



UNIVERSITY OF LEEDS

This is a repository copy of *Clostridium difficile* infection..

White Rose Research Online URL for this paper:  
<http://eprints.whiterose.ac.uk/99592/>

Version: Accepted Version

---

**Article:**

Smits, WK, Lyras, D, Lacy, DB et al. (2 more authors) (2016) *Clostridium difficile* infection. *Nature Reviews Disease Primers*, 2. 16020. ISSN 2056-676X

<https://doi.org/10.1038/nrdp.2016.20>

---

**Reuse**

Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.



[eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk)  
<https://eprints.whiterose.ac.uk/>

## *Clostridium difficile* infection

Wiep Klaas Smits<sup>1</sup>, Dena Lyras<sup>2</sup>, D. Borden Lacy<sup>3</sup>, Mark H. Wilcox<sup>4</sup> and Ed J. Kuijper<sup>1</sup>

<sup>1</sup>Section Experimental Bacteriology, Department of Medical Microbiology, Leiden

University Medical Center, PO Box 9600, 2300RC, Leiden, The Netherlands

<sup>2</sup>Infection and Immunity Program, Monash Biomedicine Discovery Institute and

Department of Microbiology, Monash University, Victoria, Australia

<sup>3</sup>Department of Pathology, Microbiology and Immunology, Vanderbilt University

Medical Center, Nashville TN, USA and The Veterans Affairs Tennessee Valley Healthcare

System, Nashville TN, USA

<sup>4</sup>Institute of Biomedical and Clinical Sciences, University of Leeds, Leeds, UK

Correspondence to:

W.K.S.

Email: [w.k.smits@lumc.nl](mailto:w.k.smits@lumc.nl)

### **Abstract**

Infection of the colon with the Gram-positive bacterium *Clostridium difficile* is potentially life threatening, especially in elderly people and in patients who have dysbiosis of the gut microbiome following antimicrobial drug exposure. *C. difficile* is the

leading cause of infective healthcare-associated diarrhoea. The lifecycle of *C. difficile* is influenced by the host microbiota and its associated metabolites, antimicrobial agents and the host immune system. The primary mediators of inflammation in *C. difficile* infection (CDI) are the large clostridial toxins Toxin A (TcdA) and Toxin B (TcdB), [CE: please leave abbreviations in for field preference] and, in some bacterial strains, the binary toxin CDT. The toxins trigger a complex cascade of host cellular responses to cause diarrhoea, inflammation and tissue necrosis — the major symptoms of CDI. The factors responsible for the epidemic of some *C. difficile* strains are poorly understood. Recurrent infections are common and can be debilitating. Toxin detection for diagnosis is important for accurate epidemiological study, and optimal management and prevention strategies. Infections are commonly treated with specific antimicrobial agents, but faecal microbiota transplants have shown promise for recurrent infections. Future biotherapies for *C. difficile* infections are likely to involve defined combinations of key gut microbiota.

## [H1] Introduction

*Clostridium difficile* is a Gram-positive obligate anaerobic bacterium that was originally identified as part of the flora of healthy infants in 1935, described as an ‘actively motile, heavy-bodied rod with elongated subterminal or nearly terminal spores’<sup>1</sup> (Figure 1). At that time, the strain was named *Bacillus difficilis* to reflect the difficulty experienced by the authors in isolating and culturing it. Despite the organism being present as a commensal in neonates, researchers noted that it could induce disease in animals that

was probably caused by the production of a secreted toxin<sup>1</sup>. Later work established the high molecular weight clostridial toxins, Toxin A (TcdA) and/or Toxin B (TcdB) as the main virulence (disease-causing) factors of *C. difficile*<sup>2,3</sup>. A hallmark feature of *C. difficile* that sets it apart from other species in the class Clostridia is its ability to decarboxylate parahydroxyphenylacetic acid to produce *p*-cresol, which gives *C. difficile* its characteristic tar-like or pig-like smell<sup>4</sup>.

It was not until the 1970s that a detailed characterization of the bacterium, then called *C. difficile*, revealed its involvement in human disease<sup>5</sup>. This disease became widely known as *C. difficile* associated disease/diarrhoea (CDAD); more recently, the term ‘*C. difficile* infection’ (CDI) is preferred. In the early 2000s, an increase in severe cases of CDI was noted in Canada, the United States and Europe<sup>6</sup> that was attributed to the emergence of certain epidemic types of *C. difficile*<sup>7,8</sup>. The first complete genome sequence for *C. difficile*<sup>9</sup>, together with the development of tools for the genetic manipulation of *C. difficile*<sup>10,11</sup>, has greatly stimulated research on the bacterium. *C. difficile* is now recognized as the leading cause of infective healthcare-associated diarrhoea and is increasingly linked to community-acquired cases of colitis<sup>12</sup>. *C. difficile* can be found in the intestinal tract of both humans and animals, but its spores are also ubiquitous in the environment and can be isolated from food<sup>13</sup>. Importantly, people with an adequate immune response will either eliminate the infection and/or become asymptomatic carriers<sup>14</sup>. In 2013, it was proposed that *C. difficile* should be reclassified as *Peptoclostridium difficile* on the basis of a detailed phylogenetic analysis<sup>15</sup> and this has

been adopted by the National Center for Biotechnology Information. However, considering the public awareness of the disease, the large body of scientific literature using *C. difficile*, and the lack of formal acceptance of this proposal, we will refer to the organism as *C. difficile* throughout this Primer, and to the disease it causes as CDI. We describe key aspects of the epidemiology of *C. difficile* infections, the mechanisms behind the disease, strategies for diagnosis, prevention and management and summarize the impact CDIs have on patients and society.

## [H1] Epidemiology

Molecular typing (**Box 1**) is the characterization beyond the species level, enabling clustering of individual bacterial isolates in a meaningful manner<sup>16</sup>. Typing is crucial for epidemiological studies, and facilitates effective infection prevention and disease management. Different types of *C. difficile* are known; here, we will refer to PCR ribotypes when relevant, a typing system that is based on a banding pattern obtained from PCR amplifying ribosomal 16S-23S intergenic spacer sequences<sup>17</sup>. Certain PCR ribotypes of *C. difficile* (such as PCR ribotype 010) are non-pathogenic, as they lack the toxin genes. Epidemic PCR ribotypes are distinguished from non-epidemic types by their frequent occurrence in multiple settings across several countries.

Due to a lack of systematic surveillance, no comprehensive data are available on circulating *C. difficile* types prior to 2003. After 2003, large increases in incidence and mortality rates in North America — and subsequently in several European countries —

were observed, which were associated with PCR ribotype 027 (Ref. <sup>8</sup>) and, to a lesser extent, PCR ribotype 078 (Ref. <sup>7</sup>). Such increases have also been observed in Australia, Asia and Central America after 2008 (Ref. <sup>18</sup>). It should be noted, however, that CDI and CDI-related epidemics are not limited to these types. Ribotypes 001, 002 and 014/020 frequently cause CDI clusters in the United States and Europe<sup>19,20</sup>. Furthermore, outbreaks have also been reported for strains of other PCR ribotypes, such as 017 (Ref. <sup>12</sup>), 018 (Ref. <sup>21</sup>), 106 (Ref. <sup>12</sup>), 176 (Ref. <sup>22</sup>) and 244 (Ref. <sup>23</sup>). Epidemiological data on *C. difficile* in Africa and the Middle-East are sparse<sup>12</sup>.

CDI is historically regarded as a nosocomial infection; antibiotic exposure (either prophylactic or as treatment) during hospitalization is the foremost risk factor for CDI. However, *C. difficile* is increasingly being recognized as a cause of community-associated diarrhoea. Indeed, PCR ribotypes of strains isolated from patients with community-associated CDI have a large overlap with strains cultured from patients with healthcare-associated CDI in an endemic setting, suggesting a common source (or sources) of *C. difficile*<sup>24,25</sup>. The incidence of community-associated CDI is estimated at 30 to 120 cases per 100,000 persons per year in the United States<sup>26</sup>. The incidence of community-associated CDI in The Netherlands is estimated at 390 to 730 per 100,000 person years, similar to the incidence of *Campylobacter* spp. infection, and higher than the incidence of *Salmonella* spp. infection<sup>27</sup>. More than 30% of patients who developed community-associated CDI do not have typical risk factors for CDI, such as antibiotic treatment or recent hospitalization (see below)<sup>28,29</sup>.

The US Centers for Disease Control and Prevention (CDC) estimated almost 500,000 patients with CDI and 29,000 deaths in the United States in 2011 (Ref. <sup>26</sup>); however, there is uncertainty about the precision of these estimates given the accuracy of testing methodology, although data have been adjusted based on the frequency of nucleic acid amplification test use. Between 2001 and 2010, the incidence of CDI among hospitalized adults in the United States approximately doubled, according to International Classification of Diseases (ICD)-9 discharge diagnoses<sup>30</sup>. Again, ascertainment bias secondary to awareness (frequency of requesting) and to diagnostic methods could be relevant here.

The first European Centre for Disease Prevention and Control (ECDC) point prevalence survey in 2011-2012 estimated that ~124,000 patients develop healthcare-associated CDI within the European Union each year<sup>31</sup>. However, this surveillance was performed with a variety of diagnostic tests and CDI was often only tested upon physician request, resulting in considerable underestimation of the true CDI incidence; on average, approximately 80 cases of CDI are missed per hospital per annum in Europe<sup>32</sup>. A pilot study supported by the ECDC using standardized CDI surveillance performed in 37 hospitals in 14 European countries demonstrated large differences in the incidence of CDI per hospital and per country<sup>33</sup>. The incidence of healthcare-associated CDI by hospital was in the range 4.2–131.8 per 10,000 discharges (median 16.4 per 10,000 discharges) and 0.6–18.5 per 10,000 patient-days (median 3.7 per 10,000 patient-days).

In some countries, a high incidence of PCR ribotype 027 strains has been noted, but other countries demonstrated a decrease in the incidence of these strains, most likely as a consequence of effective management strategies (see below)<sup>32</sup>.

The all-cause mortality associated with CDI due to non-epidemic PCR ribotypes has been reported to be ~15-20% within a month of diagnosis, and about half of the deaths are due directly to CDI<sup>34</sup>. Given the multiple co-morbidities (such as respiratory disease and renal failure) typically present in patients with CDI, mortality is often related to one or more of these.

*C. difficile* is a human pathogen and can also infect and cause disease in animals that can enter the food chain, but the relevance of food-borne transmission in human disease is unclear<sup>13</sup>. Since the beginning of 2000, *C. difficile* has been reported as a major cause of neonatal enteritis in piglets. The predominant strains found in piglets (belonging to PCR ribotype 078) are similar to isolates from some human patients with CDI and to isolates from asymptomatic farm workers, suggesting zoonotic transmission<sup>13,35</sup>. As a consequence of increasing pressure from spores present in the environment and animals, humans might become colonized more frequently. One meta-analysis revealed an increased rate (>8% of admitted patients) of asymptomatic colonization by toxigenic isolates in patients at the time of admission to the hospital<sup>36</sup>. It should be noted, however, that patients admitted to the hospital frequently have had prior hospital



exposures and, therefore, have a much higher colonization than people in the community.

### [H1] Mechanisms/pathophysiology

#### [H2] *C. difficile* lifecycle

*C. difficile* is transmitted via the oral–faecal route (**Figure 2**). Spores are dormant cells that are highly resistant to environmental conditions<sup>37</sup>, including many antimicrobials (**Box 2**) — which generally target metabolically active cells — and some disinfectants. Spores are thought to be the infectious vehicle, given that vegetative (metabolically active) cells of obligate anaerobic bacteria are unlikely to survive the oxygenated environment outside the host or the acidic environment of the stomach. Indeed, an asporogenic strain of *C. difficile* is unable to persist in the environment or transmit between hosts<sup>38</sup>.

Germination of spores is dependent on sensing of primary bile acids from the liver, such as taurocholate, by the germinant receptor CspC and is inhibited by secondary bile acids in the colon<sup>37,39,40</sup>. Additionally, glycine can act as a germinant via an uncharacterized mechanism<sup>41</sup>. A proteolytic cascade then leads to the degradation of the spore peptidoglycan, release of calcium dipicolinic acid and rehydration of the spore — ultimately resulting in outgrowth of the cells<sup>37,40</sup>.

The propensity of spores to outgrow and colonize the intestine is greatly influenced by the host microbiota and its associated metabolome<sup>39,42</sup>. For example, antibiotic-induced shifts in the microbiota can generate an environment conducive to *C. difficile* infection<sup>43</sup>. Mucolytic enzymes, such as cell surface protein Cwp84 (Ref. <sup>44</sup>), are secreted by the bacterium and degrade the colonic mucosa. Bacterial cell surface-associated proteins have been shown to affect the adhesion of the bacterium to colon epithelial cells *in vitro*<sup>45–48</sup>; mutations in genes encoding these proteins, or in the genes encoding proteins for their processing, generally attenuate virulence<sup>49,50</sup>. The expression of at least a subset of colonization factors by the bacteria, such as cell surface protein Cwp84 and surface layer protein A (SlpA), is stimulated in the presence of antibiotics ampicillin and clindamycin<sup>51</sup>.

Before germination into vegetative cells, spores are also capable of adhering to colon cells<sup>53</sup>. *C. difficile* is a motile bacterium, and the switch between the sessile and motile phase is regulated by the secondary messenger cyclic-di-GMP<sup>54–56</sup>. *C. difficile* is also capable — at least *in vitro* — of forming robust biofilms<sup>57–59</sup>. Cell–cell signalling contributes to both colonization and virulence factor expression<sup>60,61</sup>. Host recognition of *C. difficile* is mediated via pattern recognition receptors and MYD88- and nucleotide-binding oligomerization domain-containing protein 1 (NOD1)-dependent pathways<sup>62,63</sup> (**Figure 3**). Specifically, SlpA can activate a Toll-like receptor 4 (TLR4)-dependent response<sup>64</sup>, flagellin can stimulate TLR5 (Ref.<sup>65</sup>) and NOD1 is likely activated via peptidoglycan-derived compounds<sup>66</sup>. The first line of host defence against *C. difficile* is

the production of antimicrobial compounds such as lysozyme and cationic antimicrobial peptides<sup>67,68</sup>. Interestingly, the bactericidal  $\alpha$ -defensins, but not  $\beta$ -defensin 1 or cathelicidin antimicrobial peptide (known as LL-37), can also inhibit the activity of the TcdB (see below) via a mechanism that involves direct binding to the toxin<sup>67</sup>. Innate lymphoid cells, specifically class 1, are implicated in resistance against *C. difficile* disease<sup>52</sup>. [Au:OK?]

Resistance of the bacterium to host-produced antimicrobial compounds is multifactorial<sup>69</sup> and mediated by, for example, the extracytoplasmic function (ECF) sigma factor CsfV<sup>70</sup>, the site-1 protease PrsW<sup>71</sup>, the proteins encoded by the *cpr* locus<sup>72</sup> and modulation of cell wall charge<sup>73</sup>.

## [H2] The large clostridial toxins TcdA and TcdB

**[H3] Regulation of expression.** Although several virulence factors contribute to retention of the *C. difficile* within the gastrointestinal tract<sup>74,75</sup>, the symptoms of CDI correlate with the presence of a toxin-encoding pathogenicity locus (PaLoc) in the bacterial genome<sup>76,77</sup>. In most strains, the PaLoc is located at the same site in the chromosome<sup>77,78</sup>. The PaLoc in most pathogenic *C. difficile* strains encodes two large homologous toxins (TcdA and TcdB), and three proteins that seem to regulate toxin production and secretion (TcdR, TcdE and TcdC) (**Figure 4A**)<sup>74,75,78</sup>.

TcdR is a member of the ECF family of alternative sigma factors and is critical for the initiation of TcdA and TcdB production in *C. difficile*<sup>79,80</sup>. TcdC is thought to encode an anti-sigma factor that negatively regulates toxin production<sup>81</sup>. Epidemic ribotype 027 strains carry a nonsense mutation within the *tcdC* gene, leading to the suggestion that derepression of the toxin genes by the inactivation of TcdC might contribute to the increased virulence of these strains<sup>82</sup>. However, despite many studies aimed at defining the role of TcdC in toxin production and virulence, conflicting findings have been reported and the functional role of this protein remains unclear<sup>75</sup>.

TcdE has homology with bacteriophage holin proteins, which are involved in the release of progeny phages from infected bacterial cells<sup>83</sup>. The role of TcdE is also poorly understood, although some evidence suggests that it facilitates toxin (TcdA and TcdB) secretion<sup>78,84,85</sup>. TcdA and TcdB do not possess any recognizable signal or export sequences, suggesting that they might be exported from the bacterial cell by lysis or a non-classic secretion pathway, possibly involving TcdE<sup>84,85</sup>.

The synthesis of TcdR and the subsequent activation of *tcdA* and *tcdB* expression is influenced by many environmental stimuli, including short-chain fatty acids such as butyric acid that are common in the gut and sub-inhibitory concentrations of certain antimicrobials that may be relevant in the context of disease<sup>79,86–89</sup>. Amino acids such as proline, cysteine and certain branched chain amino acids in the local environment of the bacterium repress toxin production through the action of the global transcriptional

regulator CodY (known as GTP-sensing transcriptional pleiotropic repressor CodY)<sup>90</sup>. The presence of glucose or other rapidly metabolizable carbon sources in the local environment of the bacterium also inhibits the production of TcdA and TcdB via the carbon catabolite control protein A (CcpA)<sup>91,92</sup>. The sigma factor SigD, which is associated with the expression of motility genes, promotes toxin gene expression by binding to a SigD-dependent promoter sequence upstream of *tcdR*<sup>93,94</sup>. The master regulator of sporulation in both *Bacillus* and *Clostridium* species, Spo0A, can also regulate toxin production in *C. difficile*, but only in some strains<sup>95</sup>. Specifically, Spo0A negatively regulates TcdA and TcdB production in epidemic type PCR ribotype 027 strains but not in others that have been tested<sup>95-97</sup>. These results highlight the heterogeneous nature of *C. difficile* isolates and the need to study strains belonging to distinct evolutionary lineages<sup>95,98</sup>. Finally, growth signals and cell density play an important part in toxin regulation<sup>60,61</sup>. Cell-cell signalling is at least in part dependent on an accessory gene regulator quorum signalling system, which is mediated by a novel thiolactone quorum signalling peptide<sup>60,61</sup>. Overall, *C. difficile* toxin synthesis is closely connected to the metabolic state of the bacterium and its environment<sup>99</sup>.

**[H3] Mechanism of action.** Structural and functional studies have provided insights into the mechanisms of action of all of the *C. difficile* toxins, particularly TcdA and TcdB. Once secreted, TcdA and TcdB bind and enter the colonic epithelium to cause inflammatory chemokine and cytokine production, an influx of neutrophils, disruption of tight junctions, fluid secretion, and epithelial cell death (**Figures 5 and 6**)<sup>100</sup>. Given the

homology between the two proteins, it is notable that TcdA and TcdB have very different functions in animal toxicity models. Historically, TcdA has been viewed as the more potent enterotoxin, as administration of purified TcdA into the intestines of rabbits and rodents was shown to cause tissue necrosis and an intense infiltration of immune cells<sup>101–103</sup>. Higher levels of TcdB in identical experiments failed to induce these effects, although it should be noted that most of these studies were conducted in an ileal loop model and, accordingly, represent only the response of the small intestine. In studies involving human colonic tissue, TcdB seems to be a potent inflammatory toxin<sup>104,105</sup>; TcdA is weaker<sup>104</sup> [Au:OK?]. These data suggest that the differential toxin responses might in part stem from differences in receptor tropism and highlight the importance of conducting mechanistic studies within the colon, which is the site of bacterial outgrowth in the host.

TcdA and TcdB have four functional domains<sup>100,106</sup>: an N-terminal glucosyltransferase domain (GTD), an autoprotease domain (APD), a pore-forming and delivery domain and the CROPS domain, which extends from around residue 1,830 to the C-terminus (**Figure 5A and B**). A combination of electron microscopy and X-ray crystallography studies has revealed the structural organization of these domains in TcdA and suggests that the structure of TcdB is similar<sup>106,107</sup>. TcdA and TcdB enter cells via receptor-mediated endocytosis<sup>108</sup>. Historically, receptor-binding has been associated with a combined repetitive oligopeptides (CROPS) domain located at the C-terminal ends of TcdA and TcdB<sup>109</sup>. The CROPS domain is capable of binding carbohydrates, which is consistent

with the model wherein TcdA engages glycosylated receptors<sup>110</sup>. Evidence supporting the idea that the TcdA CROPS contributes to receptor binding includes the observations that antibodies against the TcdA CROPS domain can block intoxication<sup>111</sup>, and that excess TcdA CROPS domain can compete with TcdA holotoxin for cell binding<sup>112</sup>. TcdA binds a variety of carbohydrates, and while multiple glycolipids and glycosylated proteins have been proposed as receptors<sup>109</sup>, the specific receptors used to bind human epithelial cells remain unknown. However, accumulating evidence suggests that domains other than CROPS participate in receptor binding. Indeed, TcdA and TcdB toxins lacking CROPS domains are still capable of intoxicating cells<sup>113,114</sup>, and the homologous TpeL toxin from *C. perfringens* lacks a CROPS domain entirely<sup>115</sup>. Recently, two protein receptors have been reported for TcdB: poliovirus receptor-like protein 3 (PVRL3, also called nectin 3)<sup>116</sup> and chondroitin sulfate proteoglycan 4 (CSPG4)<sup>117</sup>. PVRL3 is highly expressed on the surface of human colon epithelial cells and co-localizes with TcdB in tissue resected from a *C. difficile*-infected individual<sup>116</sup>, suggesting that PVRL3 could serve as the initial receptor that TcdB encounters in the context of infection. CSPG4 is highly expressed in the intestinal subepithelial myofibroblasts of mouse and human intestines<sup>118</sup>, suggesting that this receptor could be engaged after initial damage to the colonic epithelium<sup>117</sup>. Both CSPG4 and PVRL3 bind outside the CROPS domain<sup>116,117</sup>. It is conceivable that additional alternative receptors for TcdB exist.

Following receptor binding and endocytosis, acidification of the endosome is thought to trigger a structural change in the delivery domain, allowing for pore formation and

translocation of the GTD into the cytosol (**Figure 5C**)<sup>109</sup>. The APDs share sequence homology with the cysteine protease of the MARTX family of toxins<sup>119,120</sup>, but one publication has shown that the catalytic dyad of TcdA and TcdB serves to coordinate a zinc ion that is essential for function<sup>106</sup>. Activation of the APD by eukaryotic inositol hexakisphosphate (InsP6) results in the release of the GTD into the cell, enabling access to cytosolic substrates<sup>119,120</sup>. Host S-nitrosylation at the conserved cysteine of the APD can inactivate the protease activity in an InsP6-dependent manner<sup>121</sup>. It has been hypothesized that the autoprotease and translocation efficiency contribute to the increase in virulence of the epidemic PCR ribotype 027 strain<sup>122</sup>. The GTD transfers glucose from UDP-glucose onto Rho family GTPases such as Rho, Rac1, and Cdc42 (Refs<sup>123,124</sup>). These modifications cause a cytopathic effect resulting from rearrangement of the actin cytoskeleton and can lead to apoptosis<sup>125</sup> (**Figure 5C**). At higher concentrations, TcdB is also capable of coordinating the assembly of the NADPH oxidase complex on endosomes<sup>126</sup>. The resulting production of reactive oxygen species (ROS) leads to cell death by a necrotic mechanism<sup>126</sup> (**Figure 5D**). Both mechanisms might be important in the context of disease; cytopathic effects promote inflammation and disruption of the tight junctions, whereas TcdB-induced necrosis contributes to the colonic tissue damage observed in severe cases of CDI.

Knowledge of the toxin mechanisms of action has served as a foundation for several pre-clinical studies aimed at the identification of small-molecule inhibitors of intoxication, especially those that are already approved for other uses<sup>127</sup>. A recent



screen for inhibitors of TcdB cytopathic effects revealed compounds that act by inhibiting toxin binding to cells, endosomal maturation or glucosyltransferase function<sup>128</sup>. Another screen, conducted using an activity-based probe for inhibitors of the APD, identified ebselen, a US Food and Drug Administration (FDA)-approved compound, which reduced tissue pathology in a mouse infection model<sup>129</sup>. Of note, ebselen has also been reported to block NADPH oxidase 1 activity<sup>130</sup>, a function that could contribute to a decrease in toxin-induced ROS. Similarly, N-acetylcysteine, an FDA-approved antioxidant, has been shown to prevent TcdB-induced tissue damage in a colonic explant model<sup>126</sup>.

**[H3] Pathology.** Although the roles of TcdA and TcdB in the context of CDI have been difficult to assess, recent progress has come through advances in the genetic manipulation of *C. difficile*. Four studies have been conducted in both hamster and mouse models of infection. All studies indicate that TcdB is capable of inducing the phenotypes of disease in the absence of TcdA, but differ on the interpretation of the role of TcdA in the absence of TcdB on survival of animals<sup>2,3,131,132</sup>. Histological examination of colonic and caecal tissue from mice infected with TcdB-positive *C. difficile* strains (either wild type TcdA<sup>+</sup>/TcdB<sup>+</sup> or TcdA<sup>-</sup>/TcdB<sup>+</sup> mutants) showed severe gut damage associated with eroded and often absent crypts, mucosal ulceration and goblet cell loss<sup>132</sup>. Polymorphonuclear cell (PMN) influx into the lamina propria, enterocyte hyperplasia and severe submucosal oedema associated with haemorrhage was also observed in these tissues. TcdB-negative strains (TcdA<sup>+</sup>/TcdB<sup>-</sup>) caused less

tissue damage that was confined to mild oedema and PMN influx<sup>132</sup>. Tissue damage was strictly dependent on TcdB or TcdA given that tissues from mice infected with a strain that did not produce TcdA or TcdB (TcdA<sup>-</sup>/TcdB<sup>-</sup>) resembled those of mock-infected control animals (**Figure 6**)<sup>132</sup>.

Consistent with the finding that TcdB is independently capable of causing disease, a considerable number of clinical *C. difficile* isolates only express TcdB<sup>133</sup>. The prevalence of these strains, which include PCR ribotype 017, has been increasing, sometimes to epidemic proportions<sup>134</sup>. Recently the first strain with an intact *tcdA* gene, but no *tcdB* gene, in a different genomic context than the PaLoc has been characterized<sup>78</sup>. This work has raised the hypothesis that the single toxin-encoding loci might have fused to form the typical two-toxin locus (PaLoc), which is the most common form currently detected in clinical isolates. The study also suggests a conserved relationship between the presence of toxin genes and holin genes, and demonstrates that the PaLoc does not always encode a *tcdC* homolog<sup>78</sup>. However, it should be noted that confirmed clinical cases of CDI caused by strains that only produce TcdA are extremely limited<sup>78</sup>.

## **[H2] Binary toxin CDT**

**[H3] Regulation of expression.** *C. difficile* transferase (CDT; or binary toxin) is a third toxin produced by some *C. difficile* strains, including the epidemic PCR ribotypes 027 and 078. CDT has received attention in recent years because of its increasing prevalence in isolates of both human and animal origin<sup>135</sup>. CDT is encoded by two genes, *cdtA* and

*cdtB*, that are located in an operon on the CdtLoc (**Figure 3B**)<sup>136,137</sup>. In binary toxin-negative strains, this locus contains a ~2 kb deletion<sup>138</sup>. The CdtLoc also harbours a response regulator gene, *cdtR*, upstream of the *cdtAB* operon<sup>139</sup>. CdtR is an orphan LytTR-like positive transcriptional regulator of the *cdt* operon and CDT production. The cognate sensor histidine kinase that interacts with the orphan histidine kinase CdtR has yet to be identified<sup>139</sup>. A truncation in the *C. difficile* PCR ribotype 078 CdtR does not abrogate CDT expression, suggesting that full-length CdtR is not essential for expression<sup>140</sup>. Unlike the PaLoc, the environmental signals that regulate expression of the CdtLoc genes are not known.

**[H3] Mechanism of action.** Recent studies have provided insights into the mechanisms of action of CDT, although the role of this toxin in disease pathogenesis remains unclear. CDT belongs to the binary ADP-ribosylating toxin family and comprises two components: the enzymatic component (CDTa) that has ADP ribosyltransferase activity and the binding/translocation component (CDTb) that facilitates the passage of the enzymatic component to the cell cytosol (**Figure 7**)<sup>135</sup>. CDTa ultimately leads to the complete destruction of the actin cytoskeleton and, ultimately, cell death<sup>135,141</sup>.

**[H3] Pathology.** Despite a thorough understanding of the mechanism of action of CDT on intoxicated cells, the role of this toxin in disease pathogenesis is not clear. Experimental data has suggested that CDT results in the formation of microtubule-based protrusions on epithelial cells that might increase the adherence and colonization of *C.*

*difficile*<sup>142</sup>. Importantly, the increasing presence of CDT in clinically relevant strain types commonly associated with severe CDI, such as PCR ribotype 027 and 078, and the isolation of TcdA<sup>-</sup>/TcdB<sup>-</sup>/CDT<sup>+</sup> strains suggest that this toxin is likely to play an important but as yet undefined part in CDI<sup>143,144</sup>.

## [H2] Experimental models

Multiple experimental models have been developed as a proxy for CDI and its treatment in humans<sup>145–147</sup>. The most common models are the female Golden Syrian Hamster model, which is exquisitely sensitive to toxin and is primarily suited to study acute disease, and the mouse model. The mouse model mimics certain aspects of human disease that are difficult to assess in hamsters; for instance, mice can be colonized asymptotically, there is differential sensitivity towards different PCR ribotypes and they can experience relapsing disease. For these reasons, the model is suitable to study colonization, transmission and persistence phenotypes<sup>38,148,149</sup>. A piglet model is of special interest to study *C. difficile* strains that are problematic in both animal and human populations<sup>13,35,150</sup>. *In vitro* gut models have been developed to study interactions of *C. difficile* with therapeutics in the context of a complex microbiome<sup>13,151,152</sup>. Each model is greatly influenced by variables such as qualitative and quantitative differences in inoculum and the choice of *C. difficile* strain<sup>147</sup>. Non-animal models (for example, the *in vitro* gut models) additionally may not fully reflect the interaction with the host, but some have been shown to be more reflective of human CDI than animal models<sup>147</sup>.

## [H1] Diagnosis, screening and prevention

### [H2] Symptoms and risk factors

The clinical symptoms associated with CDI range from mild, self-limiting diarrhoea to fulminant colitis and can include pseudomembranous colitis (**Figure 1D**), toxic megacolon (severe dilatation of the colon), bowel perforation and sepsis, and/or multiple organ dysfunction syndrome<sup>14,132,153</sup>. Given the characteristics of patients who can acquire CDI are highly variable, there is considerable variation in the possible severity assessments for this disease, which is reflected in the differing criteria used in guidelines<sup>154,155</sup>. Severe diarrhoea associated with *C. difficile* is often accompanied by a typical endoscopic picture of pseudomembranous colitis with haemorrhage and deep ulcerations. Toxin megacolon is considered the most serious disease entity and is characterized by systemic toxicity and high mortality. Extra-intestinal manifestations of CDI (including bacteraemia) are extremely rare, which emphasizes that it is the localized effects of toxins, associated with depleted intestinal microbiota, that cause the range of signs and symptoms of CDI. *C. difficile* toxins in sera from patients with CDI can be detected with an ultrasensitive cell-based assay<sup>156</sup>, but studies are required to assess the relationship between severe CDI and levels of toxemia.

Known risk factors are previous hospitalization, underlying disease, advanced age (>65 years), and most importantly, the use of antibiotics. All antibiotic classes can be associated with CDI, but clindamycin, cephalosporins and fluoroquinolones are most

frequently cited<sup>157</sup>. Antibiotic-induced dysbiosis of the protective intestinal microbiota often underlies *C. difficile* outgrowth and toxin production<sup>39,43</sup>. Thus, even low-risk antibiotics (such as trimethoprim and piperacillin-tazobactam) can predispose the patient to CDI, especially when two or more courses of (different) antibiotics are prescribed; the cumulative damage to the intestinal microbiota could be sufficient to enable *C. difficile* to proliferate.

Besides the antibiotic class, the number of administered antibiotics, dose and duration of therapy have been identified as risk factors for CDI. Given that disruption of the intestinal flora persists for >3 months after antibiotic therapy, patients can remain susceptible to CDI development long after ending the treatment<sup>28</sup>. Acid suppression by proton pump inhibitors (PPIs; commonly used for dyspepsia, peptic ulcer disease and gastroesophageal reflux disease) has frequently been associated with CDI<sup>158,159</sup> but the precise role (and a causal relationship) of PPIs in CDI remains unclear<sup>160,161</sup>. Of all patients with antibiotic-associated diarrhoea, 20–30% is caused by *C. difficile*<sup>162</sup>. A differential diagnosis could consider a role for *Staphylococcus aureus*, *C. perfringens*, *C. sordellii* or *Klebsiella oxytoca* as causative agents of antibiotic-associated diarrhoea<sup>163</sup>.

## [H2] Diagnosis

The mainstay for diagnosing CDI is the presence of clinical symptoms plus a well-chosen laboratory assay. The diagnostic tests for *C. difficile* can be divided into tests for *C. difficile* products (glutamate dehydrogenase (GDH), aromatic fatty acids, TcdA and/or

TcdB); culture methods for the detection of toxin-producing *C. difficile* (toxigenic culture); and nucleic acid amplification tests for *C. difficile* genes (detecting 16S rRNA, toxin genes or the gene encoding GDH)<sup>162</sup>. The test selection is important to differentiate between patients with CDI and asymptomatic carriers<sup>34,164</sup>. Tests that detect toxin are specific to CDI, whereas those that detect (a component of) the bacterium could indicate colonization rather than disease<sup>34,164</sup>.

Exclusive reliance on molecular tests for CDI diagnosis without tests for toxins likely results in over-diagnosis and over-treatment<sup>34,165</sup>. Due to large variations of sensitivity and specificity of various diagnostic tests, the European Society of Clinical Microbiology and Infectious Diseases recommends using a two-step algorithm, including a test for the presence of *C. difficile* and one to detect free toxins in the faeces<sup>166</sup>. Since tests remain positive for toxin during treatment and can even be found after successful treatment<sup>167</sup>, regular monitoring using toxin tests as follow up for treatment is not advised. If free toxins are absent, CDI is highly unlikely (**Figure 8**). Importantly, *C. difficile* toxin assays vary markedly in their sensitivity<sup>34,164,168</sup>. If *C. difficile* is present but the toxin test result is negative, CDI cannot be definitively excluded. Patients could be either (asymptotically) colonized by *C. difficile* with diarrhoea owing to an alternative cause, or experience CDI with toxin levels below the lower limit of detection of the assay used. For these patients, clinical evaluation is required to decide if treatment for CDI is warranted.

An alternative diagnostic algorithm uses a coupled enzyme immune assay that simultaneously detects both GDH and TcdA/B<sup>169</sup>. As the sensitivity of the toxin component is unclear; samples that are GDH-positive but toxin-negative could undergo reflex testing using a nucleic acid amplification test to determine if a toxigenic *C. difficile* strain is present. Ideally, every laboratory should also have the opportunity to isolate *C. difficile* from faecal samples. Isolation enables toxigenic culture and susceptibility testing, and offers the ability to perform molecular typing that is required for surveillance (**Box 1**). Many countries have implemented reference laboratories for this purpose<sup>33</sup>. The most recent US (the Society for Healthcare Epidemiology of America and the Infectious Diseases Society of America) guidelines on testing were published in 2010 and did not make a firm recommendation regarding the routine diagnosis of CDI<sup>154</sup>.

## [H2] Screening

There is a great variation between and within countries in the diagnostic algorithm applied but also the frequency of testing (when to test). A study involving almost 500 hospitals in 20 countries across Europe revealed that 23% of diarrhoeal samples with a positive CDI test result (at a reference laboratory) were initially missed owing to lack of clinical suspicion<sup>32</sup>. Hence, restricting testing of samples to those for which a physician has request for CDI testing will lead to under-diagnosis. All stool samples from hospitalized patients with diarrhoea should be tested unless a plausible alternative explanation (such as laxative use or diagnosis of inflammatory bowel disease) is available<sup>155,164,170</sup>, or if the patient is <2 years of age. Indeed, *C. difficile* is commonly



found in the faeces of healthy infants, and there is no general agreement on how to define CDI in children or when to test for CDI in children, especially with respect to age, underlying disease and use of antibiotics<sup>1,171</sup>. However, CDI can occasionally occur in infants and young children, and can cause microscopic intestinal lesions with symptoms other than diarrhoea. The American Academy of Pediatrics has recently recommended testing for CDI only if age-specific clinical criteria are met<sup>172</sup>.

As *C. difficile* is increasingly recognized as a causative agent of community-associated diarrhoea, one can consider testing all diarrhoeal samples from community patients but it can be cost-prohibitive to test a large number of samples. Application of specific algorithms, such as testing those with diarrhoea who have previously been hospitalized or used antibiotics, results in recognition of only 61% of patients with CDI in the community<sup>28</sup>. The introduction of multiplex molecular tests for enteric pathogens makes it easier to implement routine testing (screening) for CDI, although positive tests of *C. difficile* should be followed by a stool toxin detection test (two-step algorithm). In a European, multicentre, quarterly point-prevalence study of community-acquired diarrhoea applying molecular tests, *C. difficile* was found among 709 samples as the third most frequently occurring pathogen, after enteropathogenic *Escherichia coli* and *Campylobacter sp.*<sup>173</sup> In that study, children were also included (potentially identifying colonized rather than infected individuals) and a large variation per country was observed<sup>173</sup>. *C. difficile* occurred more frequently in the >60-year age group than in other age groups. Application of molecular diagnostics in a case–control study of

patients with diarrhoea attending a general practitioner in the Netherlands revealed that *C. difficile* was found in 4.2% of 1,515 cases and 0.8% of 1,195 healthy controls<sup>174</sup>. This is considerably higher than the prevalence of *Salmonella sp.* and *Shigella sp.* and confirmed that *C. difficile* is frequent in general practice<sup>24</sup>.

## [H2] Asymptomatic carriage

For both healthcare and community-associated infection, it is necessary to differentiate between colonization and disease<sup>34,164,165</sup>. Carriage and colonization are often deemed as interchangeable terms<sup>175,176</sup>. Indeed, the criteria used to determine asymptomatic carriage and/or colonization vary markedly between studies. A clarification of terminology is required, as a single *C. difficile*-positive faecal sample could indicate anything from colonization, transient carriage or 'pass-through'<sup>177</sup>. We prefer to use the term 'carriage' to refer to persistent 'colonization'.

Most studies use just one single culture and, therefore, evaluate passage or transient colonization, here defined as asymptomatic colonization. Asymptomatic *C. difficile* colonization is common in healthcare facilities and in the community, and can be attributable to toxin-positive or toxin-negative strains<sup>36,178–180</sup>. In hospitals, the prevalence of asymptomatic colonization varies from 7–18%, dependent on the length of stay, exposure to antibiotics and to *C. difficile* (infection pressure), underlying disease and possibly use of acid-suppressive medication. Indeed, the environment is most contaminated in rooms of patients with CDI, less so in rooms of patients

asymptomatically colonized with *C. difficile* and least in patients who are not colonized<sup>181</sup>. During outbreaks, colonization rates may further increase to >50%<sup>179</sup>. Asymptomatic colonization in the community is lower than in the healthcare setting and is in the range of 2–4%. Several studies report on high carriage rates (25-35%) in children in the first year; the rate drops (to 15%) between the ages of 1–8 years<sup>182–184</sup>. This variation is probably associated with the unstable intestinal microbiota in the first 2–3 years of life, which enables *C. difficile* to remain established in the intestinal tract<sup>185</sup>. Interestingly, high levels of free toxin can also be detected in faecal samples of young children without diarrhoeal symptoms — further reinforcing the need for information on the effects of toxins on intestinal epithelial cells in children.

Asymptomatic colonization has been considered a protective factor against the acquisition of new *C. difficile* isolates. A frequently cited meta-analysis of four studies from 1994 showed that patients colonized with *C. difficile* actually had a lower risk of subsequently developing CDI, but no distinction was made between colonization by toxigenic versus non-toxigenic strains<sup>186</sup>. A recent meta-analysis included studies in which patients were colonized with toxigenic strains at hospital admission only<sup>36</sup>. It should be noted that in this study, unlike the previous<sup>186</sup>, patients with previous CDI were not excluded and so could have confounded the results. Overall, the colonized patients had an increased risk of developing CDI (relative risk 5.86; 95% CI: 4.21–8.16). By contrast, patients asymptotically colonized by non-toxigenic strains do not seem to have an increased risk or are even protected from progressing to CDI. This concept

was recently tested in humans; patients who could be colonized by a non-toxigenic *C. difficile* strain after receiving standard of care treatment for CDI had significantly reduced CDI recurrence rates<sup>187</sup>. However, further explorations of this approach should consider that non-toxinogenic strains can become toxinogenic by horizontal gene transfer<sup>188</sup>, though it is unknown if this also occurs in a human host.

Asymptomatically colonized patients can shed spores into their environment and subsequently to other patients. As early as 1992 it was recognized that nosocomial acquisition of a *C. difficile* strain was preceded by introduction of that strain to the ward by an asymptomatically colonized patient<sup>189</sup>. On the basis of an epidemiological model of *C. difficile* transmission in healthcare settings, admission of colonized patients was shown to play an important part in sustaining ward-based transmission<sup>190</sup>. This observation needs confirmation as it could have major implications for infection control prevention measures.

## **[H1] Management**

### **[H2] Infection control**

Several reviews and guidelines for control of CDI have been published<sup>154,155,157,191–195</sup>.

Although some differences exist, most of these guidelines have similar recommendations (**Box 3**). If a patient is suspected of having CDI, rapid diagnostic testing should be performed to enable treatment initiation as soon as possible. Spores are highly infectious and problematic in healthcare settings as they are able to persist

on surfaces and are resistant to many disinfectants and alcohol-based hand washes<sup>37</sup>. Up to  $1 \times 10^7$  spores per gram of faeces are present in patients with CDI, representing a considerable potential for environmental contamination. Treatment should, therefore, always be combined with patient isolation to prevent spread of *C. difficile* or other enteropathogenic microorganisms.

In a healthcare setting, transmission of *C. difficile* spores occurs mainly via the contaminated hands of healthcare workers, but contact with a contaminated environment, utensils or medical devices has also been implicated; *C. difficile* spores have been identified in rooms of patients who have tested negative. Environmental decontamination of clinical areas, ideally using chlorine-releasing agents or a sporicidal product, is recommended, but in practice compliance with cleaning protocols is often suboptimal<sup>154</sup>. Newer alternatives for environmental decontamination have been introduced, notably gaseous hydrogen peroxide and, more recently, UV decontamination<sup>196</sup>. The former is particularly effective at killing *C. difficile* spores, but the cost-effectiveness of these approaches is unclear.

## **[H2] Antimicrobial therapy and surgery**

The currently available antibiotics that are recommended for treatment of CDI are metronidazole, vancomycin and fidaxomicin (**Figure 8**). Stopping the inciting antibiotics and clinical observation can treat very mild CDI that has been induced by antibiotics<sup>155</sup>. Patients with mild-to-moderate CDI can be treated with oral metronidazole but oral

vancomycin is recommended for severe or complicated infections<sup>154,155,193</sup>. Two multinational randomized controlled trials included patients managed with either vancomycin or metronidazole<sup>197</sup>. Metronidazole was inferior to vancomycin on an intention to treat basis (clinical cure rates 72.7% versus 81.1%). Also, in a post-hoc multivariate analysis, vancomycin, treatment-naïve status and mild-to-moderate CDI severity predicted treatment success.

Concomitant antibiotics are associated with reduced clinical cure, increased recurrence rates, and longer time to cessation of diarrhoea<sup>198</sup>. Additional measures to curb CDI, therefore, include discontinuation of unnecessary antimicrobial therapy (that is, for the presenting infection), as well as avoidance of anti-motility medications and reviewing PPI use<sup>155</sup>. Patients with complicated CDI with ileus (paralysed bowel) or toxic megacolon, in whom oral antibiotics cannot reach the disease site, can be treated with vancomycin delivered per rectum plus intravenous metronidazole.

Fulminant CDI is a highly lethal disease with mortality rates of up to 80%. These patients often require a total abdominal colectomy, but there is no established management protocol. Alternatively, a diverting loop ileostomy and colonic lavage might be associated with reduced morbidity and mortality<sup>199</sup>. Surgical therapy should be considered in patients with toxic megacolon, clinical signs of sepsis and severe organ dysfunction, acute abdomen and severe ileus. A white blood cell count  $\geq 15,000$ –

20,000/ $\mu$ l and elevated serum lactate (>5.0 mM) might serve as markers for severity<sup>154,155,200</sup>.

## [H2] Recurrent infection

After treatment of an initial episode of CDI, the chance of a recurrence within 8 weeks is 15–25%; for a patient with 1–2 previous recurrences, the risk of further recurrences is 40–65%<sup>201</sup>. Recurrences are associated with an impaired immune response to *C. difficile* toxins and/or alteration of the colonic microbiota. Fewer recurrences occur after treatment with oral fidaxomicin (13%) than with vancomycin (25%)<sup>202,203</sup>. However, after a first recurrence, optimal treatment options are less clear, but fidaxomicin might be effective<sup>198,202,203</sup>. Despite these shortcomings, fidaxomicin is generally used for treating a first recurrence of CDI, unless disease has progressed from non-severe to severe (**Figure 8**). Given that the main strength of fidaxomicin is prevention of recurrent infections (except for those due to PCR ribotype 027 that generally respond less well to antibiotics), clinical prediction markers for recognizing patients at risk for recurrent CDI could be helpful. Multiple risk factors for recurrent CDI have been suggested in the literature, but as not all of these are evident at the time of treatment initiation, it is difficult to select appropriate parameters. Age >65 years, concomitant antibiotics, renal failure, history of previous CDI, possibly continued use of antacid medications and initial disease severity<sup>155,204</sup> are associated with increased risk of recurrence.

## [H2] Bacteriotherapy and faecal microbiota transplantation

Limited evidence supports the use of probiotics to decrease recurrences of CDI, and no effective immunotherapy is currently available<sup>205</sup>. Faecal microbiota transplantation (FMT) is a very effective rescue treatment and should be considered in patients who have had >2 recurrences, as the efficacy of antibiotics in those patients is ~30%. A randomized controlled trial of FMT revealed that it is highly effective (~81%) in treating multiple recurrent CDI (**Figure 9**)<sup>206</sup>. FMT is best reserved for patients with multiple recurrences of CDI that have failed other treatment options. Importantly, FMT is a non-standardized procedure, and the long-term consequences of altering a patient's gut microbiota are unknown. Several national guidelines have, therefore, been developed to standardize FMT including donor screening and selection<sup>207–209</sup>. Results from a preliminary study among patients with relapsing CDI revealed that administration of FMT using frozen encapsulated inoculum from unrelated donors also resulted in a good outcome<sup>210</sup>. It is likely that future research will define mixtures of selected microbes, designed according to their roles in the microbiota against CDI, as 'pharmacological' alternatives to FMT. For example, a mixture of 33 bacteria has been shown to be effective in two patients with CDI<sup>211</sup>, although the selection of the isolates here was not based on microbiota studies. Rectal bacteriotherapy with a mixture of 12 bacteria from healthy donors **[Au:OK?]** resolved CDI and prevented recurrence within 30 days in 64% of the patients<sup>212</sup>. A combination of four bacterial species selected on the strongest association with resistance to CDI, protected mice from infection, most likely indirectly by an effect on the bile acids metabolism<sup>42</sup>. As noted for FMT, long term safety data will be needed, given the far-reaching effects of gut microbiota in health and disease.



## [H2] Novel therapeutics

Several therapeutics targeting different stages of CDI are currently in clinical development (**Table 1**). In short, these comprise treatments to restore a complex microbiota (SER-109)<sup>213</sup>, to prevent off-target effects of antibiotic treatment on the intestinal microbiota (SYN-004), to neutralize *C. difficile* toxins (including monoclonal antibodies)<sup>214</sup>, or to inhibit *C. difficile* proliferation (SMT19969, LFF571, surotomycin, cadazolid, PolyCAb, CRS3123).

## [H1] Quality of life

### [H2] Economic burden of CDI

The burden of healthcare-associated CDI can be expressed in terms of mortality, recurrence, (additional) length of hospital stay or economic cost<sup>215–217</sup>. Economic analyses of healthcare-associated CDI have shown that direct healthcare cost and costs due to increased length of stay were the main cost drivers. An integrative review showed a wide variation in the difference in length of stay between people with and those without CDI (2.8–16.1 days), which was attributed to differences in design and data collection<sup>218</sup>. However, overall, people with CDI stay longer in hospital than people without CDI despite this variation.

A systematic review of the effects of CDI in Europe showed that the median length of stay for patients with CDI was in the range of 8–27 days, with an additional length of stay (due to CDI) between 2.8–18 days<sup>217</sup>. The incremental per-case cost of CDI in this

study was £4,577 in Ireland and £8,843 in Germany, after standardization to 2010 prices<sup>217</sup>. Others have estimated the incremental per-case cost of CDI, after standardization to 2008 prices, at US\$2,871–90,644 (Refs<sup>216,219</sup>) (**Figure 10**). A recent meta-analysis identified a total of 45 studies (mostly from North America) that measured the economic impact of CDI. For hospitalized patients, attributable mean CDI costs ranged from \$8,911 to \$30,049. However, the authors noted that costing methods were heterogeneous, making inter-study and setting comparisons difficult. Standardization of such measurements would be helpful, although differences between healthcare systems remain a barrier when comparing financial costs<sup>220</sup>.

The total direct cost of CDI to the European Union in 2006 was estimated at €3 billion per year<sup>6</sup>. Assuming a 3% annual inflation rate, this approximates to over €4 billion in 2015. Estimates for the economic burden of CDI in the United States and Canada are in excess of US\$1 billion<sup>221</sup> and CAN\$280 million<sup>222</sup>, respectively. These figures do not include the indirect socioeconomic costs (see below). Only for Canada does the estimate include a parameter for community-associated CDI in addition to healthcare associated CDI<sup>222</sup>; so, the total burden in the United States and European Union probably exceeds the numbers given above.

## **[H2] Patient-reported quality of life**

The stark mortality rates associated with CDI emphasize the serious consequences of this disease. Furthermore, given that CDI is characterized by diarrhoea, relatively

frequent symptomatic recurrences, and often altered bowel habit for possibly weeks or months following cessation of acute symptoms, it is perhaps not surprising that patients regularly report that this disease is one of the worst they have experienced<sup>223</sup>. As patients are typically older and have comorbidities, the additional burden of CDI can affect both their dignity and ability to cope. Despite these well-recognized effects of CDI, very few data are available to formally measure how the disease affects an individual's health status, functionality and quality of life. Two recent studies have begun to explore these under-reported issues.

A prospective study of 66 out-patients with CDI used the RAND Short-Form 36 (SF-36) Health Survey and concluded that CDI significantly decreased overall quality of life but that a more-specific health-related questionnaire is needed. The Patient-Reported Outcome Measurement Information System (PROMIS) is a large, NIH-funded, database of questions to measure patient-reported health status for physical, mental and social well-being<sup>224</sup>. PROMIS has recently been explored in a prospective, observational, multi-centre study as a potential way of evaluating self-reported health status in patients with CDI<sup>225</sup>. Patients ( $n=95$ ) with active CDI (58%) or who were hospitalized (42%) had worse scores in regards to bowel function, nausea, and belly pain compared with controls ( $P < 0.001$ ). Those with recurrent CDI had worse anxiety scores than any other group (patients with first-occurrence of CDI and controls;  $P < 0.001$ ). The authors concluded that the 18 patient-reported health status questions were discriminatory for active CDI and primary versus recurrent CDI. These questions might be suitable for measuring

short-term and long-term differences in patient-reported health status in people with CDI.

CDI can also have long lasting effects on families, but there is no systematic evaluation of these effects.

More work is needed to optimize these measurements and to determine which interventions are associated with the best improvements in outcomes for both patients and relatives.

## **[H1] Outlook**

### **[H2] Outstanding research questions**

Great progress has been made in our understanding of *C. difficile* physiology and pathogenesis. Studies have not only provided insight in the workings of the pathogen, but also highlighted aspects of its biology that differ from the situation in other studied bacteria. For instance, the order, activation and function of sporulation sigma factors of *C. difficile* deviates from what is known for the best studied Gram-positive spore former, *Bacillus subtilis*<sup>226</sup>. Perhaps this should not come as a surprise, as the last common ancestor of bacilli and clostridia dates back about 2.7 billion years, only shortly after the divergence of Gram-positive and Gram-negative bacteria (3.2 billion years ago)<sup>227</sup>. It is conceivable that more-detailed investigations of the molecular biology of clostridia in general, and *C. difficile* in particular, will reveal unexpected features.

Laboratory investigations under controlled conditions have clearly demonstrated that the production of enterotoxins is regulated in a complex manner and integrates signals from both the bacterial metabolism as well as the culture conditions<sup>99</sup>. It is uncertain, however, whether this reflects infection within the host. Mutants that are used to assess these effects in the laboratory might display reduced virulence as a result of reduced fitness. Although the role of enterotoxins in disease is well established, it remains unknown how toxin production is triggered *in vivo*, and how or when the toxins are secreted into the gastrointestinal tract. Similarly, it is unknown what triggers sporulation during infection. Both toxins (production and activity) and spores have been implicated in epidemics<sup>82,122,228</sup>. However, strong evidence for this is lacking and the ability of *C. difficile* to cause epidemics is likely a multifactorial process that involves a delicate balance in factors that affect virulence and transmissibility<sup>74,75</sup>. It should be noted that increased virulence might not correlate with transmissibility, which might be favoured when hosts remain relatively healthy<sup>75</sup>.

Epidemic types of *C. difficile* have received a lot of attention as a result of their higher mortality and morbidity<sup>7,8,12,18,82</sup>. Often, enhanced infection control measures are taken when transmission of epidemic *C. difficile* types are detected, which has likely contributed to the decline of PCR ribotype 027 in different countries in 2014<sup>32</sup>. But is the increased vigilance towards these strains warranted? First, epidemiological analyses ignore the fact that not all strains of the same PCR ribotype exhibit the same characteristics as has been demonstrated for sporulation<sup>229</sup>. Second, other PCR

ribotypes can also cause outbreaks of CDI<sup>20,21,230</sup>. Third, with the advent of sequence based typing methods, it is becoming clear that strains with different PCR ribotypes can be highly related<sup>98,231</sup>. For instance, strains of PCR ribotypes 244 and 176, which are related to PCR ribotype 027, can cause outbreaks of severe CDI<sup>22,23</sup>. PCR ribotype 244 seems to be primarily implicated in community-associated CDI, indicating that highly related strains might emerge as epidemic types in different settings<sup>232</sup>. Finally, new types could emerge. Thus, care should be taken to not generate an unjustified bias towards certain strains in epidemiological vigilance.

## **[H2] Colonization and pathogenesis**

What determines whether *C. difficile* successfully establishes an infection is an important question. The host microbiota and its associated metabolites greatly influence the ability of *C. difficile* spores to germinate and colonize the gut<sup>39,43</sup>. However, niche-specific competition<sup>233</sup>, or collaboration (for instance, in a multi-species biofilm<sup>57,59</sup>) might also contribute. Most of the metagenomic studies have focused on bacterial species whereas the contribution of fungal species and viruses (bacteriophages) is poorly explored. Notably, population groups with relatively unstable microbiomes (that is, infants<sup>185</sup> and the elderly<sup>234</sup>) are most commonly colonized by *C. difficile*.

Other host factors might also play a part. Failure to mount a protective immune response is associated with disease progression; patients with an adequate response

could either eliminate the infection, or become asymptomatic carriers<sup>14</sup>. Host-dependent expression levels of toxin or colonization factor receptors could also be an important determinant for disease development. It has been postulated that infants remain asymptomatic in the presence of high levels of toxins due to the absence of receptors in their still-developing gastrointestinal tract, but so far there is no evidence to support this hypothesis. Detailed studies on the interaction of *C. difficile* with the host are necessary to delineate the contribution of host factors to colonization and pathogenesis.

## [H2] Clinical needs

Even though antimicrobial resistance of *C. difficile* is not a major issue in the clinic, novel narrow-spectrum therapeutics are needed. The primary reason is that current (broad spectrum) antibiotics with activity against *C. difficile*, such as metronidazole and vancomycin, can concurrently predispose patients to CDI (and possibly recurrent CDI) due to their effects on other microbiota<sup>235</sup>. [Au:OK?] Furthermore, some antibiotics are not cost-effective as first-line treatment options. It is possible that specific prophylactic elimination of *C. difficile* in high-risk groups could reduce the risk of CDI without altering the host microbiome. It is of interest that bacteriocins and viruses (bacteriophages) seem to be able to target *C. difficile* specifically<sup>233,236,237</sup>.

FMT is an excellent potential alternative for antibiotic therapy<sup>206</sup>, but long-term safety, public acceptance and relative lack of standardized donor material are limiting broad

application. Steps have been taken to generate standardized formulations of FMT or bacteria<sup>42,149,211,212</sup>. However, it remains to be established whether a single species of bacteria or mixtures of different bacteria are effective for all (or most) patients. It is likely that bacterial or metabolic signatures need to be identified that confer broad protection or activity against CDI (**Figure 9**).

Anti-virulence strategies<sup>238</sup> might become a valuable addition or alternative to the current therapeutic spectrum. Neutralizing anti-toxin antibodies have shown clinical promise (**Table 1**)<sup>214,239</sup>, and toxin activity has also been targeted using small molecules<sup>128,129</sup>. Interference with quorum sensing or colonization factors has been underexplored so far, though it is clear that these can also be targeted by antibodies<sup>240,241</sup>. Small molecule inhibition of extracellular protein processing or function could prove a viable strategy to reduce colonization or transmission of CDI.

A final issue is the clinical need for accurate prediction models<sup>155</sup>. Accurate risk assessment tools that can be applied in real time would be beneficial to target diagnostic methods and for optimized treatment of those at risk of severe or complicated CDI or recurrence<sup>242–245</sup>. Though several tools have been developed, there is considerable room for simplification and improvements in predictive values to make these applicable at the bedside.

## **[H2] The burden of CDI**



Current conservative estimates of the economic burden of CDI are based on estimates of incidence and an incremental — per (hospitalized) patient — cost. These estimates fail to take into account the changes in demographics that are projected over the upcoming years. Age is a risk factor for CDI, though it is unclear if this is an independent factor or caused by underlying confounders (such as immune senescence, comorbidities, need to stay at long term care facilities and additional required health care). The European Union has projected that the demographic old-age dependency ratio (the ratio of those aged >65 years old to those aged 15–64 years) will increase from 27.8% to 50.1% between 2013 and 2060 (Ref. <sup>246</sup>). Similarly, US-based population projections foresee an increase in the percentage of people aged >65 years of 13.7% to 20.9% between 2012 and 2050 (Ref. <sup>247</sup>). On the basis of these projections, the impact of CDI is expected to become considerable in coming years.

Epidemiological evidence suggests that an increasing number of cases of CDI are linked to populations that are generally considered to be at low risk for CDI. These community-associated infections generally affect a different demographic (younger patients) who have frequently not been exposed to antibiotics. Further studies are required to determine risk factors for community-associated CDI. As many cases of community acquired CDI go undetected<sup>24,27,29</sup>, more studies are required to determine the contribution to the total burden of CDI at a national and international level.

Finally, *C. difficile* is increasingly recognized in veterinary medicine with highly variable disease entities in different species of animals. No information is available to date on the economic burden of CDI in food (animal) production industry.

### **Acknowledgements**

This work was supported, in part, by a Vidi fellowship from the Netherlands Organization for Scientific Research and a Gisela Thier Fellowship from the Leiden University Medical Center to W.K.S., National Institute of Health Award AI95755 and a Burroughs Wellcome Investigator in the Pathogenesis of Infectious Disease Award to D.B.L., and a Future Fellowship FT120100779 of the Australian Research Council to D.L. The authors thank the ESCMID Study Group for *Clostridium difficile* (ESGCD) for their advice and suggestions and apologize to authors whose work could not be cited due to restrictions imposed by the format of this Primer. W. Knetsch is acknowledged for drafting the illustration used in Box 1.

### **Author contributions**

Introduction (W.K.S.); Epidemiology (M.H.W., E.J.K. and W.K.S.); Mechanisms/pathophysiology (D.B.L., D.L. and W.K.S.); Diagnosis, screening, and prevention (M.H.W., E.J.K. and W.K.S.); Management (M.H.W., E.J.K. and W.K.S.); Quality of life (M.H.W., E.J.K. and W.K.S.); Outlook (W.K.S. and E.J.K.); overview of the Primer (W.K.S.).

**Competing interests**

W.K.S. has performed research for Cubist. D.L. has performed research for Immuron and Adenium Biotech. D.B.L. has performed research for MedImmune and Merck. M.H.W. has received consulting fees from Abbott Laboratories, Actelion, Astellas, AstraZeneca, Bayer, Cerexa, Cubist, Durata, The European Tissue Symposium, The Medicines Company, MedImmune, Merck, Motif Biosciences, Nabriva, Optimer, Paratek, Pfizer, Roche, Sanofi-Pasteur, Seres, Summit, and Synthetic Biologics; has received lecture fees from Abbott, Alere, Astellas, Astra-Zeneca, Pfizer & Roche; and received grant support from Abbott, Actelion, Astellas, bioMerieux, Cubist, Da Volterra, The European Tissue Symposium, Merck and Summit. E.J.K. has performed research for Cubist, Novartis and Qiagen; and has participated in advisory forums of Astellas, Optimer, Actelion, Pfizer, Sanofi-Pasteur and Seres. These companies had no role in the writing of this Primer.

**Box 1.** Molecular typing of *Clostridium difficile*

Epidemiological studies are dependent on standardized typing methods. Many different typing methods have been developed for *C. difficile* that evaluate either phenotypic or genotypic traits<sup>17</sup> (illustration). Given their higher reproducibility, typability (ability to type a strain unambiguously) and discriminatory power, genotyping methods have become standard for typing of *C. difficile*. Band-based typing methods, such as restriction enzyme analysis (REA), pulsed-field gel electrophoresis (PFGE), and PCR ribotyping (RT), are common. Historically, REA and PFGE have been the methods of choice in North America, whereas PCR ribotyping has primarily been used in Europe. As a result, epidemic strains are often indicated with multiple typing designations<sup>248</sup>. For instance, PCR ribotype 027 strains that have caused outbreaks globally<sup>8</sup> have been classified as REA group BI and PFGE type NAP1. Similarly, PCR ribotype 078 strains are known as REA group BK and PFGE type NAP7/NAP8. Global surveillance is becoming key for health care management, and efforts have been made to harmonize the different typing schemes. Capillary gel-based electrophoresis ribotyping (CE-RT) has been standardized and validated in a collaborative effort of the European Centre for Disease Control and Prevention, the US Centers for Disease Control and Prevention and the Public Health Agency of Canada and is likely to become commonplace throughout the world<sup>249</sup>. Additionally, sequence based methods, such as multi-locus sequence typing (MLST) and whole genome sequencing (WGS; specifically single nucleotide polymorphism (SNP) typing) have gained interest specifically to study evolutionary relationships between various *C. difficile* strains (phylogeny)<sup>17</sup>. Overall, different

lineages can be discriminated and several different PCR ribotypes have been shown to be closely related to the epidemic types using these sequence based methods<sup>98,231</sup>. WGS is also used to study transmission and outbreaks<sup>25,232</sup>, although this approach can be costly and is mainly performed retrospectively. Relatedness of strains in an outbreak setting is more commonly performed using multi-locus variable-number tandem repeat analysis (MLVA)<sup>17</sup>.

**Box 2.** Antibiotic resistance of *Clostridium difficile*.

Most antimicrobial compounds target metabolically active cells and have limited or no activity against dormant cells, such as spores. This intrinsic resistance of spores ensures that *C. difficile* can persist in the presence of antibiotics or the host immune system<sup>250,251</sup>. *C. difficile* also demonstrates extensive acquired antimicrobial resistance<sup>9,252</sup>. Interestingly, *C. difficile* vegetative cells are sensitive to teicoplanin and vancomycin, despite harbouring a genomic region that resembles a *vanG* glycopeptide resistance cluster<sup>9,253</sup>. This cluster can confer vancomycin resistance to a heterologous host, but why it is not functional in *C. difficile* is unclear<sup>254</sup>. The mobile genome of *C. difficile* (comprising transposons, insertion sequences and (pro)phages) probably contributes to antibiotic resistance because these elements commonly contain resistance determinants<sup>9,255</sup>. For example, the Tn6218 element of *C. difficile* contains a *cfr*-like gene that can confer resistance to peptidyl transferase inhibitors such as linezolid<sup>256</sup> and the Tn5397 element carries a tetracyclin resistance determinant<sup>257</sup>.  
Reduced susceptibility or resistance to the commonly used antibiotics (vancomycin,

metronidazole and fidaxomicin) has been noted<sup>258-261</sup>. Although this is cause for concern, the clinical relevance of resistance to these antibiotics so far is limited. However, *C. difficile* antibiotic resistance is only part of the reason why *C. difficile* has been classified as an Urgent Antibiotic Resistance Threat by the US Centers for Disease Control and Prevention<sup>262</sup>. Other major factors include that the bacterium affects people treated by antibiotics for other infections, the ageing of the general population and the emergence of epidemic types, such as PCR ribotype 027. At least in this ribotype, epidemic lineages are associated with resistance against fluoroquinolones<sup>8</sup>; although this class of antibiotics is not used for the treatment of *C. difficile* infections, the antibiotics can select for *C. difficile* when used to treat other infections. Fluoroquinolone resistance is also common in other PCR ribotypes<sup>263</sup>.

### **Box 3. Infection control and prevention of *Clostridium difficile* infection**

- Ensure rapid diagnostic testing of patients with diarrhoeal illness acquired in the hospital or associated with antimicrobial therapy
- A hospital-based infection control programme combined with active surveillance can help to decrease the incidence of *Clostridium difficile* infection (CDI); locally defined thresholds/triggers for the addition of enhanced control measures are needed
- Antibiotic stewardship, including restriction of specific high-risk antimicrobials (such as clindamycin, cephalosporins and fluoroquinolones), is recommended to reduce the risk of CDI

- Patient isolation and contact precautions (including hand hygiene with soap and water) should be maintained until at least the diarrhoea has resolved
- If isolation in a single room is not possible, alternatives are segregation within wards and/or cohorting of cases
- Disinfection of environmental surfaces is recommended using chlorine-releasing agents as a minimum in clinical areas with CDI cases
- Educate healthcare personnel, cleaning staff and patient visitors on contact precautions to minimize the transmission of spores

**Figure 1.** *Clostridium difficile*. a | Typical image of *C. difficile* colonies on a blood agar plate. b | Phase contrast microscopy image of a *C. difficile* culture with vegetative cells (elongated rods), phase dark spores (subterminal dark spots) and phase bright spores (bright ellipsoids). Inset: Gram stain of culture. c | Scanning electron micrograph of *C. difficile* spores. d | Endoscopic picture of pseudomembranous colitis caused by *C. difficile*. Healthy colon tissue is pink, pseudomembranes resulting from *C. difficile* infection are yellow.

**Figure 2.** Stages of the *Clostridium difficile* lifecycle in the human gastrointestinal tract.

Three sources of infection (healthcare, animal and environmental) are indicated. A range of host factors influence the *C. difficile* lifecycle, and the relative numbers of spores and vegetative (metabolically active) cells in the gut (as indicated in the figure).

Note that passage through the stomach eliminates most vegetative cells (but spores survive), and spores germinate and grow out in the duodenum. In the caecum and colon, *C. difficile* starts producing spores again, but during infection vegetative cells are also excreted by the patient. Toxin is produced in the colon. As *C. difficile* is an obligate anaerobic bacterium, transmission occurs primarily via spores. SCFA: short chain fatty acids (such as butyrate).

**Figure 3. Innate immune response of host cells towards *Clostridium difficile*.** *C. difficile* elicits the innate immune response via at least four different effectors, leading to the induction of pro-inflammatory cytokines and chemokines via NF- $\kappa$ B and transcription factor AP-1. Toxins act via NLRP3 (NOD-, LRR- and pyrin domain-containing 3) inflammasome-dependent and independent pathways. Flagellin and surface layer protein A (SlpA) act via myeloid differentiation primary response protein MyD88 (MyD88)-dependent pathways through Toll-like receptor 4 (TLR4) and TLR5, respectively. The nucleotide-binding oligomerization domain-containing protein 1 (NOD1)-dependent pathway of induction most likely detects fragments of peptidoglycan (PG\*), derived from the cell wall of *C. difficile*. Dashed lines indicate indirect effects.

**Figure 4. Regulation of the *Clostridium difficile* toxins.** a | Schematic representation of the pathogenicity locus (PaLoc) and the flanking regions with regulatory interactions of *C. difficile*. Boxes with arrows indicate open reading frames with the direction of the arrows showing the direction of transcription. Toxin genes (*tcdA* and *tcdB*) are shaded in



blue, regulatory genes are in orange (positive) and green (negative); *tcdE* is in yellow and genes located outside the PaLoc are in grey. Dashed arrows indicate the production of protein from a gene transcript. Other regulators (Sigma D (SigD), the nutritional repressor CodY (known as GTP-sensing transcriptional pleiotropic repressor CodY), catabolite control protein A (CcpA), Stage 0 sporulation protein A (Spo0A) and quorum sensing (QS)) that affect toxin gene transcription (boxed) mostly act via expression of the *tcdR* gene. The TcdR protein is involved in the initiation of the production of TcdA and TcdB. b | Schematic representation of the binary toxin locus (CdtLoc) and flanking regions with regulatory interactions. Boxes with arrows indicate open reading frames with arrows showing the direction of transcription. The *cdtA* and *cdtB* toxin genes are shaded in blue, the regulatory gene *cdtR* is in orange and genes located outside the CdtLoc are in grey.

**Figure 5. Structure and function of the large clostridial toxins.** a | Schematic of the TcdA/TcdB primary structure highlighting the four functional domains; the glucosyltransferase domain (GTD; red), the autoprotease domain (APD; blue), the delivery domain (yellow) and the combined repetitive oligopeptides (CROPS) domain (green) that binds carbohydrates on the host cell surface to facilitate bacterial entry. b | Overlay of an electron microscopy reconstruction of the structure of TcdA with the X-ray crystal structure of TcdA lacking CROPS (Protein Data Bank code 4R04). Colour-coding reflects the domain structure in panel a. c | The discrete structural and functional domains of the toxins contribute to a multi-step mechanism of intoxication. Toxins bind

to one or more receptors (carbohydrate and/or protein) on the cell surface (step 1) and are internalized by receptor mediated endocytosis (step 2). As the endosome matures, the V-ATPase contributes to a decrease in pH (step 3). The acidic pH causes a conformational change in the toxin delivery domain, resulting in pore formation (step 4) and the translocation of the APD and GTD into the cytosol (step 5). Inositol hexakisphosphate (InsP6) binds and activates the APD resulting in the release of the GTD (step 6), which can inactivate Rho family proteins (step 7) to cause apoptosis and cytopathic 'rounding' effects. d | At concentrations >0.1 nM, TcdB can promote Ras-related C3 botulinum toxin substrate 1 (Rac1) activation (step 1) and complex formation between p22phox (also known as cytochrome b-245 light chain), NADPH oxidase 1 (NOX1), NADPH oxidase activator 1 (NOXA1), NADPH oxidase organizer 1 (NOXO1) and Rac1 on the endosomal membrane to form the NOX complex (step 2). The fully assembled NOX complex generates superoxide by transferring an electron from NADPH to molecular oxygen (step 3). Superoxide generation leads to the production of reactive oxygen species (ROS), which — at high levels — promote necrosis by causing mitochondrial damage, lipid peroxidation and protein oxidation (step 5).

**Figure 6. Histopathology of *Clostridium difficile* infection in a mouse model.**

Histopathological analysis of haematoxylin and eosin-stained caecal and colonic tissues collected from mice infected with a wild-type PCR ribotype 027 strain (TcdA<sup>+</sup>/TcdB<sup>+</sup>), infected with an isogenic double *tcdA* and *tcdB* mutant (TcdA<sup>-</sup>/TcdB<sup>-</sup>), or mock-infected with phosphate buffered saline (Mock). Note that both wild-type and double mutant

strains contain an intact binary toxin locus. Arrows indicate major histological differences; oedema and polymorphonuclear cell influx into the lamina propria (black), erosion of crypts and goblet cell loss (yellow) and hyperplasia (white).

**Figure 7.** Mechanism of action of *Clostridium difficile* transferase (binary toxin).

*Clostridium difficile* transferase (CDT) is a binary toxin consisting of the CDTa ADP-ribosyltransferase (in red) and the CDTb protein (in yellow and green). The monomeric form of CDTb binds to the lipolysis-stimulated lipoprotein receptor (LSR)<sup>264</sup>, which is found in many tissues including the gut. CDTb undergoes proteolytic activation and oligomerizes to form a heptameric prepore, which facilitates the binding of CDTa to the prepore-receptor complex. This complex enters cells by endocytosis and as the endosome matures, the V-ATPase contributes to a decrease in pH. The low pH of the endosome triggers pore formation and the translocation of CDTa into the cell. Once in the cytosol CDTa, ribosylates actin at arginine 177, resulting in a dual effect whereby G-actin polymerization is inhibited and F-actin depolymerization is favoured, which leads to the complete destruction of the actin cytoskeleton and, ultimately, cell death<sup>135,141</sup>.

Inset: structure of CTDa (Protein Data Bank code 2WN7).

**Figure 8. Diagnosis and treatment options for *Clostridium difficile* infections.** When a patient is suspected of having *Clostridium difficile* infection (CDI), the recommended option is to detect toxins of *C. difficile* in the stool. Several diagnostic algorithms have been condensed into this figure<sup>265</sup>. Treatment options indicated here are based on

reports by Leffler and Lamont<sup>14</sup> and Debast *et al.*<sup>155</sup> \*Fidaxomicin is a treatment option if the risk of recurrence is high, but not for complicated CDI. For moderate CDI, metronidazole is given orally, in severe cases intravenously. Hospitalization refers to admission as a result of CDI (not as a result of comorbidities; patients might already be hospitalized). Note that recurrence after clinical cure (resolution of symptoms) can be observed. Faecal microbiota transplant is an effective but non-standard form of treatment and, therefore, indicated with a dashed line.

**Figure 9. Faecal microbiota transplant.** In faecal microbiota transplant (FMT), faecal material from a healthy donor is harvested. The material is processed (blending, filtration) into pills or a solution. As part of this process, a check for the presence of pathogenic and multi-drug resistant organisms is performed. The processed material can be stored prior to (one-off) administration by nasoduodenal infusion, colonoscopic infusion or rectal enema for solution formulations or orally for pill formulations. Antibiotic treatment generally precedes the administration of the FMT to reduce *C. difficile* levels. Alongside FMT, [Au:OK?] efforts are ongoing to standardize bacteriotherapy. On the basis of microbiome and metabolome analyses, signatures of resistance to colonization by *C. difficile* are identified. After harvesting faecal material from healthy donors, species identified in these microbiome signatures or believed to be responsible for the metabolomic signature are cultured. Defined mixtures of these strains are tested for safety and ability to confer colonization resistance in preclinical trials and subsequently validated in clinical studies. Colored bars indicate microbial

diversity of the microbiome, which is severely reduced in the patient with CDI compared with the healthy subject.

**Figure 10. Cost per case of *Clostridium difficile* infection.** The data depicted in this figure are from Ghantaji *et al.*<sup>219</sup> (indicated with a superscript 1) and Vonberg *et al.*<sup>216</sup> (indicated with a superscript 2); last names and years on the right in the panel indicate the original studies described in these. Conversion between respective US\$ and € amount is done based on 2008 exchange rates. Note that several studies have estimated the cost of *C. difficile* infections more recently<sup>220,266,267</sup>. IBD: inflammatory bowel disease. ICU: intensive care unit.

**Table 1.** Selected agents for the treatment and prevention of CDI in clinical trial.

Agent (manufacturer)	Indication	Notes	Clinical trial identifier
Phase III			
Actoxumab and bezlotoxumab alone or in combination (Merck)	Prevention of recurrent CDI	Anti-toxin A (MK-3415) and anti-toxin B (MK-6072) monoclonal antibodies given intravenously as adjuncts to standard treatment	NCT01241552 NCT01513239
Surotomycin (Merck)	Treatment	Cyclic lipopeptide antibiotic related to daptomycin but administered orally	NCT01598311 NCT01597505
Cadazolid (Actelion)	Treatment	Hybrid antibiotic molecule, comprising fluoroquinolone and oxazolidinone moieties, for oral administration.	NCT01987895 NCT01983683
Cdiffense (Sanofi Pasteur)	Prevention	Vaccine containing toxoids of toxin A and B (TcdA and TcdB) from <i>C. difficile</i>	NCT01887912
Phase II			
IC84 vaccine (Valneva)	Prevention	Vaccine comprising recombinant protein of two truncated toxins A and B (TcdA and TcdB) from <i>C. difficile</i>	NCT02316470
LFF571 (Novartis)	Treatment of moderate CDI	Semi-synthetic thiopeptide	NCT01232595
SER-109 (Seres Therapeutics)	Treatment of recurrent CDI	Oral microbiome therapeutic (mixture of bacterial spores) granted orphan drug designation	NCT02437500
SMT19969 (Summit Plc)	Treatment	Oral non-absorbable antibiotic with a narrow spectrum of activity and high selectivity for <i>C. difficile</i>	NCT02092935
<i>C. difficile</i> vaccine (Pfizer)	Prevention	Bivalent toxin vaccine	NCT02561195 NCT02117570
SYN-004 (Synthetic Biologics)	Prevention	Class A $\beta$ -lactamase designed to protect gut microbiota from the action of systemically administered $\beta$ -lactam antibiotics that might otherwise predispose for CDI	NCT02563106
VP20621(Shire)	Prevention of recurrent CDI	Orally administered non-toxicogenic <i>C. difficile</i>	NCT01259726
Phase I			
PolyCAB (Micropharm)	Treatment of severe CDI	Polyclonal antibodies against <i>C. difficile</i> given intravenously	Not available
CRS3123 (REP3123)	Treatment	Methionyl-tRNA synthetase inhibitor oral antibiotic	NCT02106338 NCT01551004

## References

1. Hall, I. C. & O'Toole, E. Intestinal flora in new-born infants: with a description of a new pathogenic anaerobe, *Bacillus difficilis*. *Am.J.Child.Dis.* **49**, 390–402 (1935).
2. Lyras, D. *et al.* Toxin B is essential for virulence of *Clostridium difficile*. *Nature* **458**, 1176–1179 (2009).
3. Kuehne, S. A. *et al.* The role of toxin A and toxin B in *Clostridium difficile* infection. *Nature* **467**, 711–713 (2010).
4. Hafiz, S. & Oakley, C. L. *Clostridium difficile*: isolation and characteristics. *J.Med.Microbiol.* **9**, 129–136 (1976).
5. Bartlett, J. G. *Clostridium difficile*: history of its role as an enteric pathogen and the current state of knowledge about the organism. *Clin. Infect. Dis.* **18 Suppl 4**, S265–72 (1994).

### **An exceptional overview of the early experiments demonstrating the involvement of *C. difficile* in (antibiotic-associated) colitis.**

6. Kuijper, E. J., Coignard, B. & Tüll, P. Emergence of *Clostridium difficile*-associated disease in North America and Europe. *Clin. Microbiol. Infect.* **12 Suppl 6**, 2–18 (2006).
7. Goorhuis, A. *et al.* Emergence of *Clostridium difficile* infection due to a new hypervirulent strain, polymerase chain reaction ribotype 078. *Clin.Infect.Dis.* **47**, 1162–1170 (2008).
8. He, M. *et al.* Emergence and global spread of epidemic healthcare-associated *Clostridium difficile*. *Nat.Genet.* **45**, 109–113 (2013).

**A large-scale whole genome sequencing study that, for the first time, demonstrated the potential of the technique to trace the emergence of epidemic strains and relatedness between isolates.**

9. Sebahia, M. *et al.* The multidrug-resistant human pathogen *Clostridium difficile* has a highly mobile, mosaic genome. *Nat.Genet.* **38**, 779–786 (2006).
10. Minton, N. *et al.* The development of *Clostridium difficile* genetic systems. *Anaerobe.* **10**, 75–84 (2004).
11. Kuehne, S. A., Heap, J. T., Cooksley, C. M., Cartman, S. T. & Minton, N. P. Clostron-mediated engineering of *Clostridium*. *Methods Mol.Biol.* **765**, 389–407 (2011).
12. Freeman, J. *et al.* The changing epidemiology of *Clostridium difficile* infections. *Clin. Microbiol. Rev.* **23**, 529–49 (2010).
13. Hensgens, M. P. *et al.* *Clostridium difficile* infection in the community: a zoonotic disease? *Clin.Microbiol.Infect.* **18**, 635–645 (2012).
14. Leffler, D. A. & LaMont, J. T. *Clostridium difficile* infection. *N.Engl.J.Med.* **372**, 1539–1548 (2015).
15. Yutin, N. & Galperin, M. Y. A genomic update on clostridial phylogeny: Gram-negative spore formers and other misplaced clostridia. *Environ.Microbiol.* **15**, 2631–2641 (2013).
16. Nadon, C. A. *et al.* Development and application of MLVA methods as a tool for inter-laboratory surveillance. *Euro.Surveill* **18**, 20565– (2013).
17. Knetsch, C. W. *et al.* Current application and future perspectives of molecular



typing methods to study *Clostridium difficile* infections. *Euro.Surveill* **18**, 20381– (2013).

**An updated review [Au:OK?] of typing methods for *C. difficile*.**

18. Clements, A. C., Magalhaes, R. J., Tatem, A. J., Paterson, D. L. & Riley, T. V. *Clostridium difficile* PCR ribotype 027: assessing the risks of further worldwide spread. *Lancet Infect.Dis.* **10**, 395–404 (1992).
19. Tickler, I. A. et al. Strain types and antimicrobial resistance patterns of *Clostridium difficile* isolates from the United States, 2011 to 2013. *Antimicrob.Agents Chemother.* **58**, 4214–4218 (2014).
20. Bauer, M. P. et al. *Clostridium difficile* infection in Europe: a hospital-based survey. *Lancet* **377**, 63–73 (2011).

**The first pan-European study to the epidemiology of CDI.**

21. Baldan, R. et al. *Clostridium difficile* PCR Ribotype 018, a Successful Epidemic Genotype. *J.Clin.Microbiol.* **53**, 2575–2580 (2015).
22. Pituch, H. et al. Hospital-based *Clostridium difficile* infection surveillance reveals high proportions of PCR ribotypes 027 and 176 in different areas of Poland, 2011 to 2013. *Euro.Surveill* **20**, 30025– (2015).
23. Lim, S. K. et al. Emergence of a ribotype 244 strain of *Clostridium difficile* associated with severe disease and related to the epidemic ribotype 027 strain. *Clin.Infect.Dis.* **58**, 1723–1730 (2014).
24. Hensgens, M. P. et al. Diarrhoea in general practice: when should a *Clostridium difficile* infection be considered? Results of a nested case-control study.

- Clin.Microbiol.Infect.* **20**, O1067–O1074 (2014).
25. Eyre, D. W. *et al.* Diverse sources of *C. difficile* infection identified on whole-genome sequencing. *N.Engl.J.Med.* **369**, 1195–1205 (2013).
  26. Lessa, F. C. *et al.* Burden of *Clostridium difficile* infection in the United States. *N.Engl.J.Med.* **372**, 825–834 (2015).
  27. Bouwknecht, M., Van, D. S. & Kuijper, E. Burden of *Clostridium difficile* infection in the United States. *N.Engl.J.Med.* **372**, 2368– (2015).
  28. Hensgens, M. P. *et al.* *Clostridium difficile* infection in an endemic setting in the Netherlands. *Eur.J.Clin.Microbiol.Infect.Dis.* **30**, 587–593 (2011).
  29. Wilcox, M. H., Mooney, L., Bendall, R., Settle, C. D. & Fawley, W. N. A case-control study of community-associated *Clostridium difficile* infection. *J.Antimicrob.Chemother.* **62**, 388–396 (2008).
  30. Reveles, K. R., Lee, G. C., Boyd, N. K. & Frei, C. R. The rise in *Clostridium difficile* infection incidence among hospitalized adults in the United States: 2001-2010. *Am.J.Infect.Control* **42**, 1028–1032 (2014).
  31. European Centre for Disease Prevention and Control. Point prevalence survey of healthcare-associated infections and antimicrobial use in European acute care hospitals 2011-2012 [online], [http://www.ecdc.europa.eu/en/publications/Publications/healthcare-as. -](http://www.ecdc.europa.eu/en/publications/Publications/healthcare-as.-) (2013). at <<http://www.ecdc.europa.eu/en/publications/Publications/healthcare-associated-infections-antimicrobial-use-PPS.pdf>>

32. Davies, K. A. *et al.* Underdiagnosis of *Clostridium difficile* across Europe: the European, multicentre, prospective, biannual, point-prevalence study of *Clostridium difficile* infection in hospitalised patients with diarrhoea (EUCLID). *Lancet Infect.Dis.* **14**, 1208–1219 (2014).

**A large, contemporaneous, pan-European study demonstrating the extent of missed diagnoses of CDI.**

33. European surveillance of *Clostridium difficile* infections. Surveillance protocol version 2.1. - (2015). at <http://ecdc.europa.eu/en/publications/Publications/Clostridium-difficile-infections-surveillance-protocol-version-2.1.pdf>
34. Planche, T. D. *et al.* Differences in outcome according to *Clostridium difficile* testing method: a prospective multicentre diagnostic validation study of *C difficile* infection. *Lancet Infect.Dis.* **13**, 936–945 (2013).

**A large multi-centre study demonstrating the importance of toxin detection as part of diagnostic algorithm for CDI.**

35. Knetsch, C. W. *et al.* Whole genome sequencing reveals potential spread of *Clostridium difficile* between humans and farm animals in the Netherlands, 2002 to 2011. *Euro.Surveill* **19**, 20954– (2014).
36. Zacharioudakis, I. M., Zervou, F. N., Pliakos, E. E., Ziakas, P. D. & Mylonakis, E. Colonization with toxinogenic *C. difficile* upon hospital admission, and risk of infection: a systematic review and meta-analysis. *Am.J.Gastroenterol.* **110**, 381–390 (2015).

37. Paredes-Sabja, D., Shen, A. & Sorg, J. A. Clostridium difficile spore biology: sporulation, germination, and spore structural proteins. *Trends Microbiol.* **22**, 406–416 (2014).

**A comprehensive overview of *C. difficile* sporulation, including the role of bile acids in germination.**

38. Deakin, L. J. *et al.* The Clostridium difficile spo0A gene is a persistence and transmission factor. *Infect.Immun.* **80**, 2704–2711 (2012).
39. Theriot, C. M. & Young, V. B. Interactions Between the Gastrointestinal Microbiome and Clostridium difficile. *Annu. Rev. Microbiol.* **69**, 445–61 (2015).
40. Bhattacharjee, D. *et al.* Reexamining the Germination Phenotypes of Several Clostridium difficile Strains Suggests Another Role for the CspC Germinant Receptor. *J. Bacteriol.* **198**, 777–86 (2015).
41. Sorg, J. A. & Sonenshein, A. L. Bile salts and glycine as cogermnants for Clostridium difficile spores. *J.Bacteriol.* **190**, 2505–2512 (2008).
42. Buffie, C. G. *et al.* Precision microbiome reconstitution restores bile acid mediated resistance to Clostridium difficile. *Nature* **517**, 205–208 (2015).
43. Theriot, C. M., Bowman, A. A. & Young, V. B. Antibiotic-Induced Alterations of the Gut Microbiota Alter Secondary Bile Acid Production and Allow for Clostridium difficile Spore Germination and Outgrowth in the Large Intestine. *mSphere* **1**, e00045–15 (2016).
44. Janoir, C., Pechine, S., Grosdidier, C. & Collignon, A. Cwp84, a surface-associated protein of Clostridium difficile, is a cysteine protease with degrading activity on

- extracellular matrix proteins. *J.Bacteriol.* **189**, 7174–7180 (2007).
45. Merrigan, M. M. *et al.* Surface-layer protein A (SlpA) is a major contributor to host-cell adherence of *Clostridium difficile*. *PLoS.One.* **8**, e78404– (2013).
  46. Tasteyre, A., Barc, M. C., Collignon, A., Boureau, H. & Karjalainen, T. Role of FliC and FliD flagellar proteins of *Clostridium difficile* in adherence and gut colonization. *Infect.Immun.* **69**, 7937–7940 (2001).
  47. Spigaglia, P. *et al.* Surface-layer (S-layer) of human and animal *Clostridium difficile* strains and their behaviour in adherence to epithelial cells and intestinal colonization. *J.Med.Microbiol.* **62**, 1386–1393 (2013).
  48. Lin, Y. P., Kuo, C. J., Koleci, X., McDonough, S. P. & Chang, Y. F. Manganese binds to *Clostridium difficile* Fbp68 and is essential for fibronectin binding. *J.Biol.Chem.* **286**, 3957–3969 (2011).
  49. Kovacs-Simon, A. *et al.* Lipoprotein CD0873 is a novel adhesin of *Clostridium difficile*. *J.Infect.Dis.* **210**, 274–284 (2014).
  50. Tulli, L. *et al.* CbpA: a novel surface exposed adhesin of *Clostridium difficile* targeting human collagen. *Cell Microbiol.* **15**, 1674–1687 (2013).
  51. Deneve, C., Delomenie, C., Barc, M. C., Collignon, A. & Janoir, C. Antibiotics involved in *Clostridium difficile*-associated disease increase colonization factor gene expression. *J.Med.Microbiol.* **57**, 732–738 (2008).
  52. Abt, M. C. *et al.* Innate Immune Defenses Mediated by Two ILC Subsets Are Critical for Protection against Acute *Clostridium difficile* Infection. *Cell Host Microbe* **18**, 27–37 (2015).

53. Paredes-Sabja, D. & Sarker, M. R. Adherence of *Clostridium difficile* spores to Caco-2 cells in culture. *J.Med.Microbiol.* **61**, 1208–1218 (2012).
54. Bordeleau, E. & Burrus, V. Cyclic-di-GMP signaling in the Gram-positive pathogen *Clostridium difficile*. *Curr.Genet.* **61**, 497–502 (2015).
55. Purcell, E. B., McKee, R. W., McBride, S. M., Waters, C. M. & Tamayo, R. Cyclic diguanylate inversely regulates motility and aggregation in *Clostridium difficile*. *J.Bacteriol.* **194**, 3307–3316 (2012).
56. Peltier, J. et al. Cyclic diGMP Regulates Production of Sortase Substrates of *Clostridium difficile* and Their Surface Exposure through Zmpl Protease-mediated Cleavage. *J.Biol.Chem.* **290**, 24453–24469 (2015).
57. Crowther, G. S. et al. Comparison of planktonic and biofilm-associated communities of *Clostridium difficile* and indigenous gut microbiota in a triple-stage chemostat gut model. *J.Antimicrob.Chemother.* **69**, 2137–2147 (2014).
58. Dapa, T. & Unnikrishnan, M. Biofilm formation by *Clostridium difficile*. *Gut Microbes.* **4**, 397–402 (2013).
59. Semenyuk, E. G. et al. Analysis of bacterial communities during *C. difficile* infection in the mouse. *Infect. Immun.* **83**, 4383–4391 (2015).
60. Darkoh, C., DuPont, H. L., Norris, S. J. & Kaplan, H. B. Toxin synthesis by *Clostridium difficile* is regulated through quorum signaling. *MBio.* **6**, e02569– (2015).
61. Martin, M. J. et al. The agr locus regulates virulence and colonization genes in *Clostridium difficile* O27. *J.Bacteriol.* **195**, 3672–3681 (2013).

62. Sun, X. & Hirota, S. A. The roles of host and pathogen factors and the innate immune response in the pathogenesis of *Clostridium difficile* infection. *Mol.Immunol.* **63**, 193–202 (2015).
63. Cowardin, C. A. & Petri Jr., W. A. Host recognition of *Clostridium difficile* and the innate immune response. *Anaerobe.* **30**, 205–209 (2014).
64. Ryan, A. et al. A role for TLR4 in *Clostridium difficile* infection and the recognition of surface layer proteins. *PLoS.Pathog.* **7**, e1002076– (2011).
65. Yoshino, Y. et al. *Clostridium difficile* flagellin stimulates toll-like receptor 5, and toxin B promotes flagellin-induced chemokine production via TLR5. *Life Sci.* **92**, 211–217 (2013).
66. Hasegawa, M. et al. Nucleotide-binding oligomerization domain 1 mediates recognition of *Clostridium difficile* and induces neutrophil recruitment and protection against the pathogen. *J.Immunol.* **186**, 4872–4880 (2011).
67. Gieseemann, T., Guttenberg, G. & Aktories, K. Human alpha-defensins inhibit *Clostridium difficile* toxin B. *Gastroenterology* **134**, 2049–2058 (2008).
68. Hing, T. C. et al. The antimicrobial peptide cathelicidin modulates *Clostridium difficile*-associated colitis and toxin A-mediated enteritis in mice. *Gut* **62**, 1295–1305 (2013).
69. McQuade, R., Roxas, B., Viswanathan, V. K. & Vedantam, G. *Clostridium difficile* clinical isolates exhibit variable susceptibility and proteome alterations upon exposure to mammalian cationic antimicrobial peptides. *Anaerobe.* **18**, 614–620 (2012).

70. Ho, T. D. *et al.* Clostridium difficile extracytoplasmic function sigma factor sigmaV regulates lysozyme resistance and is necessary for pathogenesis in the hamster model of infection. *Infect.Immun.* **82**, 2345–2355 (2014).
71. Ho, T. D. & Ellermeier, C. D. PrsW is required for colonization, resistance to antimicrobial peptides, and expression of extracytoplasmic function sigma factors in Clostridium difficile. *Infect.Immun.* **79**, 3229–3238 (2011).
72. Suarez, J. M., Edwards, A. N. & McBride, S. M. The Clostridium difficile cpr locus is regulated by a noncontiguous two-component system in response to type A and B lantibiotics. *J.Bacteriol.* **195**, 2621–2631 (2013).
73. McBride, S. M. & Sonenshein, A. L. The dlt operon confers resistance to cationic antimicrobial peptides in Clostridium difficile. *Microbiology* **157**, 1457–1465 (2011).
74. Awad, M. M., Johanesen, P. A., Carter, G. P., Rose, E. & Lyras, D. Clostridium difficile virulence factors: Insights into an anaerobic spore-forming pathogen. *Gut Microbes.* **5**, 579–593 (2014).
75. Smits, W. K. Hype or hypervirulence: a reflection on problematic C. difficile strains. *Virulence* **4**, 592–596 (2013).
76. Hammond, G. A. & Johnson, J. L. The toxigenic element of Clostridium difficile strain VPI 10463. *Microb.Pathog.* **19**, 203–213 (1995).
77. Braun, V., Hundsberger, T., Leukel, P., Sauerborn, M. & von Eichel-Streiber, C. Definition of the single integration site of the pathogenicity locus in Clostridium difficile. *Gene* **181**, 29–38 (1996).



78. Monot, M. *et al.* Clostridium difficile: New Insights into the Evolution of the Pathogenicity Locus. *Sci.Rep.* **5**, 15023– (2015).
79. Mani, N. *et al.* Environmental response and autoregulation of Clostridium difficile TxeR, a sigma factor for toxin gene expression. *J.Bacteriol.* **184**, 5971–5978 (2002).
80. Mani, N. & Dupuy, B. Regulation of toxin synthesis in Clostridium difficile by an alternative RNA polymerase sigma factor. *Proc.Natl.Acad.Sci.U.S.A* **98**, 5844–5849 (2001).
81. Dupuy, B., Govind, R., Antunes, A. & Matamouros, S. Clostridium difficile toxin synthesis is negatively regulated by TcdC. *J.Med.Microbiol.* **57**, 685–689 (2008).
82. Warny, M. *et al.* Toxin production by an emerging strain of Clostridium difficile associated with outbreaks of severe disease in North America and Europe. *Lancet* **366**, 1079–1084 (2005).
83. Tan, K. S., Wee, B. Y. & Song, K. P. Evidence for holin function of tcdE gene in the pathogenicity of Clostridium difficile. *J.Med.Microbiol.* **50**, 613–619 (2001).
84. Govind, R. & Dupuy, B. Secretion of Clostridium difficile toxins A and B requires the holin-like protein TcdE. *PLoS.Pathog.* **8**, e1002727– (2012).
85. Olling, A. *et al.* Release of TcdA and TcdB from Clostridium difficile cdi 630 is not affected by functional inactivation of the tcdE gene. *Microb.Pathog.* **52**, 92–100 (2012).
86. Karlsson, S. *et al.* Expression of Clostridium difficile toxins A and B and their sigma factor TcdD is controlled by temperature. *Infect.Immun.* **71**, 1784–1793 (2003).

87. Karlsson, S., Lindberg, A., Norin, E., Burman, L. G. & Akerlund, T. Toxins, butyric acid, and other short-chain fatty acids are coordinately expressed and down-regulated by cysteine in *Clostridium difficile*. *Infect.Immun.* **68**, 5881–5888 (2000).
88. Aldape, M. J., Packham, A. E., Nute, D. W., Bryant, A. E. & Stevens, D. L. Effects of ciprofloxacin on the expression and production of exotoxins by *Clostridium difficile*. *J.Med.Microbiol.* **62**, 741–747 (2013).
89. Chilton, C. H. *et al.* Co-amoxiclav induces proliferation and cytotoxin production of *Clostridium difficile* ribotype 027 in a human gut model. *J.Antimicrob.Chemother.* **67**, 951–954 (2012).
90. Dineen, S. S., McBride, S. M. & Sonenshein, A. L. Integration of metabolism and virulence by *Clostridium difficile* CodY. *J.Bacteriol.* **192**, 5350–5362 (2010).
91. Antunes, A. *et al.* Global transcriptional control by glucose and carbon regulator CcpA in *Clostridium difficile*. *Nucleic Acids Res.* **40**, 10701–10718 (2012).
92. Dupuy, B. & Sonenshein, A. L. Regulated transcription of *Clostridium difficile* toxin genes. *Mol.Microbiol.* **27**, 107–120 (1998).
93. McKee, R. W., Mangalea, M. R., Purcell, E. B., Borchardt, E. K. & Tamayo, R. The second messenger cyclic Di-GMP regulates *Clostridium difficile* toxin production by controlling expression of sigD. *J.Bacteriol.* **195**, 5174–5185 (2013).
94. El Meouche, I. *et al.* Characterization of the SigD regulon of *C. difficile* and its positive control of toxin production through the regulation of tcdR. *PLoS.One.* **8**, e83748– (2013).
95. Mackin, K. E., Carter, G. P., Howarth, P., Rood, J. I. & Lyras, D. Spo0A differentially

- regulates toxin production in evolutionarily diverse strains of *Clostridium difficile*. *PLoS.One.* **8**, e79666– (2013).
96. Rosenbusch, K. E., Bakker, D., Kuijper, E. J. & Smits, W. K. C. *difficile* 630Deltaerm Spo0A regulates sporulation, but does not contribute to toxin production, by direct high-affinity binding to target DNA. *PLoS.One.* **7**, e48608– (2012).
97. Pettit, L. J. *et al.* Functional genomics reveals that *Clostridium difficile* Spo0A coordinates sporulation, virulence and metabolism. *BMC.Genomics* **15**, 160– (2014).
98. Knetsch, C. W. *et al.* Comparative analysis of an expanded *Clostridium difficile* reference strain collection reveals genetic diversity and evolution through six lineages. *Infect.Genet.Evol.* **12**, 1577–1585 (2012).
99. Bouillaut, L., Dubois, T., Sonenshein, A. L. & Dupuy, B. Integration of metabolism and virulence in *Clostridium difficile*. *Res.Microbiol.* **166**, 375–383 (2015).
100. Shen, A. *Clostridium difficile* toxins: mediators of inflammation. *J.Innate.Immun.* **4**, 149–158 (2012).
101. Lyerly, D. M., Saum, K. E., MacDonald, D. K. & Wilkins, T. D. Effects of *Clostridium difficile* toxins given intragastrically to animals. *Infect.Immun.* **47**, 349–352 (1985).
102. Mitchell, T. J. *et al.* Effect of toxin A and B of *Clostridium difficile* on rabbit ileum and colon. *Gut* **27**, 78–85 (1986).
103. Triadafilopoulos, G., Pothoulakis, C., O'Brien, M. J. & LaMont, J. T. Differential effects of *Clostridium difficile* toxins A and B on rabbit ileum. *Gastroenterology* **93**, 273–279 (1987).

104. Riegler, M. *et al.* Clostridium difficile toxin B is more potent than toxin A in damaging human colonic epithelium in vitro. *J.Clin.Invest* **95**, 2004–2011 (1995).
105. Savidge, T. C. *et al.* Clostridium difficile toxin B is an inflammatory enterotoxin in human intestine. *Gastroenterology* **125**, 413–420 (2003).
106. Chumbler, N. M. *et al.* Crystal structure of Clostridium difficile Toxin A. *Nat.Microbiol.* **1**, - (2016).

**A structural study that provided insight in to mode of action of autoproteolytic activity and allosteric activation of the large clostridial toxins.**

107. Pruitt, R. N. *et al.* Structural determinants of Clostridium difficile toxin A glucosyltransferase activity. *J.Biol.Chem.* **287**, 8013–8020 (2012).
108. Papatheodorou, P., Zamboglou, C., Genisyuerek, S., Guttenberg, G. & Aktories, K. Clostridial glucosylating toxins enter cells via clathrin-mediated endocytosis. *PLoS.One.* **5**, e10673– (2010).
109. Pruitt, R. N. & Lacy, D. B. Toward a structural understanding of Clostridium difficile toxins A and B. *Front. Cell. Infect. Microbiol.* **2**, 28 (2012).
110. Greco, A. *et al.* Carbohydrate recognition by Clostridium difficile toxin A. *Nat.Struct.Mol.Biol.* **13**, 460–461 (2006).
111. Murase, T. *et al.* Structural basis for antibody recognition in the receptor-binding domains of toxins A and B from Clostridium difficile. *J.Biol.Chem.* **289**, 2331–2343 (2014).
112. Sauerborn, M., Leukel, P. & von Eichel-Streiber, C. The C-terminal ligand-binding domain of Clostridium difficile toxin A (TcdA) abrogates TcdA-specific binding to

- cells and prevents mouse lethality. *FEMS Microbiol.Lett.* **155**, 45–54 (1997).
113. Genisyuerek, S. *et al.* Structural determinants for membrane insertion, pore formation and translocation of *Clostridium difficile* toxin B. *Mol.Microbiol.* **79**, 1643–1654 (2011).
114. Olling, A. *et al.* The repetitive oligopeptide sequences modulate cytopathic potency but are not crucial for cellular uptake of *Clostridium difficile* toxin A. *PLoS.One.* **6**, e17623– (2011).
115. Schorch, B. *et al.* LRP1 is a receptor for *Clostridium perfringens* TpeL toxin indicating a two-receptor model of clostridial glycosylating toxins. *Proc.Natl.Acad.Sci.U.S.A* **111**, 6431–6436 (2014).
116. LaFrance, M. E. *et al.* Identification of an epithelial cell receptor responsible for *Clostridium difficile* TcdB-induced cytotoxicity. *Proc.Natl.Acad.Sci.U.S.A* **112**, 7073–7078 (2015).
117. Yuan, P. *et al.* Chondroitin sulfate proteoglycan 4 functions as the cellular receptor for *Clostridium difficile* toxin B. *Cell Res.* **25**, 157–168 (2015).
118. Terada, N. *et al.* Immunohistochemical study of NG2 chondroitin sulfate proteoglycan expression in the small and large intestines. *Histochem.Cell Biol.* **126**, 483–490 (2006).
119. Shen, A. *et al.* Defining an allosteric circuit in the cysteine protease domain of *Clostridium difficile* toxins. *Nat.Struct.Mol.Biol.* **18**, 364–371 (2011).
120. Egerer, M., Giesemann, T., Jank, T., Satchell, K. J. & Aktories, K. Auto-catalytic cleavage of *Clostridium difficile* toxins A and B depends on cysteine protease

- activity. *J.Biol.Chem.* **282**, 25314–25321 (2015).
121. Savidge, T. C. *et al.* Host S-nitrosylation inhibits clostridial small molecule-activated glucosylating toxins. *Nat.Med.* **17**, 1136–1141 (2011).
  122. Lanis, J. M., Hightower, L. D., Shen, A. & Ballard, J. D. TcdB from hypervirulent *Clostridium difficile* exhibits increased efficiency of autoprocessing. *Mol.Microbiol.* **84**, 66–76 (2012).
  123. Just, I. *et al.* The enterotoxin from *Clostridium difficile* (ToxA) monoglucosylates the Rho proteins. *J.Biol.Chem.* **270**, 13932–13936 (1995).
  124. Just, I. *et al.* Glucosylation of Rho proteins by *Clostridium difficile* toxin B. *Nature* **375**, 500–503 (1995).
  125. Brito, G. A. *et al.* Mechanism of *Clostridium difficile* toxin A-induced apoptosis in T84 cells. *J.Infect.Dis.* **186**, 1438–1447 (2002).
  126. Farrow, M. A. *et al.* *Clostridium difficile* toxin B-induced necrosis is mediated by the host epithelial cell NADPH oxidase complex. *Proc.Natl.Acad.Sci.U.S.A* **110**, 18674–18679 (2013).
  127. Slater, L. H. *et al.* Identification of novel host-targeted compounds that protect from anthrax lethal toxin-induced cell death. *ACS Chem.Biol.* **8**, 812–822 (2013).
  128. Tam, J. *et al.* Small molecule inhibitors of *Clostridium difficile* toxin B-induced cellular damage. *Chem.Biol.* **22**, 175–185 (2015).
  129. Bender, K. O. *et al.* A small-molecule antivirulence agent for treating *Clostridium difficile* infection. *Sci.Transl.Med.* **7**, 306ra148– (2015).
  130. Smith, S. M. *et al.* Ebselen and congeners inhibit NADPH oxidase 2-dependent

superoxide generation by interrupting the binding of regulatory subunits.

*Chem.Biol.* **19**, 752–763 (2012).

131. Kuehne, S. A. *et al.* Importance of toxin A, toxin B, and CDT in virulence of an epidemic *Clostridium difficile* strain. *J.Infect.Dis.* **209**, 83–86 (2014).
132. Carter, G. P. *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.* **6**, e00551– (2015).

#### **A histopathological analysis of the effects of TcdA and TcdB in a mouse model of infection.**

133. Drudy, D., Fanning, S. & Kyne, L. Toxin A-negative, toxin B-positive *Clostridium difficile*. *Int. J. Infect. Dis.* **11**, 5–10 (2007).
134. King, A. M., Mackin, K. E. & Lyras, D. Emergence of toxin A-negative, toxin B-positive *Clostridium difficile* strains: epidemiological and clinical considerations. *Future.Microbiol.* **10**, 1–4 (2015).
135. Gerding, D. N., Johnson, S., Rupnik, M. & Aktories, K. *Clostridium difficile* binary toxin CDT: mechanism, epidemiology, and potential clinical importance. *Gut Microbes.* **5**, 15–27 (2014).

#### **A review of different aspects of the binary toxin CDT.**

136. Perelle, S., Gibert, M., Bourlioux, P., Corthier, G. & Popoff, M. R. Production of a complete binary toxin (actin-specific ADP-ribosyltransferase) by *Clostridium difficile* CD196. *Infect.Immun.* **65**, 1402–1407 (1997).
137. Goncalves, C., Decre, D., Barbut, F., Burghoffer, B. & Petit, J. C. Prevalence and

- characterization of a binary toxin (actin-specific ADP-ribosyltransferase) from *Clostridium difficile*. *J.Clin.Microbiol.* **42**, 1933–1939 (2004).
138. Stare, B. G., Delmee, M. & Rupnik, M. Variant forms of the binary toxin CDT locus and *tcdC* gene in *Clostridium difficile* strains. *J.Med.Microbiol.* **56**, 329–335 (2007).
139. Carter, G. P. et al. Binary toxin production in *Clostridium difficile* is regulated by CdtR, a LytTR family response regulator. *J.Bacteriol.* **189**, 7290–7301 (2007).
140. Metcalf, D. S. & Weese, J. S. Binary toxin locus analysis in *Clostridium difficile*. *J.Med.Microbiol.* **60**, 1137–1145 (2011).
141. Sundriyal, A., Roberts, A. K., Shone, C. C. & Acharya, K. R. Structural basis for substrate recognition in the enzymatic component of ADP-ribosyltransferase toxin CDTa from *Clostridium difficile*. *J.Biol.Chem.* **284**, 28713–28719 (2009).
142. Schwan, C. et al. Cholesterol- and sphingolipid-rich microdomains are essential for microtubule-based membrane protrusions induced by *Clostridium difficile* transferase (CDT). *J.Biol.Chem.* **286**, 29356–29365 (2011).
143. Androga, G. O. et al. Infection With Toxin A-Negative, Toxin B-Negative, Binary Toxin-Positive *Clostridium difficile* In A Young Patient With Ulcerative Colitis. *J.Clin.Microbiol.* - (2015).
144. Eckert, C. et al. Prevalence and pathogenicity of binary toxin-positive *Clostridium difficile* strains that do not produce toxins A and B. *New Microbes.New Infect.* **3**, 12–17 (2015).
145. Hutton, M. L., Mackin, K. E., Chakravorty, A. & Lyras, D. Small animal models for



- the study of *Clostridium difficile* disease pathogenesis. *FEMS Microbiol.Lett.* **352**, 140–149 (2014).
146. Lawley, T. D. & Young, V. B. Murine models to study *Clostridium difficile* infection and transmission. *Anaerobe.* **24**, 94–97 (2013).
147. Best, E. L., Freeman, J. & Wilcox, M. H. Models for the study of *Clostridium difficile* infection. *Gut Microbes.* **3**, 145–167 (2012).
148. Collignon, A. Methods for working with the mouse model. *Methods Mol.Biol.* **646**, 229–237 (2010).
149. Lawley, T. D. et al. Targeted restoration of the intestinal microbiota with a simple, defined bacteriotherapy resolves relapsing *Clostridium difficile* disease in mice. *PLoS.Pathog.* **8**, e1002995– (2012).
150. Steele, J., Feng, H., Parry, N. & Tzipori, S. Piglet models of acute or chronic *Clostridium difficile* illness. *J.Infect.Dis.* **201**, 428–434 (2010).
151. Baines, S. D. et al. Mixed infection by *Clostridium difficile* in an in vitro model of the human gut. *J.Antimicrob.Chemother.* **68**, 1139–1143 (2013).
152. Crowther, G. S. et al. Development and validation of a chemostat gut model to study both planktonic and biofilm modes of growth of *Clostridium difficile* and human microbiota. *PLoS.One.* **9**, e88396– (2014).
153. Dobson, G., Hickey, C. & Trinder, J. *Clostridium difficile* colitis causing toxic megacolon, severe sepsis and multiple organ dysfunction syndrome. *Intensive Care Med.* **29**, 1030– (2003).
154. Cohen, S. H. et al. Clinical practice guidelines for *Clostridium difficile* infection in

- adults: 2010 update by the society for healthcare epidemiology of America (SHEA) and the infectious diseases society of America (IDSA). *Infect.Control Hosp.Epidemiol.* **31**, 431–455 (2010).
155. Debast, S. B., Bauer, M. P. & Kuijper, E. J. European Society of Clinical Microbiology and Infectious Diseases: update of the treatment guidance document for Clostridium difficile infection. *Clin.Microbiol.Infect.* **20 Suppl 2**, 1–26 (2014).
156. Yu, H. et al. Identification of toxemia in patients with Clostridium difficile infection. *PLoS.One.* **10**, e0124235– (2015).
157. Slimings, C. & Riley, T. V. Antibiotics and hospital-acquired Clostridium difficile infection: update of systematic review and meta-analysis. *J.Antimicrob.Chemother.* **69**, 881–891 (2014).
158. Kwok, C. S. et al. Risk of Clostridium difficile infection with acid suppressing drugs and antibiotics: meta-analysis. *Am.J.Gastroenterol.* **107**, 1011–1019 (2012).
159. McDonald, E. G., Milligan, J., Frenette, C. & Lee, T. C. Continuous Proton Pump Inhibitor Therapy and the Associated Risk of Recurrent Clostridium difficile Infection. *JAMA Intern.Med.* **175**, 784–791 (2015).
160. Novack, L. et al. Acid suppression therapy does not predispose to Clostridium difficile infection: the case of the potential bias. *PLoS.One.* **9**, e110790– (2014).
161. Tleyjeh, I. M. et al. Association between proton pump inhibitor therapy and Clostridium difficile infection: a contemporary systematic review and meta-analysis. *PLoS.One.* **7**, e50836– (2012).

162. Bartlett, J. G. & Gerding, D. N. Clinical recognition and diagnosis of *Clostridium difficile* infection. *Clin.Infect.Dis.* **46 Suppl 1**, S12–S18 (2008).
163. Zollner-Schwetz, I. et al. Role of *Klebsiella oxytoca* in antibiotic-associated diarrhea. *Clin.Infect.Dis.* **47**, e74–e78 (2008).
164. Planche, T. & Wilcox, M. H. Diagnostic pitfalls in *Clostridium difficile* infection. *Infect.Dis.Clin.North Am.* **29**, 63–82 (2015).
165. Polage, C. R. et al. Overdiagnosis of *Clostridium difficile* Infection in the Molecular Test Era. *JAMA Intern. Med.* **175**, 1792–1801 (2015).

**Confirmation (see REF. 34) that reliance on molecular tests alone for diagnosing CDI will probably lead to overdiagnosis, overtreatment and increased health care costs.**

166. Crobach, M. J., Dekkers, O. M., Wilcox, M. H. & Kuijper, E. J. European Society of Clinical Microbiology and Infectious Diseases (ESCMID): data review and recommendations for diagnosing *Clostridium difficile*-infection (CDI). *Clin.Microbiol.Infect.* **15**, 1053–1066 (2009).
167. Louie, T. J. et al. Fidaxomicin preserves the intestinal microbiome during and after treatment of *Clostridium difficile* infection (CDI) and reduces both toxin reexpression and recurrence of CDI. *Clin.Infect.Dis.* **55 Suppl 2**, S132–S142 (2012).
168. Eastwood, K., Else, P., Charlett, A. & Wilcox, M. Comparison of nine commercially available *Clostridium difficile* toxin detection assays, a real-time PCR assay for *C. difficile* tcdB, and a glutamate dehydrogenase detection assay to cytotoxin testing and cytotoxigenic culture methods. *J.Clin.Microbiol.* **47**, 3211–3217 (2009).
169. Ota, K. V & McGowan, K. L. *Clostridium difficile* testing algorithms using

- glutamate dehydrogenase antigen and *C. difficile* toxin enzyme immunoassays with *C. difficile* nucleic acid amplification testing increase diagnostic yield in a tertiary pediatric population. *J.Clin.Microbiol.* **50**, 1185–1188 (2012).
170. Reigadas, E. *et al.* Missed diagnosis of *Clostridium difficile* infection; a prospective evaluation of unselected stool samples. *J.Infect.* **70**, 264–272 (2015).
171. Faust, S. N. *et al.* Lack of evidence for an unmet need to treat *Clostridium difficile* infection in infants aged <2 years: expert recommendations on how to address this issue. *Clin.Infect.Dis.* **60**, 912–918 (2015).
172. Schutze, G. E. & Willoughby, R. E. *Clostridium difficile* infection in infants and children. *Pediatrics* **131**, 196–200 (2013).
173. Spina, A. *et al.* Spectrum of enteropathogens detected by the FilmArray GI Panel in a multicentre study of community-acquired gastroenteritis. *Clin.Microbiol.Infect.* **21**, 719–728 (2015).
174. Buijnesteijn van Coppenraet, L. E. *et al.* Case-control comparison of bacterial and protozoan microorganisms associated with gastroenteritis: application of molecular detection. *Clin.Microbiol.Infect.* **21**, 592 (2015).
175. Curry, S. R. *et al.* Use of multilocus variable number of tandem repeats analysis genotyping to determine the role of asymptomatic carriers in *Clostridium difficile* transmission. *Clin.Infect.Dis.* **57**, 1094–1102 (2013).
176. Kyne, L., Warny, M., Qamar, A. & Kelly, C. P. Asymptomatic carriage of *Clostridium difficile* and serum levels of IgG antibody against toxin A. *N.Engl.J.Med.* **342**, 390–397 (2000).

177. Donskey, C. J., Kundrapu, S. & Deshpande, A. Colonization versus carriage of *Clostridium difficile*. *Infect.Dis.Clin.North Am.* **29**, 13–28 (2015).
178. Ziakas, P. D. et al. Asymptomatic carriers of toxigenic *C. difficile* in long-term care facilities: a meta-analysis of prevalence and risk factors. *PLoS.One.* **10**, e0117195– (2015).
179. Riggs, M. M. et al. Asymptomatic carriers are a potential source for transmission of epidemic and nonepidemic *Clostridium difficile* strains among long-term care facility residents. *Clin.Infect.Dis.* **45**, 992–998 (2007).
180. Loo, V. G. et al. Host and pathogen factors for *Clostridium difficile* infection and colonization. *N.Engl.J.Med.* **365**, 1693–1703 (2011).
181. Samore, M. H., Venkataraman, L., DeGirolami, P. C., Arbeit, R. D. & Karchmer, A. W. Clinical and molecular epidemiology of sporadic and clustered cases of nosocomial *Clostridium difficile* diarrhea. *Am. J. Med.* **100**, 32–40 (1996).
182. Enoch, D. A., Butler, M. J., Pai, S., Aliyu, S. H. & Karas, J. A. *Clostridium difficile* in children: colonisation and disease. *J.Infect.* **63**, 105–113 (2011).
183. Furuichi, M. et al. Characteristics of *Clostridium difficile* colonization in Japanese children. *J.Infect.Chemother.* **20**, 307–311 (2014).
184. Leibowitz, J., Soma, V. L., Rosen, L., Ginocchio, C. C. & Rubin, L. G. Similar proportions of stool specimens from hospitalized children with and without diarrhea test positive for *Clostridium difficile*. *Pediatr.Infect.Dis.J.* **34**, 261–266 (2015).
185. Bergstrom, A. et al. Establishment of intestinal microbiota during early life: a

longitudinal, explorative study of a large cohort of Danish infants.

*Appl. Environ. Microbiol.* **80**, 2889–2900 (2014).

186. Shim, J. K., Johnson, S., Samore, M. H., Bliss, D. Z. & Gerding, D. N. Primary symptomless colonisation by *Clostridium difficile* and decreased risk of subsequent diarrhoea. *Lancet* **351**, 633–636 (1998).
187. Gerding, D. N. *et al.* Administration of spores of nontoxigenic *Clostridium difficile* strain M3 for prevention of recurrent *C. difficile* infection: a randomized clinical trial. *JAMA* **313**, 1719–1727 (2015).
188. Brouwer, M. S. *et al.* Horizontal gene transfer converts non-toxigenic *Clostridium difficile* strains into toxin producers. *Nat. Commun.* **4**, 2601– (2013).
189. Clabots, C. R., Johnson, S., Olson, M. M., Peterson, L. R. & Gerding, D. N. Acquisition of *Clostridium difficile* by hospitalized patients: evidence for colonized new admissions as a source of infection. *J. Infect. Dis.* **166**, 561–567 (1992).
190. Lanzas, C., Dubberke, E. R., Lu, Z., Reske, K. A. & Grohn, Y. T. Epidemiological model for *Clostridium difficile* transmission in healthcare settings. *Infect. Control Hosp. Epidemiol.* **32**, 553–561 (2011).
191. Vonberg, R. P. *et al.* Infection control measures to limit the spread of *Clostridium difficile*. *Clin. Microbiol. Infect.* **14 Suppl 5**, 2–20 (2008).
192. Dubberke, E. R. *et al.* Strategies to prevent *Clostridium difficile* infections in acute care hospitals: 2014 update. *Infect. Control Hosp. Epidemiol.* **35 Suppl 2**, S48–S65 (2014).
193. Surawicz, C. M. *et al.* Guidelines for diagnosis, treatment, and prevention of

- Clostridium difficile infections. *Am.J.Gastroenterol.* **108**, 478–498 (2013).
194. Dancer, S. J. Controlling hospital-acquired infection: focus on the role of the environment and new technologies for decontamination. *Clin.Microbiol.Rev.* **27**, 665–690 (2014).
195. Feazel, L. M. *et al.* Effect of antibiotic stewardship programmes on Clostridium difficile incidence: a systematic review and meta-analysis. *J.Antimicrob.Chemother.* **69**, 1748–1754 (2014).
196. Barbut, F. How to eradicate Clostridium difficile from the environment. *J.Hosp.Infect.* **89**, 287–295 (2015).
197. Johnson, S. *et al.* Vancomycin, metronidazole, or tolevamer for Clostridium difficile infection: results from two multinational, randomized, controlled trials. *Clin.Infect.Dis.* **59**, 345–354 (2014).
- A large randomized study that shows, for the first time, the significantly improved outcome following vancomycin as opposed to metronidazole therapy for CDI on an intention-to-treat basis.**
198. Cornely, O. A., Miller, M. A., Louie, T. J., Crook, D. W. & Gorbach, S. L. Treatment of first recurrence of Clostridium difficile infection: fidaxomicin versus vancomycin. *Clin.Infect.Dis.* **55 Suppl 2**, S154–S161 (2012).
199. Neal, M. D., Alverdy, J. C., Hall, D. E., Simmons, R. L. & Zuckerbraun, B. S. Diverting loop ileostomy and colonic lavage: an alternative to total abdominal colectomy for the treatment of severe, complicated Clostridium difficile associated disease. *Ann.Surg.* **254**, 423–427 (2011).

200. Bauer, M. P. *et al.* Renal failure and leukocytosis are predictors of a complicated course of *Clostridium difficile* infection if measured on day of diagnosis. *Clin.Infect.Dis.* **55 Suppl 2**, S149–S153 (2012).
201. Kelly, C. P. Can we identify patients at high risk of recurrent *Clostridium difficile* infection? *Clin.Microbiol.Infect.* **18 Suppl 6**, 21–27 (2012).
202. Cornely, O. A. *et al.* Fidaxomicin versus vancomycin for infection with *Clostridium difficile* in Europe, Canada, and the USA: a double-blind, non-inferiority, randomised controlled trial. *Lancet Infect.Dis.* **12**, 281–289 (2012).
203. Louie, T. J. *et al.* Fidaxomicin versus vancomycin for *Clostridium difficile* infection. *N.Engl.J.Med.* **364**, 422–431 (2011).

**A study that formed the basis for the addition of fidaxomicin as a therapeutic for the treatment of recurrent CDI.**

204. D’Agostino Sr., R. B., Collins, S. H., Pencina, K. M., Kean, Y. & Gorbach, S. Risk estimation for recurrent *Clostridium difficile* infection based on clinical factors. *Clin.Infect.Dis.* **58**, 1386–1393 (2014).
205. Goldenberg, J. Z. *et al.* Probiotics for the prevention of *Clostridium difficile*-associated diarrhea in adults and children. *Cochrane.Database.Syst.Rev.* **5**, CD006095– (2013).
206. van Nood, E. *et al.* Duodenal infusion of donor feces for recurrent *Clostridium difficile*. *N.Engl.J.Med.* **368**, 407–415 (2013).

**The first randomized controlled trial demonstrating the superiority of FMT over vancomycin for the treatment of patients with multiple recurrences of CDI.**

207. Sokol, H. *et al.* Faecal microbiota transplantation in recurrent *Clostridium difficile*



- infection: Recommendations from the French Group of Faecal microbiota Transplantation. *Dig.Liver Dis.* **48**, 242–247 (2015).
208. Varier, R. U. *et al.* Cost-effectiveness analysis of fecal microbiota transplantation for recurrent *Clostridium difficile* infection. *Infect.Control Hosp.Epidemiol.* **36**, 438–444 (2015).
209. Kump, P. K. *et al.* [Recommendations for the use of faecal microbiota transplantation ‘stool transplantation’: consensus of the Austrian Society of Gastroenterology and Hepatology (OGGH) in cooperation with the Austrian Society of Infectious Diseases and Tropical Medicine]. *Z.Gastroenterol.* **52**, 1485–1492 (2014).
210. Youngster, I. *et al.* Oral, capsulized, frozen fecal microbiota transplantation for relapsing *Clostridium difficile* infection. *JAMA* **312**, 1772–1778 (2014).
211. Petrof, E. O. *et al.* Stool substitute transplant therapy for the eradication of *Clostridium difficile* infection: ‘RePOOPulating’ the gut. *Microbiome.* **1**, 3– (2013).
212. Tvede, M., Tinggaard, M. & Helms, M. Rectal bacteriotherapy for recurrent *Clostridium difficile*-associated diarrhoea: results from a case series of 55 patients in Denmark 2000-2012. *Clin.Microbiol.Infect.* **21**, 48–53 (2015).
213. Khanna, S. *et al.* A Novel Microbiome Therapeutic Increases Gut Microbial Diversity and Prevents Recurrent *Clostridium difficile* Infection. *J. Infect. Dis.* jiv766 (2016). doi:10.1093/infdis/jiv766
214. Wilcox, M. *et al.* Abstract 067. Bezlotoxumab alone and with actoxumab for prevention of recurrent *C. difficile* infection in patients on standard of care

antibiotics: integrated results of 2 phase 3 studies (MODIFY I and MODIFY II).

(2015). at <[http://ofid.oxfordjournals.org/content/2/suppl\\_1/S3.1.short?rss=1](http://ofid.oxfordjournals.org/content/2/suppl_1/S3.1.short?rss=1)>

215. Wilcox, M. H., Cunniffe, J. G., Trundle, C. & Redpath, C. Financial burden of hospital-acquired *Clostridium difficile* infection. *J.Hosp.Infect.* **34**, 23–30 (1996).
216. Vonberg, R. P. *et al.* Costs of nosocomial *Clostridium difficile*-associated diarrhoea. *J.Hosp.Infect.* **70**, 15–20 (2008).
217. Wiegand, P. N. *et al.* Clinical and economic burden of *Clostridium difficile* infection in Europe: a systematic review of healthcare-facility-acquired infection. *J.Hosp.Infect.* **81**, 1–14 (2012).

**A systematic review of European data on CDI-related mortality, recurrence, length of hospital stay and cost.**

218. Mitchell, B. G. & Gardner, A. Prolongation of length of stay and *Clostridium difficile* infection: a review of the methods used to examine length of stay due to healthcare associated infections. *Antimicrob.Resist.Infect.Control* **1**, 14– (2012).
219. Ghantaji, S. S., Sail, K., Lairson, D. R., DuPont, H. L. & Garey, K. W. Economic healthcare costs of *Clostridium difficile* infection: a systematic review. *J.Hosp.Infect.* **74**, 309–318 (2010).
220. Nanwa, N. *et al.* The economic impact of *Clostridium difficile* infection: a systematic review. *Am.J.Gastroenterol.* **110**, 511–519 (2015).
221. Zimlichman, E. *et al.* Health care-associated infections: a meta-analysis of costs and financial impact on the US health care system. *JAMA Intern.Med.* **173**, 2039–2046 (2013).
222. Levy, A. R. *et al.* Incidence and Costs of *Clostridium difficile* Infections in Canada.

- Open.Forum Infect.Dis.* **2**, ofv076– (2015).
223. Kwon, J. H., Olsen, M. A. & Dubberke, E. R. The morbidity, mortality, and costs associated with *Clostridium difficile* infection. *Infect.Dis.Clin.North Am.* **29**, 123–134 (2015).
224. PROMIS; dynamic tools to measure health outcomes from the patient perspective. - (2015). at <<http://www.nihpromis.org/>>
225. Vuong, N. N. *et al.* Abstract O76. Use of PROMIS Network to Evaluate Patient-Reported Health Status Associated with *Clostridium difficile* Infection. - (2015).
226. Fimlaid, K. A. & Shen, A. Diverse mechanisms regulate sporulation sigma factor activity in the Firmicutes. *Curr.Opin.Microbiol.* **24**, 88–95 (2015).
227. Battistuzzi, F. U., Feijao, A. & Hedges, S. B. A genomic timescale of prokaryote evolution: insights into the origin of methanogenesis, phototrophy, and the colonization of land. *BMC.Evol.Biol.* **4**, 44– (2004).
228. Merrigan, M. *et al.* Human hypervirulent *Clostridium difficile* strains exhibit increased sporulation as well as robust toxin production. *J.Bacteriol.* **192**, 4904–4911 (2010).
229. Burns, D. A., Heap, J. T. & Minton, N. P. The diverse sporulation characteristics of *Clostridium difficile* clinical isolates are not associated with type. *Anaerobe.* **16**, 618–622 (2010).
230. Borgmann, S. *et al.* Increased number of *Clostridium difficile* infections and prevalence of *Clostridium difficile* PCR ribotype 001 in southern Germany. *Euro.Surveill* **13**, - (2008).

231. Knetsch, C. W. *et al.* Genetic markers for *Clostridium difficile* lineages linked to hypervirulence. *Microbiology* **157**, 3113–3123 (2011).
232. Eyre, D. W. *et al.* Emergence and spread of predominantly community-onset *Clostridium difficile* PCR ribotype 244 infection in Australia, 2010 to 2012. *Euro.Surveill* **20**, 21059– (2015).
233. Rea, M. C. *et al.* Thuricin CD, a posttranslationally modified bacteriocin with a narrow spectrum of activity against *Clostridium difficile*. *Proc.Natl.Acad.Sci.U.S.A* **107**, 9352–9357 (2010).
234. Hopkins, M. J. & Macfarlane, G. T. Changes in predominant bacterial populations in human faeces with age and with *Clostridium difficile* infection. *J.Med.Microbiol.* **51**, 448–454 (2002).
235. Bingley, P. J. & Harding, G. M. *Clostridium difficile* colitis following treatment with metronidazole and vancomycin. *Postgrad.Med.J.* **63**, 993–994 (1987).
236. Gebhart, D. *et al.* A modified R-type bacteriocin specifically targeting *Clostridium difficile* prevents colonization of mice without affecting gut microbiota diversity. *MBio.* **6**, - (2015).
237. Hargreaves, K. R. & Clokie, M. R. *Clostridium difficile* phages: still difficult? *Front Microbiol.* **5**, 184– (2014).
238. Rasko, D. A. & Sperandio, V. Anti-virulence strategies to combat bacteria-mediated disease. *Nat.Rev.Drug Discov.* **9**, 117–128 (2010).
239. Lowy, I. *et al.* Treatment with monoclonal antibodies against *Clostridium difficile* toxins. *N.Engl.J.Med.* **362**, 197–205 (2010).

240. Martin, C. E. *et al.* Immunological evaluation of a synthetic *Clostridium difficile* oligosaccharide conjugate vaccine candidate and identification of a minimal epitope. *J.Am.Chem.Soc.* **135**, 9713–9722 (2013).
241. Kandalaf, H. *et al.* Targeting surface-layer proteins with single-domain antibodies: a potential therapeutic approach against *Clostridium difficile*-associated disease. *Appl.Microbiol.Biotechnol.* **99**, 8549–8562 (2015).
242. Abou Chakra, C. N., Pepin, J. & Valiquette, L. Prediction tools for unfavourable outcomes in *Clostridium difficile* infection: a systematic review. *PLoS.One.* **7**, e30258– (2012).
243. Na, X. *et al.* A Multi-Center Prospective Derivation and Validation of a Clinical Prediction Tool for Severe *Clostridium difficile* Infection. *PLoS.One.* **10**, e0123405– (2015).
244. Hensgens, M. P., Dekkers, O. M., Goorhuis, A., LeCessie, S. & Kuijper, E. J. Predicting a complicated course of *Clostridium difficile* infection at the bedside. *Clin.Microbiol.Infect.* **20**, O301–O308 (2014).
245. Zilberberg, M. D., Reske, K., Olsen, M., Yan, Y. & Dubberke, E. R. Development and validation of a recurrent *Clostridium difficile* risk-prediction model. *J.Hosp.Med.* **9**, 418–423 (2014).
246. The 2015 Ageing Report. Underlying Assumptions and Projection Methodologies. - (2014). at  
<[http://ec.europa.eu/economy\\_finance/publications/european\\_economy/2014/pdf/ee8\\_en.pdf](http://ec.europa.eu/economy_finance/publications/european_economy/2014/pdf/ee8_en.pdf)>

247. Ortman, J. M., Velkoff, V. A. & Howard, H. An Aging Nation: The Older Population in the United States. - (2014). at <<https://www.census.gov/prod/2014pubs/p25-1140.pdf>>
248. Tenover, F. C. *et al.* Comparison of strain typing results for *Clostridium difficile* isolates from North America. *J.Clin.Microbiol.* **49**, 1831–1837 (2011).
249. Fawley, W. N. *et al.* Development and validation of an internationally-standardized, high-resolution capillary gel-based electrophoresis PCR-ribotyping protocol for *Clostridium difficile*. *PLoS.One.* **10**, e0118150– (2015).
250. Baines, S. D., O’Connor, R., Saxton, K., Freeman, J. & Wilcox, M. H. Activity of vancomycin against epidemic *Clostridium difficile* strains in a human gut model. *J.Antimicrob.Chemother.* **63**, 520–525 (2009).
251. Paredes-Sabja, D., Cofre-Araneda, G., Brito-Silva, C., Pizarro-Guajardo, M. & Sarker, M. R. *Clostridium difficile* spore-macrophage interactions: spore survival. *PLoS.One.* **7**, e43635– (2012).
252. Spigaglia, P., Barbanti, F. & Mastrantonio, P. Multidrug resistance in European *Clostridium difficile* clinical isolates. *J.Antimicrob.Chemother.* **66**, 2227–2234 (2011).
253. Peltier, J. *et al.* Genomic and expression analysis of the vanG-like gene cluster of *Clostridium difficile*. *Microbiology* **159**, 1510–1520 (2013).
254. Ammam, F. *et al.* The functional vanGCd cluster of *Clostridium difficile* does not confer vancomycin resistance. *Mol.Microbiol.* **89**, 612–625 (2013).
255. Amy, J., Johanesen, P. & Lyras, D. Extrachromosomal and integrated genetic

- elements in *Clostridium difficile*. *Plasmid* **80**, 97–110 (2015).
256. Hansen, L. H. & Vester, B. A cfr-Like Gene from *Clostridium difficile* Confers Multiple Antibiotic Resistance by the Same Mechanism as the cfr Gene. *Antimicrob. Agents Chemother.* **59**, 5841–5843 (2015).
257. Roberts, A. P., Johanesen, P. A., Lyras, D., Mullany, P. & Rood, J. I. Comparison of Tn5397 from *Clostridium difficile*, Tn916 from *Enterococcus faecalis* and the CW459tet(M) element from *Clostridium perfringens* shows that they have similar conjugation regions but different insertion and excision modules. *Microbiology* **147**, 1243–1251 (2001).
258. Chong, P. M. *et al.* Proteomic analysis of a NAP1 *Clostridium difficile* clinical isolate resistant to metronidazole. *PLoS. One.* **9**, e82622– (2014).
259. Lynch, T. *et al.* Characterization of a stable, metronidazole-resistant *Clostridium difficile* clinical isolate. *PLoS. One.* **8**, e53757– (2013).
260. Leeds, J. A., Sachdeva, M., Mullin, S., Barnes, S. W. & Ruzin, A. In vitro selection, via serial passage, of *Clostridium difficile* mutants with reduced susceptibility to fidaxomicin or vancomycin. *J. Antimicrob. Chemother.* **69**, 41–44 (2014).
261. Freeman, J. *et al.* Pan-European longitudinal surveillance of antibiotic resistance among prevalent *Clostridium difficile* ribotypes. *Clin. Microbiol. Infect.* **21**, 248.e9–248.e16 (2015).
262. Threat Report 2013. - (2013). at <<http://www.cdc.gov/drugresistance/threat-report-2013/>>

**A report from the CDC that qualifies *C. difficile* as an urgent antibiotic resistance threat.**

263. Spigaglia, P. *et al.* Fluoroquinolone resistance in *Clostridium difficile* isolates from a prospective study of *C. difficile* infections in Europe. *J.Med.Microbiol.* **57**, 784–789 (2008).
264. Papatheodorou, P. *et al.* Lipolysis-stimulated lipoprotein receptor (LSR) is the host receptor for the binary toxin *Clostridium difficile* transferase (CDT). *Proc.Natl.Acad.Sci.U.S.A* **108**, 16422–16427 (2011).
265. Martin, J., Monaghan, T. & Wilcox, M. H. *Clostridium difficile* infection: advances in epidemiology, diagnosis and understanding of transmission. *Nat. Rev. Gastro. Hep.* [http://dx.](http://dx.doi.org/10.1038/nrgastro.2016.10), (2016).
266. Le, M. A. *et al.* Hospital cost of *Clostridium difficile* infection including the contribution of recurrences in French acute-care hospitals. *J.Hosp.Infect.* **91**, 117–122 (2015).
267. Gabriel, L. & Beriot-Mathiot, A. Hospitalization stay and costs attributable to *Clostridium difficile* infection: a critical review. *J.Hosp.Infect.* **88**, 12–21 (2014).



**Online only**

**Subject terms**

Health sciences / Diseases / Infectious diseases / *Clostridium difficile*  
[URI /692/699/255/1911]

Health sciences / Diseases / Gastrointestinal diseases / Intestinal diseases / Colonic diseases / Colitis  
[URI /692/699/1503/1581/1392/1388]

Health sciences / Anatomy / Gastrointestinal system / Microbiota  
[URI /692/698/2741/2135]

Biological sciences / Microbiology / Antimicrobials / Antibiotics  
[URI /631/326/22/1290]

**Notes for sensitive images**

None.

**Toc blurb for article**

This Primer describes the mechanisms underlying the serious effects of *Clostridium difficile* infection, which is the leading cause of healthcare-associated diarrhoea. Strategies for diagnosis, prevention and management are also described, illustrating the burden *C. difficile* infection places on patients and society.