Emerging Azithromycin Resistance among the Neisseria gonorrhoeae Strains Isolated in Danyang, China

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ABSTRACT

Neisseria gonorrhoeae is a human pathogen. Strain identification and effective antibiotic treatment are the main ways to prevent and control gonorrhea, but N. gonorrhoeae is now resistant to most antibiotics, and there is no vaccine available. The main purpose of this study was to understand the molecular characteristics of clinical isolates of N. gonorrhoeae and their resistance to azithromycin (AZM) in Danyang, China. Firstly, the clinical isolates of N. gonorrhoeae from January 2016 to December 2020 were collected by Matrix-Assisted Laser Desorption Ionization-Time of Flight Mass Spectrometry (MALDI-TOF MS). Secondly, the drug sensitivity of all clinical isolates was analyzed. Thirdly, polymerase chain reaction (PCR) and DNA sequencing were used to analyze the genes related to AZM resistance (AZM-R), including 23s rRNA allele mutation, mtrR promoter and coding region mutation, rplD and rplV mutation. Finally, the clinical isolates resistant to AZM were typed by N. gonorrhoeae multiantigen sequence typing (NG-MAST). 388 clinical isolates of N. gonorrhoeae were identified, of which 373, 329, 298, 5, 11 and 5 strains were resistant to ciprofloxacin, penicillin, tetracycline, AZM, spectinomycin and ceftriaxone, respectively. The mutation detection of AZM-R related gene showed that there were single (A) nucleotide deletion mutation in mtrR promoter region, G45D mutation in mtrR coding region, G70 mutation in rplD and A2047G mutation in 23s rRNA allele, but no mutation was found in rplV. A total of 8 different STs were identified in 5 AZM-R strains, of which two ST1866 isolates showed a high level of AZM-R. The clinical isolates of N. gonorrhoeae in Danyang have high genetic diversity. ST1866 isolates showed a high level of AZM-R. Therefore, measures should be taken to monitor the spread of ST1866 N. gonorrhoeae clones in eastern China.

INTRODUCTION

Neisseria gonorrhoeae is a human-specific pathogen, causing 78 million new gonorrhea infections worldwide every year (Zhu et al., 2016; Ma et al., 2017; Lovett and Duncan, 2018; Quillin and Seifert, 2018). Gonorrhea can lead to serious complications, such as epididymitis in men and pelvic inflammation in women. Pelvic inflammation can result in involuntary infertility and ectopic pregnancy (Mitchell and Prabhu, 2013; Peters et al., 2021; Pottorff et al., 2021). This is because the loss of genitals in patients with HIV infection increases the virus.
Identification of strains and effective antibiotic treatment are the main ways to prevent and control gonorrhea, but *N. gonorrhoeae* are now resistant to most antibiotics and no vaccine is available (Abbasi, 2017; Baarda et al., 2018; Vincent and Jerse, 2019). Now, the double antimicrobial therapy of ceftriaxone and azithromycin (AZM) has been widely accepted worldwide, as an empirical first-line treatment for gonorrhea (Maldonado and Takhar, 2013; Unemo et al., 2021), including China (Chen et al., 2014). In most countries, 2 g AZM single therapy is used for treatment of pairs β-Gonorrhea in patients with lactam allergy. The results show that *N. gonorrhoeae* will produce resistance after introducing a new antimicrobial agent and replace the sensitive bacterial population within 20 years (Unemo and Dillon, 2011). Therefore, it is necessary to strengthen the monitoring of *N. gonorrhoeae* resistance.

In the 1990s, AZM became the first choice drug for many infectious diseases, but it was reported that AZM had drug resistance in the past decade (Steingrimsson et al., 1990). AZM was recommended to Chinese patients with mixed infection of gonorrhoea and Chlamydia trachomatis around 2000 (Duan et al., 2019), and was widely used because of its wide availability and easy management. However, the widespread use of AZM may lead to resistance of *N. gonorrhoeae*. AZM resistance (AZM-R) *N. gonorrhoeae* was first found in China from 2001 to 2003, and AZM-R isolates were first identified in Guangzhou in 2009 (Liang et al., 2016). In the following years, AZM-R isolates and multi drug resistant isolates were reported in Nanjing, Hangzhou and Changsha (Ni et al., 2016; Wan et al., 2018; Yan et al., 2019; Yuan et al., 2019). Until 2013, little was known about the types of AZM-R *N. gonorrhoeae* prevalent in China. Therefore, the level of AZM-R and the molecular characteristics of AZM-R *N. gonorrhoeae* are still unclear (Jiang et al., 2017).

The multidrug resistance of *N. gonorrhoeae* is related to the overexpression of efflux pump. The most important efflux mechanism is the MtrC-MtrD-MtrE system, which is encoded by the mtr operon, in which mtrR is the regulatory gene and mtrCDE is the structural gene (Lucas et al., 1997). Another efflux pump encoded by mef gene was first found in some gram-positive bacteria and then in clinical strains of gonorrhea (Luna et al., 2000).

In the mtrR gene, specific mutations in the promoter or coding region can lead to decrease the MtrCDE efflux pump repression and subsequently increase export of the antimicrobial. Mutations in the promoter or coding sequence of mtrR gene of macrolide resistant *N. gonorrhoeae* can reduce the expression of mtrR repressor and up regulate mtrCDE efflux pump (Chen et al., 2019). In *N. gonorrhoeae*, there was a single base pair (A) deletion in the 13 bp reverse repeat of mtrR promoter region, the expression of mtrR was cancelled, and the level of mtrCDE increased, most likely because the binding affinity of RNA polymerase to mtrCDE increased (Handing et al., 2018). Missense mutations in the mtrR, such as G45D mutation in the helix trans helix motif in the mtrR repressor, can reduce the binding of the repressor to the mtrCDE promoter. The increased expression of mtrCDE efflux pump also increased AZM.

Further resistance to AZM is the result of 23S rRNA loop V mutation, which is a specific target of AZM. AZM exerts its bacteriostatic effect by directly interacting with the central ring of rrl gene domain V encoding 23S rRNA, resulting in obstruction of protein synthesis (Pham et al., 2021). Specific point mutations in this region may lead to drug resistance by reducing the affinity of AZM to its target (Zhang and van der Veen, 2019). 23S rRNA point mutations have been described, including C2611T (numbering refers to the *E. coli* genome), given low to medium levels of AZM-R (minimum inhibitory concentration MIC = 2 to 32μg/mL) or A2059G (*E. coli* numbering), awarded high level AZM-R (MICs ≥ 256 μg/mL) (Demczuk et al., 2016).

Ribosomal proteins L4 (encoded by rplD) and L22 (encoded by rplV) bind to domain I of 23S rRNA and act as channels for macrolide antibiotics to enter ribosomes (Reinert and Al-Lahham, 2005; Chisholm et al., 2010). Point mutations of rplD and rplV in *E. coli* and *Streptococcus pneumoniae* lead to resistance to macrolides; However, this mutation is rarely detected in patients with gonorrhea.

In the absence of new antibiotics for the treatment of gonorrhea, it is important to classify the emergence and dynamics of AZM-R *N. gonorrhoeae* on a regional and national basis for the successful updating of treatment recommendations. The resistance level of *N. gonorrhoeae* to azithromycin in Danyang area of eastern China is still unclear. The purpose of this study was to investigate the prevalence and molecular typing of *N. gonorrhoeae* in Danyang City.

**MATERIALS AND METHODS**

*N. gonorrhoeae* isolation and species verification

The patients with *N. gonorrhoeae* infection were identified by consulting the microbiological laboratory records of Danyang people’s Hospital of Jiangsu Province from January 2016 to December 2020. Clinical isolates are anonymous, so this study does not require ethical approval. There is no standard for selecting strains. The clinical data, such as gender and age and infection site, were
recorded. Species verification is performed biochemically using Matrix-Assisted Laser Desorption Ionization-Time of Flight Mass Spectrometry (MALDI-TOF MS) using VITEK-MS (bioMérieux).

Antimicrobial susceptibility testing

The susceptibility of *N. gonorrhoeae* to penicillin, tetracycline, ciprofloxacin, spectinomycin, ceftriaxone and AZM was determined by E-test. The results of the E-test were interpreted according to the guidelines for all antibiotics of the Institute of clinical and laboratory standards (Palmeira and Ferreira, 2019). All the strains were stored in glycerine broth and stored at -80°C until use. The quality control strain of drug sensitivity test was *N. gonorrhoeae* ATCC 49226, which was provided by the laboratory of the Ministry of Health and kept in our laboratory. The strain was stored in liquid medium of glycerine broth.

Genetic determinants associated with resistance to AZM

Genomic DNA, was extracted using DNA rapid extraction kit (Shanghai Shenggong) and stored at -20°C. To identify site-specific mutations, we sequenced the genes associated with AZM-R, including 23s rRNA allele, *rplD* and *rplV* (encoding ribosomal proteins L4 and L22, respectively), as well as *mtrR* promoter and coding region. The primers and conditions for PCR have been previously published (Allen et al., 2011; Zheng et al., 2019). PCR products were bidirectionally sequenced by Applied Biosystems 3730xl DNA automatic sequencer. DNA sequences were compared with BLAST and GenBank database. No mutation was detected in these controls included single nucleotide (A) deletion in the promoter region of *mtrR*, G70D in the *mtrR* coding region, and A2047G in the 23s rRNA allele (GenBank accession number: X67293.1) (Table I). Four allele mutations in 23s rRNA were detected in a gonorrhea isolate with high level of AZM-R. No mutation was detected in *rplV*.

Five azithromycin sensitive (AZM-S) strains were randomly selected as control group. The mutations detected in these controls included single nucleotide (A) deletion in the *mtrR* promoter region and G45D in the *mtrR* coding region in the three isolates (Table I). No mutation was found in *rplD* and *rplV* genes and 23s rRNA alleles in AZM-S group.

Molecular epidemiologic typing

Five AZM-R *N. gonorrhoeae* isolates were genotype by NG-MAST, and 8 different sequence types of (STs) were identified. ST1866 were the most common isolates of ST, followed by ST4007, ST1407, ST12746, ST3287, ST1731, ST2286, ST2318 and ST12660. Both ST1866 isolates (which were not associated with each other in epidemiology) displayed high levels of AZM-R. All the 8 STs found in this study have been reported in NG-MAST database.

Based on phylogenetic analysis, there are four
and ST2318). Group B strains include two different STs (ST12746 and ST1866). Group C strains are composed of three different STs (ST4007, ST1407, ST1731 and ST12660). Finally, the AZM-S cluster D contains a different ST (ST3287). Group A strains include two different STs (ST2286 and ST1866). Group B strains include two different STs (ST2318). Group C strains are composed of three different STs (ST4007, ST1407, ST1731 and ST3287). Finally, the AZM-S cluster D contains a different ST (ST12660).

DISCUSSION

In this study, the drug sensitivity test of N. gonorrhoeae in Danyang area from 2016 to 2020 was combined with AZM-R molecular typing. This study found for the first time that AZM-R began to appear in Danyang area, which was consistent with the previous reports from China (Yuan et al., 2011; Chen et al., 2013; Yuan et al., 2019). World Health Organization (WHO) suggested that once 5 per cent of locally acquired N. gonorrhoeae isolates develop drug resistance, the empirical use of antibiotics should be stopped. Therefore, AZM is not recommended as a monotherapy for gonococcal urethritis or cervicitis in China and many other countries in the world. To improve treatment effectiveness and delay further selection of cephalosporin-resistant N. gonorrhoeae, most current guidelines recommend a dual treatment regimen of ceftriaxone (250mg or 500mg intramuscular injection) or cefixime (400mg, if no ceftriaxone option) combined with AZM (1g or 2g oral) in the treatment of gonorrhea. However, in recent years, the decreased sensitivity of AZM-R N. gonorrhoeae to extended-spectrum cephalosporins has been reported, which seriously threatens the future efficacy of current treatment recommendations.

In recent years, there have been studies on AZM-R N. gonorrhoeae in China. For example, 32% of the isolates showed AZM-R, and 10% showed high level of drug resistance (Zheng et al., 2019). The analysis of 126 strains isolated from Hefei from 2014 to 2015 showed that 29% of the strains were AZM-R, and 10% of them showed high level of AZM-R.

Mutations in the promoter or coding sequence of mtrR gene in macrolide resistant N. gonorrhoeae strains can reduce the expression of mtrR repressor, resulting in the up regulation of mtrCDE efflux pump (Ohneck et al., 2015). In N. gonorrhoeae, there was A-deletion in the 13 bp reverse repeat of mtrR promoter, which overlaps the mtrCDE promoter at the -35 region, mtrR expression was cancelled, and mtrCDE expression was increased, which was probably because RNA polymerase had greater binding affinity for mtrCDE (Johnson and Shafer, 2015). N. gonorrhoeae resistant to macrolides can reduce the expression of MtrR repressor and up-regulate MtrCDE efflux pump (Ng et al., 2002; Cousin et al., 2003; Fernandez-Huerta and Espasa, 2019; Hall et al., 2019; Ma et al., 2020). In N. gonorrhoeae strains with deletion of 13-bp reverse repeat sequence in MtrR promoter region, the expression of MtrR was cancelled and the level of MtrCDE increased, which was probably due to the increase of binding affinity of RNA polymerase to mtrCDE (Rouquette et al., 1999). Missense mutations in the mtrR (Handing et al., 2018; Beggs et al., 2021), such as the G45D mutation in the helix-to-helix motif of the mtrR repressor, can reduce the binding of the repressor to the mtrCDE promoter. In this study, the mutation rates of mtrR promoter and coding region of AZM-R strain were...
100.0% and 60%, respectively. The mutation rate of mtrR promoter region in AZM-R group was significantly higher than that in AZM-S group, but there was no significant difference in mtrR coding region. This is consistent with the previously reported results that the mutation in the mtrR promoter region plays a more important role in the resistance of N. gonorrhoeae to azithromycin than the mutation in the mtrR coding region.

AZM exerts its bacteriostatic effect by directly interacting with the central ring of RRL gene domain V encoding 23S rRNA, resulting in obstruction of protein synthesis (Wu et al., 2011; Trembizki et al., 2015). Specific point mutations in this region may lead to drug resistance by reducing the affinity of azithromycin to its target (Ng et al., 2002; Chisholm et al., 2010; Galarza et al., 2010). The HL-AZM-R isolate had A2143G mutation in at least three of the four alleles. Including A2143G (the number in E. coli corresponds to A2059) or C2599T (the number in E. coli corresponds to C2611T) (Ng et al., 2002). Previous studies have reported that one or more of the four alleles of rrl gene in 23s rRNA domain V are associated with AZM-R, including mutation, A2059G and C2611T (corresponding to A2059G and C2611T in E. coli, respectively) (Belkacem et al., 2016). In this study, A2047G mutation was detected in the region of AZM-R gonorrhea virus, but not in AZM-S group. The 23s rRNA alleles of A2047G mutation were alleles 1 and 2, alleles 1 and 2 and 3, alleles 1 and 4, alleles 1 and 2 and 3 and 4, respectively, and the corresponding MIC values were 1 μg/mL, 4 μg/mL, 4 μg/mL and 16 μg/mL, respectively. It is worth noting that A2047G mutation was detected in all strains with MIC > 16 μg/mL. Therefore, we believe that A2047G allele is the main determinant of AZM-R.

The rplD mutation (G70D) of a N. gonorrhoeae isolate to AZM was 16 μg/mL, which was consistent with the previously reported results (Jacobsson et al., 2016). G68D and G70D were previously described by (Zheng et al., 2019), so the mutation at position 68-70 of the rplD gene of N. gonorrhoeae seems to be associated with a high level of AZM resistance. The mutant of rplD gene belongs to group B, and the NG-MAST classification of ST1866, indicates that the mutant has genetic diversity.

Gonorrhea typing methods, such as NG-MAST, are helpful to understand the spread of gonorrhea. In this study, phylogenetic analysis showed that AZM-R strains had wide differences and did not belong to any specific group. Different from the reports of other countries, the isolates with high level of AZM-R in this study belong to NG-MAST-ST1866. It is worth mentioning that the high-level N. gonorrhoeae AZM-R found in this study has the same NA-MAST type as the high-level N. gonorrhoeae AZM-R found in the Liu-YH report, which indicates that the transmission of NG-MAST ST1866 N. gonorrhoeae has occurred across the Taiwan Strait. In addition, NG-MAST ST1866 clones have been reported in Nanjing, Hangzhou and Hefei (Ni et al., 2016; Jiang et al., 2017; Wan et al., 2018), which indicates that the clone has a high level of AZM-R, has spread in eastern China, which is a matter of concern, which must be paid attention to.

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Ethics approval

Because the N. gonorrhoeae were part of the routine hospital laboratory procedures, ethics approval was not required.

Statement of conflict of interest

The authors have declared no conflicts of interest.

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