Prevalence of binary toxin positive Clostridium difficile in diarrhoeal humans in the absence of epidemic ribotype 027

Alan M. McGovern¹, Grace O. Androga¹,², Daniel R. Knight¹, Mark W. Watson³, Briony Elliott⁴, Niki F. Foster², Barbara J. Chang¹, Thomas V. Riley²,⁴,⁵,⁎

1 School of Biomedical Science, University of Western Australia, Perth, Western Australia, Australia, 2 Department of Microbiology, PathWest Laboratory Medicine, Perth, Western Australia, Australia, 3 Institute for Immunology and Infectious Diseases, Murdoch University, Perth, Western Australia, Australia, 4 School of Medical and Health Sciences, Edith Cowan University, Perth, Western Australia, Australia, 5 School of Veterinary and Life Sciences, Murdoch University, Perth, Western Australia, Australia

⁎ thomas.riley@uwa.edu.au

Abstract

Virulence of Clostridium difficile is primarily attributed to the large clostridial toxins A and B while the role of binary toxin (CDT) remains unclear. The prevalence of human strains of C. difficile possessing only CDT genes (A− B CDT+) is generally low (<5%), however, this genotype is commonly found in neonatal livestock both in Australia and elsewhere. Zoonotic transmission of C. difficile has been suggested previously. Most human diagnostic tests will not detect A− B CDT+ strains of C. difficile because they focus on detection of toxin A and/or B. We performed a prospective investigation into the prevalence and genetic characteristics of A− B CDT+ C. difficile in symptomatic humans. All glutamate dehydrogenase or toxin B gene positive faecal specimens from symptomatic inpatients over 30 days (n = 43) were cultured by enrichment, and C. difficile PCR ribotypes (RTs) and toxin gene profiles determined. From 39 culture-positive specimens, 43 C. difficile isolates were recovered, including two A− B CDT+ isolates. This corresponded to an A− B CDT+ prevalence of 2/35 (5.7%) isolates possessing at least one toxin, 2/10 (20%) A− B− isolates, 2/3 CDT+ isolates and 1/28 (3.6%) presumed true CDI cases. No link to Australian livestock-associated C. difficile was found. Neither A− B CDT+ isolate was the predominant A− B CDT+ strain found in Australia, RT 033, nor did they belong to toxinotype XI. Previous reports infrequently describe A− B CDT+ C. difficile in patients and strain collections but the prevalence of human A− B CDT+ C. difficile is rarely investigated. This study highlights the occurrence of A− B CDT+ strains of C. difficile in symptomatic patients, warranting further investigations of its role in human infection.

Introduction

Clostridium difficile is an anaerobic, spore-forming gram positive bacillus and a major cause of antibiotic associated life-threatening diarrhoea in humans and animals, particularly pigs. C. difficile infection (CDI) is the most common healthcare-associated infection in the United
Materials and methods

Study design

All faecal specimens collected between (and including) 2014/12/31 to 2015/01/29 (30 days) from two of five tertiary public hospitals in Perth, Western Australia (WA), all other public hospitals in the state and certain private laboratories were used for this study. Specimens were submitted as part of routine microbiological investigation, which included specific or reflexive testing for C. difficile. Each source referred all their routine C. difficile testing to PathWest Laboratory Medicine, the single public sector pathology service provider for WA. The combined bed capacity of all hospitals in the study was ~3700. Specimens from these referring locations were estimated to account for ~65% of all public C. difficile testing performed in the state of WA.

All patients included were symptomatic inpatients over 2 years old who had not submitted a stool for CDI testing for more than 8 weeks preceding the study period; thus all CDI cases were considered new [17]. Most samples were also routinely tested for the presence of the enteric pathogens Salmonella, Shigella and Campylobacter. Cases without these organisms but with C. difficile possessing at least one toxin gene (A, B or CDT) were assumed to be true cases of CDI. If these organisms were detected or only C. difficile with no toxin genes was recovered, then the case was assumed not to be CDI for the purposes of this study. If testing had not been performed for these organisms, the case was considered indeterminate.

Routine diagnostic C. difficile testing used the BD MAX™ Cdiff assay (BD Diagnostics), a real-time PCR that detects the tcdB gene. Only the earliest BD MAX positive specimen from each patient was collected. If no positive specimen existed, the earliest BD MAX negative specimen was used instead such that each patient was represented by one sample. BD MAX negative samples were screened for glutamate dehydrogenase (GDH), a cell wall enzyme common to all strains of C. difficile regardless of toxin production [18], using the TechLab™ CHEK™-60 (TechLab) in accordance with the manufacturer’s instructions.
Identification and isolation of *C. difficile*

BD MAX or GDH positive stool samples were inoculated into enrichment broth containing gentamicin (5 mg/L), cycloserine (200 mg/L) and cefoxitin (10 mg/L) supplemented with 0.1% (w/v) sodium taurocholate. After 48 h of incubation, inoculated broths were mixed with an equal volume of absolute ethanol and left at room temperature for 60 min before an aliquot was plated onto chromID™ *C. difficile* agar (bioMérieux). Incubation of agar plates and identification of *C. difficile* was performed as previously described [10]. Co-infection with multiple *C. difficile* RTs was analysed by subculturing and PCR ribotyping up to six randomly selected colonies per sample, with priority given to colonies of varying morphology.

Molecular characterisation of *C. difficile*

PCR ribotyping and detection of *tcdA*, *tcdB*, the CDT enzymatic component gene (*cdtA*) and CDT' binding component gene (*cdtB*) were performed as previously described [10] with slight modification. The novel primers BE-tcdA-1 (Forward: 5'-CAGTCACGATGGAAGATT-3') and BE-tcdA-2 (Reverse: 5'-AAGGCAATAGGGTATCAG-3') specific for the 3' end of *tcdA* (*tcdA*3) were multiplexed with the NK2 and NK3 primers specific for the 5' end of *tcdA* (*tcdA*1) [19]. Reaction mixes (total volume 20 μL) consisted of 4 μL of DNA extract, 10 mM Tris-HCl (pH 8.3) and 50 mM KCl, 1.5 mM MgCl2, 0.2 μM of each primer, 200 μM of each dNTP, 1.25 U AmpliTaq Gold® DNA polymerase and 0.1 mg/mL BSA. Reactions were run with an initial denaturation step of 95 °C for 10 min, followed by 35 cycles of 94 °C for 30 s, 55 °C for 30 s and 72 °C for 90 s, with a final extension step of 72 °C for 7 min. Detection of both *tcdA*1 and *tcdA*3 fragments was required for an isolate to be considered *tcdA* positive.

Identification of RTs was achieved using the BioNumerics (v7.5, Applied Maths) software package to compare banding patterns with our reference library consisting of 74 reference strains from the UK *Clostridium difficile* ribotyping network (CDRN) and various Australian RTs. Isolates that could not be matched with any reference collection strain were designated with our internal RT prefix “QX”.

For whole genome sequencing (WGS), genomic DNA was extracted from a 48 h blood agar subculture of *C. difficile* using the QuickGene Mini80 and QuickGene DNA tissue kit (Kurabo Industries) in conjunction with an MPBio FastPrep-24™ 5G (MP Biomedicals) at a speed of 6 m/s for 40 s. Multiplexed paired-end libraries were generated using the KAPA Hyper Prep (KAPA Biosystems). Pooled genomic libraries were sequenced on a MiSeq platform (illumina). Sequence data (trimmed fastq files) have been deposited in the European Nucleotide Archive under study PRJEB19597 (accession ERS1566888–ERS1566897).

Genomes were assembled *de novo* and annotated as previously described [20]. Multilocus sequence type (MLST, ST) was determined *in silico* from assembled contigs using the scheme of Griffiths et al. [21]. The presence of toxin genes was determined *in silico* by generating whole genome alignments in Mauve v2.4.0 [22] against *C. difficile* reference strain M120 (GenBank accession FN665653). High resolution single nucleotide variant (SNV) analysis was performed on the non-repetitive non-recombinant core genome as previously described [20].

Ethics statement

As this study used biospecimens that were obtained for clinical purposes and stored by an accredited pathology laboratory no specific human research ethics approval was required under the guidelines set out in the Australian National Health and Medical Research Council (NH&MRC) National Statement on Ethical Conduct in Human Research. Any patient information had been sufficiently anonymised so that neither the patients nor anyone else could identify the patients with certainty.
Results

Sample collection, isolation and identification of *C. difficile*

A sample collection and isolation summary is shown in Fig 1. The number of BD MAX or GDH positive samples was 43 (7.3%) from 592 samples. In total, 43 isolates of *C. difficile* were recovered from 39 samples. Of the 39 *C. difficile* positive patients, 28 (71.8%) were presumed as CDI, eight (20.5%) as non-CDI and three (7.7%) as indeterminate. Of the 28 patients with CDI, 27 (96.4%) were considered to be ‘typical’ (*tcdB* positive) CDI episodes, with the one remaining case being only CDT positive (3.6%).

Prevalence and molecular characteristics

Five distinct toxin profiles were identified; the majority of isolates were A’B’CDT− (*n* = 31, 72.1%) followed by non-toxigenic (A’ B’ CDT−) (*n* = 8, 18.6%), A’ B’ CDT+ (*n* = 2, 4.7%), A’ B’ CDT− (*n* = 1, 2.3%) and A’ B’ CDT+ (*n* = 1, 2.3%) strains. Most RTs possessing at least one toxin were RT 014/020 (*n* = 12, 34.3%) followed by RT 012 (*n* = 3, 8.6%) (Table 1). No RT 027 or RT 078 isolates were recovered. The prevalence of CDT+ and A’ B’ CDT+ isolates amongst isolates possessing at least one toxin was 8.6% and 5.7%, respectively (Table 1). A’ B’ CDT+ isolates comprised two of three CDT+ isolates recovered and 20% of A’ B’ isolates (Table 1).

Of the three patients with CDT+ isolates, two were considered to be true cases of CDI. This included one patient with a specimen positive only for A’B’CDT+ *C. difficile* (QX 480) and another patient with an A’ B’ CDT+ (QX 625) and A’ B’ CDT− (QX 531) *C. difficile* co-infection. The third patient with A’ B’ CDT+ *C. difficile* (QX 626) was also positive for A’ B’ CDT− (RT 051) and A’ B’ CDT− *C. difficile* (RT 020) but not considered a CDI case due to the concurrent isolation of *Salmonella* Typhimurium. None of the CDT+ RTs was a known livestock-

---

![Flowchart of sample collection and isolation](https://doi.org/10.1371/journal.pone.0187658.g001)
associated Australian strain nor could they be matched to our collection of international reference strains. Interestingly, both patients with A−B−CDT+ isolates (AM 0014 and AM 0021) were admitted to the same remote hospital at least 3 days apart. Additionally, the 3' end of tcdA was not detected by PCR in either A−B−CDT+ isolate (Table 1), suggesting they did not belong to toxinotype XI.

The apparent lack of a tcdA 3' fragment, unique RTs and epidemiological clustering of AM 0014 and AM 0021 prompted us to investigate further using WGS. The absence of the entire PaLoc and presence of the complete CdtLoc were confirmed in silico for both isolates. Neither isolate belonged to previously known STs, but were single loci variants of various clade 5 lineages. They were given the new ST numbers, ST 392 and 387, respectively (Table 2). SNV analysis conclusively showed that despite epidemiological clustering AM 0014 and AM 0021 were genetically distinct from each other (2104 SNVs) and from 7 other non-toxinotype XI A−B−CDT+ strains in our collection (Table 2).

**Discussion**

Due to previous isolations of suspected Australian livestock-associated A−B−CDT+ C. difficile in symptomatic patients, we investigated the prevalence of these strains in human CDI,

| PCR Ribotype | Toxin PCR result | PCR Toxin Profile | n  | % Ribotypes (all) | % Ribotypes (≥ 1 toxin) | % Ribotypes (CDT+) | % Ribotypes (A−B+) |
|-------------|------------------|-------------------|----|-------------------|------------------------|-------------------|-------------------|
| 1 RT 014/020 | + + + + − −     | A"B"CDT−         | 12 | 27.9              | 34.3                   |                   |                   |
| 2 RT 012    | + + + + − −     | A"B"CDT−         | 3  | 6.98              | 8.57                   |                   |                   |
| 3 RT 015    | + + + + − −     | A"B"CDT−         | 2  | 4.65              | 5.71                   |                   |                   |
| 4 RT 056    | + + + + − −     | A"B"CDT−         | 2  | 4.65              | 5.71                   |                   |                   |
| 5 RT 081    | + + + + − −     | A"B"CDT−         | 2  | 4.65              | 5.71                   |                   |                   |
| 6 QX 076    | + + + + − −     | A"B"CDT−         | 2  | 4.65              | 5.71                   |                   |                   |
| 7 RT 001    | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 8 RT 002    | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 9 RT 049    | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 10 RT 053   | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 11 RT 103   | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 12 RT 137   | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 13 QX 001   | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 14 QX 087   | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 15 RT 017   | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 16 QX 480   | + + + + − −     | A"B"CDT−         | 1  | 2.33              | 2.86                   |                   |                   |
| 17 QX 625*  | − − − + + +     | A"B"CDT+         | 1  | 2.33              | 2.86                   |                   |                   |
| 18 QX 626*  | − − − + + +     | A"B"CDT+         | 1  | 2.33              | 2.86                   |                   |                   |
| 19 RT 010   | − − − − − −     | A"B"CDT−         | 2  | 4.65              | 20                     |                   |                   |
| 20 RT 051   | − − − − − −     | A"B"CDT−         | 2  | 4.65              | 20                     |                   |                   |
| 21 RT 009   | − − − − − −     | A"B"CDT−         | 1  | 2.33              | 10                     |                   |                   |
| 22 QX 012   | − − − − − −     | A"B"CDT−         | 1  | 2.33              | 10                     |                   |                   |
| 23 QX 121   | − − − − − −     | A"B"CDT−         | 1  | 2.33              | 10                     |                   |                   |
| 24 QX 531*  | − − − − − −     | A"B"CDT−         | 1  | 2.33              | 10                     |                   |                   |

**Total, n (%)**

|          | 43 | 43 (100%) | 35 (100%) | 3 (100%) | 10 (100%) |

tcdA1, toxin A gene 5' fragment; tcdA3, toxin A gene 3' fragment

*new ribotype

https://doi.org/10.1371/journal.pone.0187658.t001

Prevalence of binary toxin positive C. difficile

PLOS ONE | https://doi.org/10.1371/journal.pone.0187658 November 8, 2017 5 / 10
Table 2. Core genome single nucleotide variant analysis of Australian A−B CDT+ C. difficile isolates.

| PCR Ribotype | ST (Clade) | Toxinotype | PCR Toxic Profile | Host | Origin | Year | Accession | Isolate ID | Pairwise SNV distances |
|--------------|------------|------------|-------------------|------|--------|------|----------|------------|-----------------------|
| RT 033       | 11 (5)     | Xia        | A’ B’ CDT+       | Human | WA     | 2007 | ERS1566894 | RPH0101     | 3163 3153 3159 3114 3080 3137 3129 3157 3084 |
| QX 625*      | 392* (5)   | NT         | A’ B’ CDT+       | Human | WA     | 2015 | ERS1566889 | AM 0014a   | 2104 2206 2707 2497 2722 2812 2124 2685 |
| QX 626*      | 397* (5)   | NT         | A’ B’ CDT+       | Human | WA     | 2015 | ERS1566890 | AM 0021a   | 2136 2663 2437 2660 2730 936 2696 |
| RT 238       | 169 (5)    | NT         | A’ B’ CDT+       | Porcine | WA | 2007 | ERS1566888 | AI 0016b | 2651 2531 2708 2762 2206 2653 |
| RT 239       | 168 (5)    | NT         | A’ B’ CDT+       | Human | WA     | 2005 | ERS1566896 | WA 0012b   | 2410 2533 2643 2735 2480 |
| RT 585       | 164 (5)    | NT         | A’ B’ CDT+       | Human | WA     | 1998 | ERS1566892 | HCD 0052b | 2327 2525 2475 2350 |
| RT 586       | 167 (5)    | NT         | A’ B’ CDT+       | Human | QLD   | 2007 | ERS1566893 | Q 0008b    | 2302 2696 2063 |
| QX 143       | 386 (5)    | NT         | A’ B’ CDT+       | Human | NSW   | 2012 | ERS1566981 | ES 054b    | 2732 2238 |
| QX 444       | 169 (5)    | NT         | A’ B’ CDT+       | Human | WA     | 2014 | ERS1566897 | WA 3103    | 2727 |
| QX 521       | 280 (5)    | NT         | A’ B’ CDT+       | Piggery soil | QLD | 2015 | ERS1566895 | SE 21C |

ST, Multilocus sequence type (https://pubmlst.org/cdifficile); NT, non-toxigenic (i.e. Paloc completely absent)
NSW, New South Wales; QLD, Queensland; WA, Western Australia

1lower value indicates closer genetic relatedness
*a new ribotype or ST
*bThis study
7Elliott et al. [6]

https://doi.org/10.1371/journal.pone.0187658.t002
isolating two human A’B’ CDT+ C. difficile strains from 592 faecal samples. Neither isolate was related to the predominant Australian A’B’ CDT+ strain of C. difficile, RT 033, nor were they known to be livestock-associated. Our overall C. difficile positive rate and RT distribution was similar to that seen previously [23]. Epidemic RTs 027 and 078 were not detected, reflecting the continuing rarity of these RTs in Australia.

Despite recent and increasingly frequent reports of A’B’ CDT+ C. difficile in humans and animals [5–9, 11, 12, 24], the prevalence of these strains in humans is seldom investigated and reports are sporadic [4–9]. Reviews of strain collections, comprising strains from diverse sources collected over many years, indicate that the prevalence of A’B’ CDT+ C. difficile in humans is generally low (< 5%) [4, 8]. A recent study estimated the prevalence of A’B’ CDT+ C. difficile by retrospectively screening 220 A’B’ consecutively obtained isolates for CDT [5]. These isolates were accumulated from two French metropolitan hospitals over nearly 2 years and Eckert et al. [5] recovered one A’B’ CDT+ RT 033-like isolate belonging to toxinotype Xib, a prevalence of 0.45% amongst A’B’ isolates. Our prevalence of A’B’ CDT+ C. difficile amongst A’B’ isolates was much higher (20%) and observed over a significantly shorter time-frame than Eckert et al. [5]. The small sample size of our study, differences in methodology and geographic variation may explain this difference.

PaLoc positive C. difficile RTs can belong to one of 34 PCR-restriction fragment length polymorphism groups known as toxinotypes [25]. RTs 033 and 288 belong to toxinotype XI, which does not produce the LCTs due to a large deletion leaving only the 3’ end of tcdA [25]. Both RT 033 and 288 are ST11 placing them within clade 5 [21]. Of these RTs, RT 033 appears to be the predominant A’B’ CDT+ strain in circulation with other toxinotype XI RTs, RT 153 and SLO 187, rarely reported [24, 25]. The absence of RT 033 C. difficile in our study was not wholly unexpected as nine of 11 (81.8%) previous RT 033 human cases were from outside WA (S1 Table). Additionally, we had previously only isolated RT 033 and RT 288 in Australian animal populations outside WA [10, 13, 15].

All A’B’ CDT+ C. difficile recovered in this study were non-toxinotype XI. Non-toxinotype XI A’B’ CDT+ strains are extremely rare; to our knowledge only seven have been described [4, 6]. We previously reported human and animal non-toxinotype XI, A’B’ CDT+ C. difficile in WA [6], yet the A’B’ CDT+ RTs encountered in this study were novel. The great heterogeneity of these strains (Table 2) suggests a diverse population of such strains locally. The molecular epidemiology of CDI in Australia appears unique, evidenced by the presence of seemingly exclusive RTs and a diverse population of clade 5 strains [6]. This means our observations may be peculiar to Australia. Conversely, these strains may be distributed globally but remain uncharacterised due to limited adoption of appropriate detection methods in routine surveillance. Recently, diagnostic testing methods have been increasingly incorporating CDT detection [26], usually in order to presumptively identify the A’B’ CDT+ RT 027. These tests have the added benefit of potentially detecting A’B’ CDT+ C. difficile. However, as a reflection of the unclear role CDT plays in disease, these tests rarely report CDT specifically and, until recently, did not report A’B’ CDT+ results unless prompted to [26].

Both patients with A’B’ CDT+ C. difficile harboured multiple strains of C. difficile and, in one case, Salmonella Typhimurium, possibly suggesting infection from a microbiologically diverse source, such as the environment or food. Community-associated CDI (CA-CDI) is understudied in general and A’B’ CDT+ C. difficile strains are likely to be missed. Additionally, the non-toxigenic C. difficile present in both our patients may have competed against toxin-producing C. difficile, protecting the patient in the process [27]. The significance of co-infection in this study and CDI in general remains unclear. Most cases of CDI appear monoclonal in origin with the prevalence of co-infection suggested to be ~10% [28–31]. The simultaneous presence of multiple C. difficile RTs might indicate an early stage of infection, with one RT yet
to dominate others. We could not assess the relative quantities of each co-infecting strain due to our use of enrichment culture. Additionally, it would have been ideal to pick more than 6 colonies from each plate.

An alternative explanation for the low prevalence of animal-associated A⁻B⁺CDT⁺ strains of C. difficile in humans may be the transient lifecycle of C. difficile within reservoirs like calves and piglets [10–13]. The prevalence of C. difficile within these populations rapidly diminishes after three weeks of age [11, 32] unless animals are given antimicrobials directly, or indirectly via the mother. These reservoirs have little link to the general human population beside the slaughter of very young calves and suckling pigs for human consumption, both of which are not widely practised in Australia.

The mild effect of A⁻B⁺CDT⁺ C. difficile seen recently in hamster and mouse models of infection [33, 34] highlights the need to conclusively prove any epidemiological association between A⁻B⁺CDT⁺ C. difficile and disease. Such investigations should not be limited to humans, nor should they be limited to symptomatic patients, as asymptomatic patients could also harbour such strains. Future studies will need to comprehensively exclude all alternative causes of CDI symptoms and ideally show symptom resolution due to C. difficile specific treatment.

To summarise, in a sample of 592 faecal specimens, LCT-negative, binary toxin-positive C. difficile comprised two of three binary toxin positive human isolates and ~4% of presumed true CDI cases. No link to Australian livestock-associated A⁻B⁺CDT⁺ C. difficile was established. This study highlights the presence of these strains in symptomatic humans and suggests a diverse population of such strains locally. Larger prevalence surveys and surveillance of animal populations are essential to clarify the relationship between A⁻B⁺CDT⁺ C. difficile and their human and animal hosts.

Supporting information
S1 Table. Previous human C. difficile RT 033 A⁻B⁺CDT⁺ isolates. (DOCX)

Acknowledgments
We would like to thank Alere™ Australia, for the provision of materials required for this study. This publication made use of the Clostridium difficile Multi Locus Sequence Typing website (https://pubmlst.org/cdifficile/) developed by Keith Jolley and sited at the University of Oxford (Jolley & Maiden 2010, BMC Bioinformatics, 11:595). The development of this site has been funded by the Wellcome Trust. Results from this study were presented at the 41st Annual Scientific Meeting of the Australian Society for Microbiology, July 2016; Perth, Australia (Abstr A243).

Author Contributions
Conceptualization: Alan M. McGovern, Briony Elliott, Thomas V. Riley.
Data curation: Alan M. McGovern.
Funding acquisition: Thomas V. Riley.
Investigation: Alan M. McGovern, Grace O. Androga, Daniel R. Knight.
Methodology: Alan M. McGovern.
Resources: Mark W. Watson, Thomas V. Riley.
**Supervision:** Briony Elliott, Niki F. Foster, Barbara J. Chang, Thomas V. Riley.

**Writing – original draft:** Alan M. McGovern.

**Writing – review & editing:** Alan M. McGovern, Grace O. Androga, Daniel R. Knight, Briony Elliott, Niki F. Foster, Thomas V. Riley.

## References

1. Magill SS, Edwards JR, Bamberg W, Beldavs ZG, Dumyati G, Kainer MA, et al. Multistate point-prevalence survey of health care-associated infections. N Engl J Med. 2014; 370(13): 1198–1208. https://doi.org/10.1056/NEJMoa1306801 PMID: 24670166

2. Hammond GA, Johnson JL. The toxigenic element of Clostridium difficile strain VPI 10463. Microb Pathog. 1995; 19(4): 203–213. PMID: 8825908

3. Carter GP, Lyras D, Allen DL, Mackin KE, Howarth PM, O’Connor JR, et al. Binary toxin production in Clostridium difficile is regulated by CdtR, a LytTR family response regulator. J Bacteriol. 2007; 189(20): 7290–7301. https://doi.org/10.1128/JB.00731-07 PMID: 17693517

4. Geric B, Johnson S, Gerding DN, Grabnar M, Rupnik M. Frequency of binary toxin genes among Clostridium difficile strains that do not produce large clostridial toxins. J Clin Microbiol. 2003; 41(11): 5227–5232. https://doi.org/10.1128/JCM.41.11.5227-5232.2003 PMID: 14605169

5. Eckert C, Emirian A, Le Monnier A, Cathala L, De Montclos H, Goret J, et al. Prevalence and pathogenicity of binary toxin-positive Clostridium difficile strains that do not produce toxins A and B. New Microbes New Infect. 2015; 3: 12–17. https://doi.org/10.1016/j.nmni.2014.10.003 PMID: 25755885

6. Elliott B, Dingle KE, Didelot X, Crook DW, Riley TV. The complexity and diversity of the Pathogenicity Locus in Clostridium difficile clade 5. Genome Biol Evol. 2014; 6(12): 3159–3170. https://doi.org/10.1093/gbe/evu248 PMID: 25381663

7. Androga GO, Hart J, Foster NF, Charles A, Forbes D, Riley TV. Infection with Toxin A-Negative, Toxin B-Negative, Binary Toxin-Positive Clostridium difficile in a Young Patient with Ulcerative Colitis. J Clin Microbiol. 2015; 53(11): 3702–3704. https://doi.org/10.1128/JCM.03951-12 PMID: 26354812

8. Spigaglia P, Barbanti F, Morandi M, Moro ML, Mastrantonio P. Diagnostic testing for Clostridium difficile in Italian microbiological laboratories. Anaerobe. 2016; 37: 29–33. https://doi.org/10.1016/j.anaerobe.2015.11.002 PMID: 26557377

9. Grandesso S, Arena F, Eseme FE, Panese S, Henrici De Angelis L, Spigaglia P, et al. Clostridium difficile ribotype 033 colitis in a patient following broad-spectrum antibiotic treatment for KPCProducing Klebsiella pneumoniae infection, Italy. New Microbiol. 2016; 39(3): 235–236. PMID: 27284989

10. Knight DR, Thean S, Putsathit P, Fenwick S, Riley TV. Cross-sectional study reveals high prevalence of Clostridium difficile non-PCR ribotype 078 strains in Australian veal calves at slaughter. Appl Environ Microbiol. 2013; 79(8): 2630–2635. https://doi.org/10.1128/AEM.03951-12 PMID: 23396338

11. Schneeberg A, Neubauer H, Schmoock G, Grossmann E, Seyboldt C. Presence of Clostridium difficile PCR ribotype clusters related to 033, 078 and 045 in diarrhoeic calves in Germany. J Med Microbiol. 2013; 62(Pt 8): 1190–1198. https://doi.org/10.1099/jmm.0.056473-0 PMID: 23639987

12. Zidaric V, Pardon B, Dos Vultos T, Deprez P, Brouwer MS, Roberts AP, et al. Different antibiotic resistance and sporulation properties within multiclonal Clostridium difficile PCR ribotypes 078, 126, and 033 in a single calf farm. Appl Environ Microbiol. 2012; 78(24): 8515–8522. https://doi.org/10.1128/AEM.02185-12 PMID: 23001653

13. Knight DR, Squire MM, Riley TV. Nationwide surveillance study of Clostridium difficile in Australian neonatal pigs shows high prevalence and heterogeneity of PCR ribotypes. Appl Environ Microbiol. 2015; 81(1): 119–123. https://doi.org/10.1128/AEM.03032-14 PMID: 25328297

14. Goorhuis A, Bakker D, Corver J, Debaest SB, Harmanus C, Notermans DW, et al. Emergence of Clostridium difficile infection due to a new hypervirulent strain, polymerase chain reaction ribotype 078. Clin Infect Dis. 2008; 47(9): 1162–1170. https://doi.org/10.1086/592297 PMID: 18809338

15. Knight DR, Putsathit P, Elliott B, Riley TV. Contamination of Australian newborn calf carcasses at slaughter with Clostridium difficile. Clin Microbiol Infect. 2016; 22(3): 266 e261–267. https://doi.org/10.1016/j.cmi.2015.11.017 PMID: 26688811

16. Knight DR, Squire MM, Riley TV. Laboratory detection of Clostridium difficile in piglets in Australia. J Clin Microbiol. 2014; 52(11): 3856–3862. https://doi.org/10.1128/JCM.01225-14 PMID: 25122859

17. McDonald LC, Coignard B, Dubberke E, Song X, Horan T, Kutt PK, et al. Recommendations for surveillance of Clostridium difficile-associated disease. Infect Control Hosp Epidemiol. 2007; 28(2): 140–145. https://doi.org/10.1086/511798 PMID: 17265394
18. Carman RJ, Wickham KN, Chen L, Lawrence AM, Boone JH, Wilkins TD, et al. Glutamate dehydrogenase is highly conserved among Clostridium difficile ribotypes. J Clin Microbiol. 2012; 50(4): 1425–1426. https://doi.org/10.1128/JCM.05600-11 PMID: 22301027

19. Kato N, Ou CY, Kato H, Bartley SL, Brown VK, Dowell VR, Jr., et al. Identification of toxigenic Clostridium difficile by the polymerase chain reaction. J Clin Microbiol. 1991; 29(1): 33–37. PMID: 1993763

20. Knight DR, Squire MM, Collins DA, Riley TV. Genome Analysis of Clostridium difficile PCR Ribotype 014 Lineage in Australian Pigs and Humans Reveals a Diverse Genetic Repertoire and Signatures of Long-Range Interspecies Transmission. Front Microbiol. 2016; 7(2138): 2138. https://doi.org/10.3389/fmicb.2016.02138 PMID: 28123380

21. Griffiths D, Fawley W, Kachrimanidou M, Bowden R, Crook DW, Fung R, et al. Multilocus sequence typing of Clostridium difficile. J Clin Microbiol. 2010; 48(3): 770–777. https://doi.org/10.1128/JCM.01796-09 PMID: 20042623

22. Darling AC, Mau B, Blattner FR, Perna NT. Mauve: multiple alignment of conserved genomic sequence with rearrangements. Genome Res. 2004; 14(7): 1394–1403. https://doi.org/10.1101/gr.2289704 PMID: 15231754

23. Collins DA, Riley TV. Routine detection of Clostridium difficile in Western Australia. Anaerobe. 2016; 37: 34–37. https://doi.org/10.1016/j.anaerobe.2015.11.007 PMID: 26592987

24. Janezic S, Potocnik M, Zidaric V, Rupnik M. Highly Divergent Clostridium difficile Strains Isolated from the Environment. PLoS One. 2016; 11(11): e0167101. https://doi.org/10.1371/journal.pone.0167101 PMID: 27880843

25. Rupnik M, Janezic S. An Update on Clostridium difficile Toxinotyping. J Clin Microbiol. 2016; 54(1): 13–18. https://doi.org/10.1128/JCM.02083-14 PMID: 26517134

26. Androga GO, McGovern AM, Elliott B, Chang BJ, Perkins TT, Foster NF, et al. Evaluation of the Cepheid Xpert C. difficile/Epi and meridian bioscience illumigene C. difficile assays for detecting Clostridium difficile ribotype 033 strains. J Clin Microbiol. 2015; 53(3): 973–975. https://doi.org/10.1128/JCM.03297-14 PMID: 25520452

27. Nagaro KJ, Phillips ST, Cheknis AK, Sambol SP, Zukowski WE, Johnson S, et al. Nontoxigenic Clostridium difficile protects hamsters against challenge with historic and epidemic strains of toxigenic BI/NAP1/027 C. difficile. Antimicrob Agents Chemother. 2013; 57(11): 5266–5270. https://doi.org/10.1128/AAC.00580-13 PMID: 23939887

28. Wroblewski D, Hennett GE, Bopp DJ, Dumyati GK, Halse TA, Dumas NB, et al. Rapid molecular characterization of Clostridium difficile and assessment of populations of C. difficile in stool specimens. J Clin Microbiol. 2009; 47(7): 2142–2148. https://doi.org/10.1128/JCM.02498-08 PMID: 19403775

29. van den Berg RJ, Ameen HA, Furusawa T, Claas EC, van der Vorm ER, Kuijper EJ. Coexistence of multiple PCR-ribotype strains of Clostridium difficile in faecal samples limits epidemiological studies. J Med Microbiol. 2005; 54(Pt 2): 173–179. https://doi.org/10.1099/jmm.0.45825-0 PMID: 15673513

30. Behroozian AA, Chludzinski JP, Lo ES, Ewing SA, Waslawski S, Newton DW, et al. Detection of mixed populations of Clostridium difficile from symptomatic patients using capillary-based polymerase chain reaction ribotyping. Infect Control Hosp Epidemiol. 2013; 34(9): 961–966. Epub 2013/08/07. https://doi.org/10.1086/671728 PMID: 23917911

31. Hell M, Permoser M, Chmelizek G, Kern JM, Maass M, Huhulescu S, et al. Clostridium difficile infection: monoclonal or polyclonal genesis? Infection. 2011; 39(5): 461–465. https://doi.org/10.1007/s15010-011-0167-8 PMID: 21826436

32. Moono P, Putsathit P, Knight DR, Squire MM, Hampson DJ, Foster NF, et al. Persistence of Clostridium difficile RT 237 infection in a Western Australian pig herd. Anaerobe. 2016; 37: 62–66. https://doi.org/10.1016/j.anaerobe.2015.11.012 PMID: 26679487

33. Kuehne SA, Collery MM, Kelly ML, Cartman ST, Cockayne A, Minton NP. Importance of toxin A, toxin B, and CDT in virulence of an epidemic Clostridium difficile strain. J Infect Dis. 2014; 209(1): 83–86. https://doi.org/10.1093/infdis/jit426 PMID: 23935202

34. Carter GP, Chaikravorty A, Pham Nguyen TA, Mileto S, Schreiber F, Li L, et al. Defining the Roles of TcdA and TcdB in Localized Gastrointestinal Disease, Systemic Organ Damage, and the Host Response during Clostridium difficile Infections. MBio. 2015; 6(3): e00551. https://doi.org/10.1128/mBio.00551-15 PMID: 26037121.