are anaerobic, unlike the more common faecal indicator, *E. coli*, which is aerobic and has been observed to persist or replicate in this environment thereby not permitting a more complete understanding of the timing of the faecal contamination (Solo-Gabriele *et al.* 2000). Thus, *Bacteroides* indicates a more recent episode of faecal contamination. Furthermore, some evidence suggests that the *Bacteroides* group is a better indicator of non-point-source human faecal pollution than *E. coli* in recreational waters (Converse *et al.* 2009).

Thus far, some epidemiological evidence from a Great Lakes point-source impacted beach demonstrates a marginally significant association between concentrations of the genus *Bacteroides* and closely related genera and gastrointestinal illness (Wade *et al.* 2006). Among the *Bacteroides* species, *Bacteroides fragilis* is a commensal organism that constitutes a significant component of the normal colonic bacterial microflora in humans (Pumbwe *et al.* 2006). Epidemiological associations specific to *B. fragilis* densities have not yet been observed owing to methodological limitations. All existing methodologies are specific to a group or class of closely related taxa merely including *B. fragilis*. Thus, a methodology specific to the quantification of only *B. fragilis* is warranted, thereby enabling the consideration of this specific species in epidemiological studies of illness risk among recreational water users.

Traditionally, *E. coli* has been used as an indicator microorganism for communicating waterborne disease risk, particularly because of their ability to be easily and safely cultured (Simpson *et al.* 2002). However, most of the bacterial species composing the mammal gut microbiota are anaerobes that are not easy to enumerate by conventional culturing techniques and the majority of that flora is not *E. coli* but of the genus *Bacteroides* (Harmsen *et al.* 2002). Many methods have recently been designed to detect members of the *Bacteroides* genus based upon their 16S rRNA gene (Bernhard & Field 2000; Matsuki *et al.* 2002, 2004; Layton *et al.* 2006; Kildare *et al.* 2007; Okabe *et al.* 2007), including a recently developed real-time PCR assay utilizing a SYBR probe and primers designed to detect the 16S rRNA gene with a limit of quantification of $4.7 \times 10^5$ gene copy per litre in environmental samples (Seurinck *et al.* 2005). A limitation of 16S rRNA genetic marker methods involves the extremely slow rate of evolution associated with 16S rRNA, which has a low interspecies polymorphism or multiple ribosomal RNA operon copies in a single bacterial genome. Recently, several housekeeping genes, such as *rpoB*, *gyrB*, elongation factor Tu (*EF-Tu*), phosphoglycerate kinase (*pgk*) and heat shock protein (*dnaK*) genes, have been reported to evolve much faster than 16S rRNA gene, thus providing better discrimination among closely related species (Volokhov *et al.* 2007).

In this study, we developed a real-time PCR assay by using a novel primers-probe set for *B. fragilis* detection based upon *gyrB* amplification and evaluated assay performance in water samples collected from untreated recreational water. *B. fragilis* is a significant component of the normal human gut microbiota as colonic commensal bacteria (Finegold 1977), and a clinically important species among the genus *Bacteroides* for its virulence in human colonic infection (Namavar *et al.* 1989; Kuwahara *et al.* 2004). *B. fragilis* is also linked to the risk of human gastrointestinal (GI) illness (Baums *et al.* 2007) and inflammatory diarrhoeal disease in both children and adults when exposed to recreational water (Sears 2009). Thus, *B. fragilis* may serve as a more human-specific faecal indicator compared with other faecal indicators.

**METHODS**

**Bacterial strain**

*Bacteroides fragilis* ATCC 25285$^T$ was obtained from the American Type Culture Collection and propagated on *B. fragilis* bile-esculin agar (BBE) (Oxyrase, Inc. Mansfield, Ohio) plates and anaerobically incubated in an anaerobic chamber containing an AnaeroPack system (Mitsubishi...
Gas Chemical, Tokyo, Japan) for 72 h at 37 °C in order to confirm purity of *B. fragilis* colonies. BBE agar is a convenient hemin-enriched medium for the selection and presumptive identification of *Bacteroides* and related taxa based upon their hydrolysis of esculin and resistance to both bile and gentamicin (Livingston *et al.* 1978). The *B. fragilis* ATCC 25285T was used to generate a standard curve, spike environmental samples and to compare the sensitivity and specificity of the primers from the two qPCR methods.

**Environmental isolates**

Three environmental strains of *B. fragilis* were isolated from field samples. Beach water from Madison Lake (Madison County, Ohio) and stream water from Glade Run (Madison County, Ohio) were collected on 10 December 2008. Three different volumes of sample (25, 50 and 100 mL) were filtered through a nylon prefilter membrane (pore size 20.0 μm, Magna, GE Water & Process Technologies, Trevose, PA, USA) in order to remove algae and other large particles while allowing passage of bacteria (Lee & Deininger 2004). After prefiltration, the prefiltered water was filtered through a 0.45-μm pore size, 47-mm diameter cellulose membrane filter (Millipore, Bedford, MA, USA) to capture bacteria present in the water samples. The filtered membranes were then placed on BBE plates and incubated in an anaerobic chamber containing an AnaeroPack system for 72 h at 37 °C. Colonies blackening BBE plates were selected and serially subcultured on pre-reduced TSA plates in an anaerobic chamber. After confirmation as a pure colony, each isolate was identified based on the analysis of the 16S rRNA sequence with an ABI Prism 3730 DNA analyzer (Applied Biosystems, Foster City, CA, USA) at the Plant and Microbes Genomics Facility of Ohio State University. Among the isolates, three strains (1AL, 1BL, 1B2) were identified as *B. fragilis* with 100% identical 16S rRNA sequences to that of *B. fragilis* ATCC 25285T by using the NCBI (National Center for Biotechnology Information) database and the BLAST program. The strains, 1AL and IBL, were originally collected from 100 mL of beach water from Madison Lake, Ohio. The strain 1B2 originated from 25 mL of stream water from Glade Run, Ohio. These three strains were stored in 40% glycerol at −80 °C for further study. The ultimate application of these strains in this study was to enable an evaluation of the generalizability of the *gyrB* PCR assay to other recreational and environmental waters via PCR detection using positively identified *B. fragilis* from environmental sources.

**Recreational water samples**

Recreational water samples were collected for water matrix interference testing, identifying minimum limits of detection and confirming the *gyrB* PCR assay results from environmental samples. Interference testing and minimum detection limit determination was performed using samples collected from the Olentangy River (Franklin County, Ohio), which has multiple designated uses, including recreation. Two-litre water samples of Olentangy River water were collected in sterile bottles (Nalgene, Rochester, NY, USA) and transported to the laboratory on ice. Samples were immediately filtered through a nylon prefilter membrane (pore size 20.0 μm, Magna, GE Water & Process Technologies, Trevose, PA, USA) in order to remove algae and other large particles while allowing passage of bacteria (Lee & Deininger 2004). The prefiltered water was filtered through a 0.45-μm pore size, 47-mm diameter cellulose membrane filter (Millipore, Bedford, MA, USA) to concentrate bacteria present in the water samples. In order to test possible interference coming from the water matrix, a PCR assay was performed with filtered Olentangy River water samples that were spiked with *B. fragilis* ATCC 25285T and three *B. fragilis* environmental isolates (1AL, 1BL, 1B2).

The Olentangy River water matrix was of interest because of its proximal location to the laboratory, recreational use designation and water quality. Presently, like many Ohio waterways, the river is defined as impaired with regards to recreational use, as it exceeds the numeric criteria for pathogens based upon the faecal coliform indicator. The *Ohio Environmental Protection Agency* (2007) indicates that the primary sources of this impairment in the upper portions of the river is failing home sewage treatment systems and manure from livestock operations; however, in the sample area, which is more urban, combined and sanitary sewer overflows are the primary contamination sources, with home sewage treatment systems contributing slightly.
DNA extraction from recreational water samples

The filtered membranes from the Olentangy River samples were transferred into 15-mL sterile tubes. Two mL of sterile phosphate buffered saline (PBS; 0.14 M NaCl, 2.7 mM KCl, 10.1 mM Na2HPO4, 1.8 mM KH2PO4 [pH 7.6]) was added to the tube to soak the filter membrane, which then was rigorously vortexed. Since the improvement of DNA extraction efficiency is important for the success of PCR assays, sonication was carried out to detach cells from the filter membranes efficiently. Sonication was done for 10 min using the Fisher Scientific FS20 sonicating water bath (Fisher Scientific, Pittsburgh, PA). After sonication, the resuspended cells were centrifuged at 10,000 g for 15 min at 4 °C and the supernatant was gently removed. The harvested cells were suspended in 1 mL of ASL buffer and DNA extraction was performed with a QIAmp DNA Stool Mini Kit (Qiagen, Valencia, CA, USA) in accordance with the manufacturer’s instruction as performed in previous studies evaluating the occurrence and diversity of Bacteroidales (Jeter et al. 2009) and other human-associated markers (McQuaig et al. 2006). In order to concentrate DNA, the final elute of 200 μL during the last step of DNA extraction was evaporated under a gentle stream of air at room temperature and then reconstituted with 20 μL elution buffer. The concentration of the DNA was determined with a NanoDrop system (Nanodrop Technologies, Wilmington, DE, USA) and the purity was checked with gel electrophoresis.

Primer design

The B. fragilis specific gyrB gene-based primers and probe set was based on 748 gyrB genes obtained from the NCBI database. From the 748 sequences of bacterial gyrB genes, 322 sequences were selected and aligned by Clustal X version 2.0 (Larkin et al. 2007) by eliminating disqualified and duplicated sequences. Unique DNA sequence regions were chosen as forward/reverse primers and one minor groove binder (MGB) probe using Primer Express® software (version 3.0, Applied Biosystems, Foster City, CA, USA).

Comparison of the primers

The newly designed primers were compared with previously known Bacteroides–Prevotella group-specific primers (Bernhard & Field 2000; Okabe et al. 2007; Okabe & Shimazu 2007). This reference primer set was designed relying on the 16S rRNA gene to detect the Bacteroides–Prevotella group in a TaqMan real-time PCR system. Another reference primer set was the B. fragilis group-specific primer which was selective not only for B. fragilis but also other members of the Bacteroides group (e.g. B. fragilis, B. ovatus, B. thetaiotaomicron and B. uniformis) in a SYBR real-time PCR system (Matsuki et al. 2002, 2004).

First, we compared our gyrB gene-based primer set with the Bacteroides–Prevotella group-specific primer set using in-silico analysis. A sequence-similarity search was done using primer-BLAST software at the NCBI database (http://www.ncbi.nlm.nih.gov/tools/primer-blast) (Altschul et al. 1997) and the Probe Match application at the Ribosomal Database Project (http://rdp.cme.msu.edu). The most similar sequences to both Bacteroides–Prevotella and gyrB gene-based primer were retrieved and entered into MEGA software (http://www.megasoftware.net) in order to construct schematic phylogenetic trees. For the illustration of the differences in the primers and the related sequences, the number of nucleotide differences was added to radial neighbour-joining trees (Saitou & Nei 1987). The degree of confidence in phylogenetic branching was assessed by repeating bootstrap analyses 1000 times (Saitou & Nei 1987).

The specificities of the primers were also tested by conventional PCR. The B. fragilis group primer (Matsuki et al. 2002) was included in this comparison. For this, DNA extracts from B. fragilis (ATCC 25285T) and three environmental isolates (1AL, 1B2, 1BL) were tested together with Bacteroides ovatus (ATCC 8483T) and Prevotella melaninogenica (ATCC 25845T) by using each Bacteroides/Prevotella, gyrB gene-based, and B. fragilis group-specific primer. Thermal cycles for PCR were similar except the variations in annealing temperature; incubation for all was at 94 °C for 3 min, followed by 30 cycles of denaturation at 94 °C for 1 min, annealing at each 60 °C (Bacteroides/Prevotella primer), 58 °C (gyrB gene-based primer) and 50 °C (B. fragilis group primer) for 30 s, extension at 72 °C for 1 min, and final extension at 72 °C for 10 min. After PCR, 5 μL aliquots of each amplification product was loaded onto 1.0% agarose slabs (15 by 5 cm) for gel electrophoresis and run in TBE (89 mM Tris-borate, 2 mM EDTA) buffer at 100 V for 30 min. The slabs were stained with ethidium
bromide and documented with a Bio-Rad Quantity One Gel Doc system (Bio-Rad, Hercules, CA, USA) with the 1-kb DNA ladder (Invitrogen, Carlsbad, CA, USA) as a molecular weight marker.

**Standard curve**

After *B. fragilis* ATCC 25285<sup>T</sup> was grown on BBE plates, two sets of serial dilution of *B. fragilis* were prepared to generate standard curves. For each set of the serial dilutions, one colony of *B. fragilis* was suspended in 1 mL of PBS and then suspension aliquots of 100 μL were serially diluted (1:10 dilution) for *B. fragilis* standard curve development. Ten microliters of the well-mixed solution of *B. fragilis* was then spread on BBE plates to enumerate *B. fragilis* as colony forming units after incubation in an anaerobic chamber for 72 h at 37 °C. At the same time, DNA was extracted from the remaining 990 μL of the same serial dilution set with a DNeasy Tissue Kit (Qiagen, Valencia, CA, USA) in accordance with the manufacturer's instructions. The DNA was regarded as being extracted from 1,000 μL of *B. fragilis* solution for convenience. The standard curve was derived by plotting cycle threshold (C<sub>T</sub>) values against the log cell counts (CFU mL<sup>–1</sup>), which were obtained from plate counts. DNA extracts were stored at 4 °C for immediate use (real-time PCR) or at −20 °C for less than a month (end-point PCR).

**Real-time PCR assays**

A TaqMan real-time quantitative PCR was performed with the reference (16S rRNA *Bacteroides/Prevotella*) and gyrB gene-based primers and probes sets by using a 48-well StepOne™ Real Time System (Applied Biosystems, Foster City, CA, USA) following the manufacturer’s instructions. The amplification reactions were performed in optical microplates using a total volume of 30 μL. The reaction mixtures contained 1x TaqMan universal PCR master mix (PCR buffer, deoxynucleoside triphosphates, AmpliTaq Gold polymerase, internal reference signal 6-carboxy-x-rhodamine [ROX], Amp Erase uracil N-glycosylase [UNG], MgCl<sub>2</sub>; Applied Biosystems), 500 nM of each oligonucleotide primer, and 250 nM of TaqMan Minor Grove Binding (MGB) probe labelled with 6-carboxy fluorescein (FAM). A mixture of all PCR reagents without template DNA was used as a negative control for each PCR reaction. For the gyrB gene-specific primers and probe, thermal cycling consisted of an initial cycle of 50 °C for 2 min (activation of the UNG) and 95 °C for 10 min (activation of the AmpliTaq Gold DNA polymerase), followed by 45 cycles of denaturation at 95 °C for 30 s and annealing and extension at 58 °C for 3 min. For the reference (16S rRNA *Bacteroides/Prevotella*) primers and probe, the thermal cycle condition was as follows: incubation at 50 °C for 2 min and at 95 °C for 10 min, followed by 45 cycles of denaturation at 95 °C for 15 s, and annealing and extension at 62 °C for 1 min.

**Nucleotide sequences accession numbers**

The DNA sequences were deposited in the GenBank database under accession numbers from GU130198 to GU130203.

**RESULTS AND DISCUSSION**

**gyrB gene-based primer design and comparison with 16S rRNA-based primers and probe**

The gyrB gene-specific primers and probe were designed to perform quantitative real-time PCR detection of *B. fragilis*. These are listed in [Table 1](#) and we used the 16S rRNA-based primers and probe as a comparison group known as *Bacteroides/Prevotella* group-specific (Okabe et al. 2007). Figures 1 and 2 show the cluster of target bacteria that can be amplified with gyrB gene-based primers. The relationships in both radial phylograms were determined by MEGA4 software with the model based on the nucleotide differences and the neighbour-joining method (1,000 replicates). The gyrB primers, Bf904F and Bf1272R, were used to root the trees in Figures 1 and 2, respectively. The reference forward primer, qHS601F, was generally specific for *Bacteroides* and *Prevotella*. However, there are three mismatches with *Arenibacter certesii* (NR_025747), *Arenibacter latericus* (NR_024893), *Aequorivita sublithincola* (NR_025031), *Amphibacillus tropicus* (NR_025192), *Acetobacterium pasteurianum* (NR_026327), which are non-*Bacteroides/Prevotella* and the same oligonucleotide sequences as *Prevotella salitae*.
Prevotella albensis (NR_025300), Prevotella pallens (NR_026417), Prevotella enoeca (NR_025281) and Prevotella intermedia (NR_026119). Thus, this reverse primer may be the major factor for most cases of 16S rRNA-based amplification that detect Bacteroides together with Prevotella. From our in-silico analysis, three additional bacteria, Arenibacter certesii (NR_025747), Campylobacter hominis (NR_025377) and Mesonia alga (NR_025263), were found to possibly cross-amplify with this reverse primer (qBac725R). In contrast, the gyrB forward primer,

### Table 1 | Nucleotide sequences of primers and probes for real-time PCR assay in this study

<table>
<thead>
<tr>
<th>Sequence (5’–3’)</th>
<th>Size of product (bp)</th>
<th>Annealing temp° (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16S gene-based primers and probe compared in this study</td>
<td>qHS601Fa&lt;sup&gt;a&lt;/sup&gt; GTTGTGAAAGTGGTCCGCTCA (Okabe et al. 2007)</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>qHS624MGB FAM-CGTAAGTTGCAGTTGA-MGB (Okabe et al. 2007)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>qBac725R CAATCGGAGTTCTCTTAGATCTA (Bernhard &amp; Field 2000)</td>
<td></td>
</tr>
<tr>
<td>gyrB gene-based primers and probe developed in this study</td>
<td>Bf904F&lt;sup&gt;b&lt;/sup&gt; GGCAGGATTCTCCGGGTTAA</td>
<td>368</td>
</tr>
<tr>
<td></td>
<td>Bf923MGB FAM-TGGCGACTGTC-MGB</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bf1272R TGGCATATATCGGAAGAAAAAG</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>The numbers correspond to numbers in the E. coli 16S rRNA gene.
<sup>b</sup>The numbers correspond to numbers of the gyrB gene (AB048185).
<sup>c</sup>Annealing temperature was determined by Primer Express<sup>®</sup> software.

![Figure 1](https://iwaponline.com/jwh/article-pdf/9/2/253/397560/253.pdf)

**Figure 1** | Radial phylogram showing the target bacterial cluster that can be amplified with gyrB gene-based primer, Bf904F. The large circle shows the boundary of sequence identity within 3-bp difference. Closed black, dark grey and light grey circles represent the sequences that are the same, 1 bp- and 3 bp-different, respectively. Scale bar 1 indicates 1 bp-sequence divergence. Numbers in parenthesis indicate Genbank accession numbers.
Bi904F, has one mismatch with *Capnocytophaga ochracea* (AB032577), three mismatches with *Flexibacter sancti* (AB032582) and *Myroides odoratus* (AB034239) (Figure 1). The gyrB reverse primer, Bf1272R, shows strikingly high specificity by not showing any mismatch within the 3-bp difference. It only matches with *B. fragilis* (Figure 2).

**Real-time PCR detection of B. fragilis and standard curves**

A series of experiments was conducted with *B. fragilis* to compare the results obtained from the primers and probes specific to the reference and gyrB gene-based approaches. Additionally, for both approaches standard curves were developed for quantitative PCR. For this, 10-fold serial dilutions of known *B. fragilis* cells were prepared in the range of $7.0 \times 10^2$ to $2 \times 10^7$ (CFU mL$^{-1}$) and $C_T$ values were checked with the 48-well StepOne™ Real Time System (Applied Biosystems) using the gyrB-based and the reference primers and probe after DNA extraction. Data points were plotted in each standard curve and the limit of quantification was illustrated in terms of $C_T$ values (data not shown). For application of logarithmic functions, 0 cells (CFU mL$^{-1}$) were temporarily regarded as 1 cell. Linear regression analyses of the results with gyrB and the *Bacteroides/Prevotella* 16S rRNA primers and probes produced...
standard curves with similar slopes ($-3.751$, $-3.506$) and good correlation coefficients ($R^2 = 0.986, 0.983$). However, different $y$-intercepts were observed, $48.2$ for gyrB-based and $39.5$ for 16S rRNA-based Bacteroides/Prevotella primer sets. This indicates that in this study the reference primers and probe had greater sensitivity for $B. fragilis$ detection than the gyrB gene-based primers and probe.

**Interference of recreational water matrix and presence of other bacteria in real-time PCR detection of $B. fragilis$**

We examined the possible interference due to the natural water matrix and the presence of other bacteria in the real-time PCR detection of $B. fragilis$. For this, $B. fragilis$ (ATCC 25285$^T$) was spiked into the recreational water sample and PBS, and their detection was compared. A variety of negative controls including sterile MilliQ water, membrane filters, and non-Bacteroides (E. coli, Prevotella melaninogenica, Pseudomonas aeruginosa, Salmonella enterica), and other Bacteroides ($B. ovatus$)-spiked water were tested using the same condition of real-time PCR. The results demonstrate that the presence of $B. fragilis$ in the recreational water and in the PBS produced very similar $C_T$ values when detected with the gyrB-based primers (Figure 3). Analysis of covariance (ANCOVA) was performed with the fitted curves from the PBS and the recreational water matrices in order to determine whether the slope and intercept between these two curves are similar. The result shows that there was no statistically significant difference between the two water matrices in measuring $B. fragilis$ using the gyrB-based real-time PCR method ($p = 0.53$). It also indicated that the entire procedure of the real-time PCR detection including DNA extraction and purification effectively removed possible interference that may be present in the natural recreational water matrix. The negative controls (sterile MilliQ water, membrane filters, non-$B. fragilis$ and non-Bacteroides) all produced negative signals.

**Comparison of real-time PCR sensitivity in detecting $B. fragilis$**

In order to determine the sensitivity of the real-time PCR method in detecting $B. fragilis$, a series of samples containing different levels of $B. fragilis$ were tested with the two sets of primers and probes (Table 2). With the real-time PCR using the gyrB-specific primers and probe, valid $C_T$ values were obtained from all four samples containing 100–1,000 cells (CFU mL$^{-1}$), and three of four samples containing 10–100 cells. The gyrB-specific primers and probe demonstrated 100% accuracy in detecting the samples containing 100–1,000 cells (CFU mL$^{-1}$), 75% accuracy in detecting 10–100 cells. No $C_T$ values were detected in samples when bacterial levels were less than 10 cells. In contrast, $C_T$ values were generated from all samples in the 16S rRNA-based Bacteroides/Prevotella primers and probe method even when there were no cells were added. In contrast, the gyrB-based assay did not generate $C_T$ values when there were no bacterial cells present. It is noteworthy that, in the range of less than 10 cells, all detected $C_T$ values using 16S rRNA-based method were above 40 (mostly 40–41). These high $C_T$ values could possibly be interpreted as invalid since they were located beyond the valid range of the standard curve which had a $y$-intercept of 39.5.

**Detection of $B. fragilis$ from recreational water samples**

Quantitative real-time PCR detection of $B. fragilis$ was performed from the Olentangy River water samples and the $C_T$ values from the different DNA concentration procedures were compared (Table 3). The positive-control after filtration of 250 mL shows a $C_T$ value of $33.35 \pm 0.26$ and this corresponds to $3.9 \pm 0.1 \log$ CFU based upon the standard curve. The detection efficiency was enhanced by increasing
the water filtration volume. Improved DNA concentration was achieved by two steps: sonication and DNA post-concentration. Sonication was used for more efficient detachment of the bacterial cells from the membrane filter. DNA post-concentration was achieved by air-drying the extracted DNA and then reconstituting it with 1/10-volume of sterile MilliQ water. The lowest level of detection within the quantification range was $CT = 37.67 \pm 0.44$, which corresponds to $63.1 \pm 0.1$ CFU/100 mL. This low detection limit was achieved by the combination of sonication and DNA concentration.

**Environmental B. fragilis isolates**

Environmental isolates (1AL, 1BL and 1B2) of B. fragilis were positively confirmed by Bacteroides/Prevotella, gyrB gene-based and B. fragilis group-specific primers (Table 4). The PCR products were visualized by agarose gel electrophoresis and the bands were located at the corresponding position of 150 bp (Bacteroides/Prevotella), 368 bp (gyrB) and 495 bp (B. fragilis group). The sequencing results showed that the three isolates amplified by all primer sets are identified as B. fragilis with 100% similarities. B. fragilis ATCC 25285T, B. ovatus ATCC 8483T and P. melaninogena ATCC 25845T were used as controls. Table 4 shows that the gyrB gene-based primer was the only one that targeted B. fragilis specifically, whereas the other two primers generated positive results for B. ovatus and P. melaninogena as well as B. fragilis. These results suggest that the gyrB gene-based approach is a specific and suitable method for
amplifying gene product from only \textit{B. fragilis} in recreational water samples when \textit{B. fragilis} is present.

**CONCLUSIONS**

The objective of this study was to develop a novel \textit{B. fragilis}-specific primers and probe set for real-time PCR detection of human faecal contamination in recreational water. Using a TaqMan probe, a new method to rapidly detect \textit{B. fragilis} in untreated recreational water samples was successful in achieving results within 3 h. The use of the 16S rRNA gene as a selective primer in PCR applications continues to be regarded as a common method; however, it is limited by only being able to successfully quantify the aggregate of \textit{B. fragilis} and other closely related taxa. Indeed, our results confirmed that 16S rRNA gene-based reference methods are inherently unable to discriminate specific \textit{Bacteroides} species from closely related taxa such as \textit{B. ovatus} or the genus \textit{Prevotella}. By targeting \textit{gyrB}, specific primers for \textit{B. fragilis} were designed with careful investigation of related sequences to avoid possible non-specific matches. The real-time PCR analysis of the \textit{Bacteroides/Prevotella}-specific primer/probe set still provided better sensitivity than the \textit{gyrB} gene-based primer/probe set. In contrast, the \textit{gyrB}-based primer/probe set provided superior specificity for \textit{B. fragilis} and generated no false-positive results with other \textit{Bacteroides} or related \textit{Prevotella}. Furthermore, the newly designed primers have good selectivity for detecting \textit{B. fragilis} despite the presence of other bacteria in recreational water samples. Statistical analysis demonstrated that the recreational water matrix did not interfere with the \textit{gyrB}-based qPCR assay.

We suggest that the \textit{gyrB}-based assay can be considered for use in marine recreational waters. The important factors that may influence differences between freshwater and marine water are suspended solids and salinity. The majority of suspended solids can be removed during the prefiltration step. The influence of salinity in marine water on DNA extraction and the downstream PCR reaction may be negligible because of the rinsing steps involved in the initial procedure of the prefiltration, filtration and elution. The stability of the \textit{gyrB} genetic marker in marine waters needs to be investigated, particularly because \textit{B. fragilis} survivability may differ substantially in freshwater and marine environments. This novel rapid method can detect human-specific faecal contamination of recreational and potentially other environmental waters with better specificity than existing human-associated 16S rRNA-based methods used in microbial source tracking studies. In our previous study, we evaluated the specificity of the \textit{gyrB}-based assay with animal and human faecal samples. Results showed superior specificity of the \textit{gyrB}-based assay in characterizing human faecal sources (Lee & Lee 2010).

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