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The *vanR_{cd}* Mutation 343A>G, Resulting in a Thr115Ala Substitution, Is Associated with an Elevated Minimum Inhibitory Concentration (MIC) of Vancomycin in *Clostridioides difficile* Clinical Isolates from Florida

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ABSTRACT *Clostridioides difficile*, the primary cause of nosocomial antibiotic-associated diarrhea, has a complex relationship with antibiotics. While the use of broad-spectrum antibiotics disrupts the gut microbiota and increases the risk of *C. difficile* infection (CDI), antibiotics are also the primary treatment for CDI. However, only a few antibiotics, including vancomycin, fidaxomicin, and rifaximin, are effective against CDI, and resistance to these antibiotics has emerged recently. In this study, we report the identification of two RT027 *C. difficile* clinical isolates (TGH35 and TGH64) obtained from symptomatic CDI-diagnosed patients in Tampa, Florida in 2016. These two strains showed an elevated minimum inhibitory concentration (MIC) of vancomycin (MIC = 4 μ g/mL, compared to the EUCAST breakpoint of 2 μ g/mL) and contained a *vanR_{cd}* 343A>G mutation resulting in a Thr115Ala substitution in the VanR_{cd} response regulator. This mutation was absent in the vancomycin-sensitive control epidemic strain RT027/R20291. TGH64 was also resistant to rifaximin (MIC \geq 128 μ g/mL) and carried the previously reported Arg505Lys and Ile548Met mutations in RpoB. Furthermore, we report on the antimicrobial resistance (AMR) and genomic characterization of additional *C. difficile* isolates, including RT106/TGH120, RT017/TGH33, and RT017/TGH51, obtained from the same patient sample cohort representing the highly prevalent and regionally distributed *C. difficile* ribotypes worldwide. Considering that the VanR_{cd} Thr115Ala mutation was also independently reported in seven *C. difficile* clinical isolates from Texas and Israel in 2019, we recommend epidemiological surveillance to better understand the impact of this mutation on vancomycin resistance.

IMPORTANCE The perpetually evolving antimicrobial resistance (AMR) of *C. difficile* is an important contributor to its epidemiology and is a grave concern to global public health. This exacerbates the challenge of treating the infections caused by this multi-drug-resistant causative organism of potentially life-threatening diarrhea. Further, the novel resistance-determining factors can be transferred between different strains and species of bacteria and cause the spread of AMR in clinical, environmental, and community settings. In this study, we have identified a mutation (*vanR_{cd}* 343A>G) that causes a Thr115Ala substitution and is linked to an increased MIC of vancomycin in clinical isolates of *C. difficile* obtained from Florida in 2016. Understanding the mechanisms of AMR, especially those of newly evolving strains, is essential to effectively guide antibiotic stewardship policies to combat antibiotic resistance as well as to discover novel therapeutic targets.

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Clostridioides difficile, which is a cause of mild to life-threatening diarrhea that was responsible for 12,800 deaths in the USA in 2017, has been declared by the CDC as one of the top five urgent antibiotic-resistant threats (1). The emergence of new strains, which are often more virulent and antibiotic-resistant, has been associated with the recent increase in the prevalence and severity of CDI (2).

As a life-threatening disease with a high incidence of recurrence and limited effective therapeutic options, the resistance of *C. difficile* to vancomycin, which is the first line of therapy that is recommended for CDI treatment, is a grave public health concern (2, 3). Vancomycin inhibits bacterial cell wall synthesis by binding with high affinity to the D-Ala-D-Ala C terminus of peptidoglycan precursors, which thereby prevents the addition of late precursors to the nascent peptidoglycan chain (4). A gene cluster called the “van operon” has been described to mediate vancomycin resistance in enterococci (4). The two-component regulatory system of van operons encompasses a sensor histidine kinase (VanS) and a response regulator (VanR). The vanG-type of operon contains the resistance genes VanG (D-Ala-D-Ser ligase), VanXY (a bifunctional D,D-dipeptidase/D,D-carboxypeptidase), and VanT (serine racemase). When vancomycin is sensed by the membrane-bound VanS, it undergoes the ATP-dependent autophosphorylation of a histidine residue. This phosphoryl group is then transferred to the cytoplasmic VanR, which, in turn, transcriptionally activates the expression of downstream resistance genes. VanT converts L-Ser to D-Ser and VanG ligates D-Ala and D-Ser, forming low-affinity precursors and modifying the vancomycin binding target. VanXY hydrolyzes peptidoglycan precursors that end with D-Ala residues, thereby eliminating the high-affinity binding targets of vancomycin (4). However, although a functional vanG operon-like gene cluster called “vanG_{cd}” has been found in about 85% of *C. difficile* clinical isolates, it was not associated with vancomycin resistance in *C. difficile* (5).

We previously reported 139 *C. difficile* clinical isolates that were obtained from symptomatic patients who were diagnosed with CDI in Tampa, FL, USA (6). Based on broth microdilution-based screening for antimicrobial susceptibility, we selected isolates that showed a reduced susceptibility to multiple antibiotics and conducted capillary PCR ribotyping at the Dutch National Reference Laboratory at the Leiden University Medical Center (LUMC), using a standardized protocol (7). Considering that the epidemiology of *C. difficile* shows distinct geographical distributions, we selected five isolates to represent the most prevalent *C. difficile* ribotypes that are found in different geographical locations around the world, namely, RT027 (Europe and North America) (2), RT106 (USA) (8), and RT017 (Asia) (9), for further analysis in the present study.

We cultured the five selected *C. difficile* isolates, namely, TGH35, TGH64, TGH120, TGH33, and TGH51, in brain heart infusion (BHI) broth (Sigma) at 37°C under anaerobic conditions. Following genomic DNA extraction with a kit (Qiagen) and whole-genome sequencing using paired-end libraries and an Illumina HiSeq 3000 platform, we *de novo* assembled reads into contigs using Qiagen CLC Genomics Workbench 11.0.1 (10) (Table S1). After ordering the contigs against the reference CD630 genome (GenBank accession: CP010905.2) using Mauve (v2.4.0) (11) and annotating them using Rapid Annotations using Subsystems Technology (RAST) (12), we compared the whole-genomes of the five isolates with three reference strain genomes, namely, CD630/RT012/Clade1, R20291/RT027/Clade2, and M68/RT017/Clade4 (GenBank accessions: CP010905.2, FN545816.1, and FN668375.1, respectively), and we visualized them using the BLAST Ring Image Generator (BRIG) (13). The housekeeping genes *adk*, *atpA*, *glyA*, *sodA*, *dxr*, *recA*, and *tpi* were used for web-based multilocus sequence typing (MLST) on a CGE MLST platform (14), and a phylogenetic analysis was conducted using MEGA7 (15). Prophages were predicted using the PHAge Search Tool (PHAST) (16). We searched for plasmids using CGEPlasmidFinder-2.0 (17) and manually evaluated the presence of sequences corresponding to pCD-METRO (GenBank: OM972905.1) (18). We

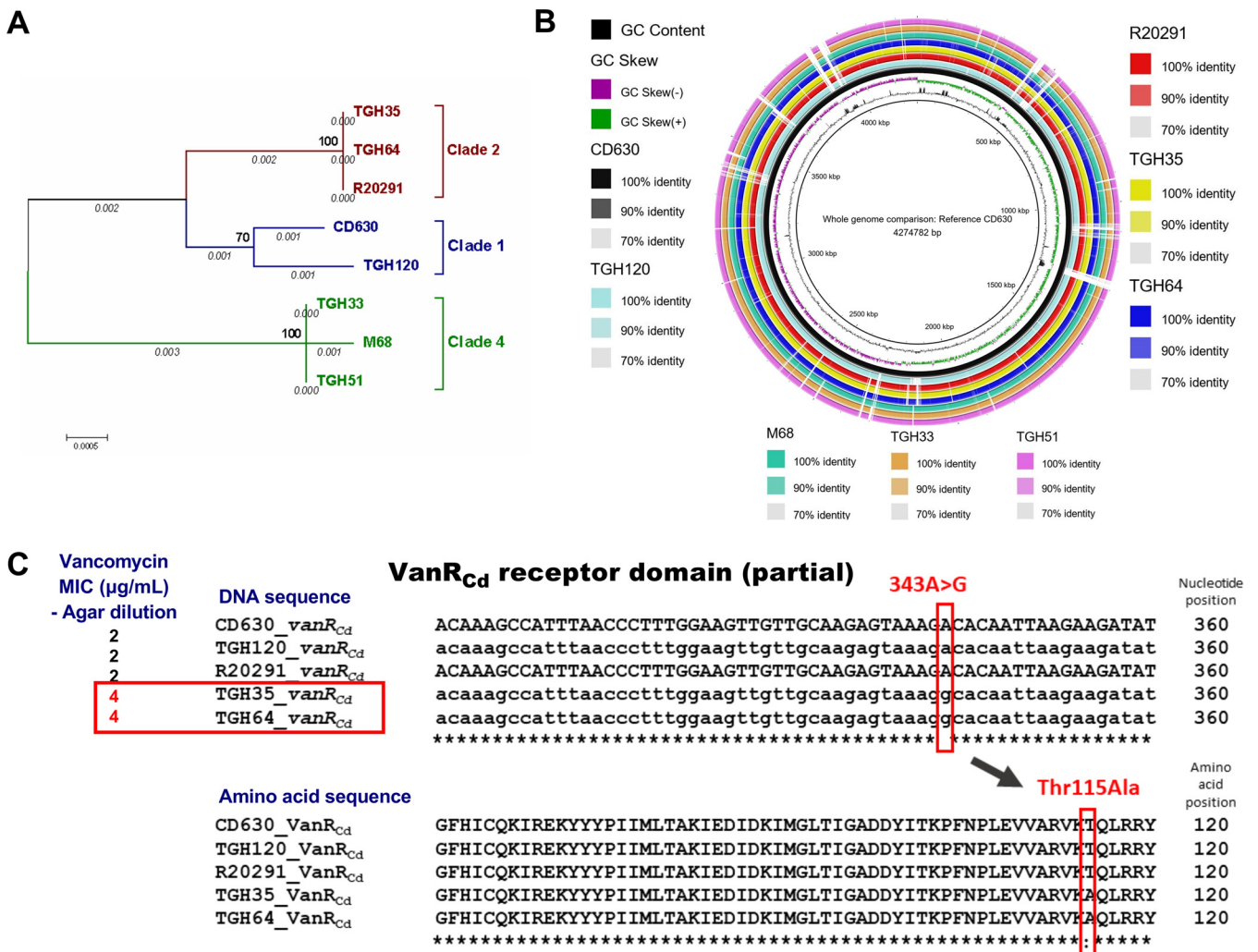


FIG 1 Genome analysis of the five *C. difficile* isolates and three control strains CD630, R20291, and M68 (GenBank accessions CP010905.2, FN545816.1, and FN668375.1, respectively). (A) Phylogenetic tree generated with seven housekeeping genes, using MEGA7 software. The seven housekeeping genes were concatenated to generate a supergene alignment using MUSCLE, and a phylogenetic tree was generated using the maximum likelihood method. A general time reversible (GTR) model was used to generate the substitution model using gamma distributed with invariant sites (G+I) and 1,000 bootstrap replications. (B) BLAST ring image generator-based comparison and visualization of the whole-genomes. (C) Multiple sequence alignment (Clustal Omega) of the *vanR_{Cd}* gene (upper panel) and amino acid sequence (lower panel) in comparison with the vancomycin MICs obtained via the agar dilution method (left) of the novel isolates and control strains. The *vanG_{Cd}* operon is absent in the RT017 strains M68, TGH33, and TGH51.

used the comprehensive antibiotic resistance database (CARD) to search for putative AMR genes using the Resistance Gene Identifier (RGI) tool for resistome predictions, based on homology and SNP models (19). The features of the characterized genomes are illustrated in Fig. 1, Table 1, and Table S2.

The antibiotic susceptibility testing (AST) of the isolates to the currently clinically used antibiotics for CDI treatment, namely, vancomycin, metronidazole, fidaxomicin, and rifaximin, was conducted using the reference standard agar dilution method, based on the Clinical and Laboratory Standards Institute (CLSI) guidelines M11-A7 (volume 27, no 2, ISBN:1-56238-626-3), using the epidemic RT027/R20291 *C. difficile* strain as a control with a minimum of three technical replicates in two independent experiments. While all strains were susceptible to metronidazole and fidaxomicin, high resistance to rifaximin (MIC ≥ 128 µg/mL) was detected only in TGH64. Rifaximin, which is an adjunct therapeutic for CDI, acts by binding to the β-subunit of RNA polymerase (RpoB), which thereby inhibits bacterial RNA synthesis (20). Since mutations in the rifamycin resistance-determining region (RRID) of RpoB have been previously associated with rifamycin resistance in *C. difficile* without imposing a fitness cost (20), we performed a EMBL Clustal Omega-based multiple

sequence alignment (MSA) (21) on the *rpoB* genes in all isolates. We detected two *rpoB* SNPs in TGH64, namely, 1514G>A and 1644A>G, that result in Arg505Lys and Ile548Met, respectively. This combination of mutations has previously been associated with rifamycin resistance in *C. difficile* clinical isolates. Structural modeling by Dang et al. suggested that Arg505Lys results in the loss of the energetically favorable pi-stacking interactions between RRID and rifaximin, which inhibits drug binding, thereby leading to resistance (20).

Two isolates that were ribotyped as RT027, namely, TGH35 and TGH64, showed elevated vancomycin MIC (MIC = 4 μ g/mL; compared to the EUCAST breakpoint of 2 μ g/mL) (Table 1) values. We further assessed the vancomycin susceptibility of these strains via two other methods: the BHI broth microdilution, based on the CLSI guidelines, and Etest, which was conducted at LUMC. In agreement with the results of previous studies, both of these methods gave lower MIC values than were obtained via the reference agar dilution method for several strains (22, 23). However, with all three methods, the elevated vancomycin MIC in TGH35 and TGH64 persisted compared to the other strains.

CARD-based AMR prediction revealed two genes of the *vanG_{cd}* operon, namely, *vanR_{cd}* and *vanXY_{cd}* in TGH35, TGH64, and TGH120. While *vanXY_{cd}* was identical in all three isolates, the *vanR_{cd}* of TGH120 differed from the two RT027 strains (Table 1). Therefore, we performed a MSA of the entire *vanG_{cd}* operon in these isolates with the reference strains CD630 and R20291. The *vanG_{cd}* operon is absent in the TGH33, TGH51, and M68 strains. Remarkably, only one nucleotide difference was detected in the whole >6 kb *vanG_{cd}* operon comparison between the five strains: 343A>G in the *vanR_{cd}* gene of TGH35 and TGH64 (Fig. 1C). The resulting sense mutation Thr115Ala in the receptor domain of VanR_{cd} likely affects the expression of the downstream resistance genes. We reported this mutation at the ASM Microbe Annual Conference in June of 2019 (24). Later, the VanR_{cd} Thr115Ala mutation was also independently reported in seven *C. difficile* clinical isolates from the Texas Medical Center, USA as well as in two *C. difficile* clinical isolates from Israel (25). These isolates showed the constitutive expression of the *vanG_{cd}* operon and elevated MICs of vancomycin, which could be reversed in the VanR_{cd}-mutant isolates by silencing *vanG_{cd}*, whereas *vanG_{cd}* silencing had no effect on the MIC of the control R20291 strain. Shen et al. also used the structural homology modeling of VanR_{cd} to propose that the Thr115Ala substitution provides better stability for its interaction with DNA, thereby enhancing the capability for the transcriptional activation of downstream genes. Since single base pair mutations under selection can quickly lead to the development of resistance, the present work highlights the need for epidemiological surveillance to monitor the prevalence of this mutation, especially in vancomycin-treated patients, to better understand its effects on the resistance to an antibiotic that is currently crucial in the treatment of *C. difficile* infection.

Data availability. The whole-genome shotgun projects for the strains TGH35, TGH64, TGH120, TGH33, and TGH51 have been deposited into DDBJ/ENA/GenBank under the accession numbers [JAJNGZ000000000](https://www.ncbi.nlm.nih.gov/nuccore/JAJNGZ000000000), [JAJNHA000000000](https://www.ncbi.nlm.nih.gov/nuccore/JAJNHA000000000), [JAJNHBO000000000](https://www.ncbi.nlm.nih.gov/nuccore/JAJNHBO000000000), [JAJNHCO000000000](https://www.ncbi.nlm.nih.gov/nuccore/JAJNHCO000000000), and [JAJNHDO000000000](https://www.ncbi.nlm.nih.gov/nuccore/JAJNHDO000000000), respectively.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, PDF file, 0.05 MB.

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