Diverse carbapenem-resistance mechanisms in 16S rRNA methylase-producing Acinetobacter baumannii

Yuki Yamada and Akira Suwabe

Correspondence
Yuki Yamada
yuyamada@iwate-med.ac.jp

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Multidrug-resistant Acinetobacter baumannii has become a global problem. This study characterized amikacin-resistant A. baumannii isolated from eight patients during April 2010–March 2011 in our university hospital and examined the possible mechanisms in three cases in which carbapenem susceptibility changed to carbapenem resistance during treatment of the patients. The armA gene, which is one of the 16S rRNA methylase genes and is associated with high MICs of aminoglycosides, was positive in all isolates. The blaOXA-51 gene and ISAba1-blaADC were positive in all isolates, but ISAba1-blaOXA-51 was positive in only three isolates. The CarO outer-membrane protein was lost in one isolate. In the first case, both the susceptible and the resistant isolates were positive for ISAba1-blaOXA-51, but the expression of the blaADC gene was increased 3.1-fold in the carbapenem-resistant isolate of the pair. In the second case, the carbapenem-resistant strain became positive for ISAba1-blaOXA-51, resulting in 21.5-fold increased expression of blaOXA-51, compared to the carbapenem-susceptible strain of the pair. In the third case, the carbapenemase genes remained negative despite the carbapenem resistance, but the expression of the adeB gene was increased 4.6-fold after acquisition of carbapenem resistance. Multilocus sequence typing analysis of two isolates showing representative pulsed-field gel electrophoresis patterns demonstrated that both isolates were classified to sequence type 2 (ST2). These results showed that the 16S rRNA methylase-producing A. baumannii, initially susceptible to carbapenem, acquired carbapenem resistance via diverse mechanisms.

INTRODUCTION

Acinetobacter baumannii is an important pathogen causing ventilator-associated pneumonias, bloodstream infections and wound infections in severely ill patients. Recently, hospital-acquired infection caused by multidrug-resistant A. baumannii that has acquired resistance to antibiotic agents such as carbapenems, fluoroquinolones and aminoglycosides has become a global problem (Peleg et al., 2008; Perez et al., 2007).

Amikacin (AMK), an aminoglycoside agent, has retained good activity against A. baumannii. Consequently, it has become difficult to treat A. baumannii if they show resistance to AMK. Resistance to aminoglycosides has been attributed mainly to enzymic inactivation by acetyltransferases, nucleotidyltransferases and phosphotransferases. In recent years, however, methylation of 16S rRNA has been reported to play an important role in aminoglycoside resistance by blocking the binding of these antibiotics to 16S rRNA. 16S rRNA methylases are often responsible for the phenotype of Gram-negative pathogens that show high MICs to most aminoglycosides. Seven types of 16S rRNA methylases have been identified: ArmA, RmtA, RmtB, RmtC, RmtD, RmtE and NpmA (Wachino et al., 2010). The ArmA methylase was first reported in a strain of Klebsiella pneumoniae in France (Galimand et al., 2003). Subsequently, ArmA methylase-producing A. baumannii were detected in Korea (Lee et al., 2006). Carbapenem-resistant ArmA methylase-producing A. baumannii strains have more recently been reported in the USA (Adams-Haduch et al., 2008) and in China (Yu et al., 2007). The dissemination of such clinical isolates with multidrug resistance has become a global threat. Yamane et al. (2007) reported that four (0.13 %) ArmA methylase-positive isolates were found out of 3116 A. baumannii in Japan, but these were susceptible to carbapenems.

The mechanisms of carbapenem resistance of A. baumannii have been explained by production of plasmid-encoded carbapenemases such as the OXA carbapenemases and metallo-ß-lactamases (MBLs), and by increased production of carbapenem resistance via diverse mechanisms.
of chromosome-encoded carbapenemases as a result of insertion of ISAba1 into the upstream region of the blaOXA-51 gene, providing a strong promoter. Aside from carbapenemases, other mechanisms include decreased expression of outer-membrane proteins (OMPs), overexpression of multidrug efflux pumps and alteration in the affinity of penicillin-binding proteins (Dijkshoorn et al., 2007).

The purposes of this study were to characterize six isolates of AMK-resistant A. baumannii from three patients in our university hospital during April 2010–March 2011 and to examine possible mechanisms of carbapenem resistance in three of six isolates in which carbapenem susceptibility changed to carbapenem resistance during treatment of the patients.

METHODS

Bacterial isolates and susceptibility testing. Six isolates of AMK-resistant A. baumannii obtained from three patients during April 2010–March 2011 were used for this study. Biochemical identification and antimicrobial susceptibility testing of isolates were conducted using a Vitek 2 Compact Automated System (BioMérieux). Criteria for antimicrobial susceptibility were based on guidelines established by the Clinical and Laboratory Standards Institute (CLSI, 2009).

Susceptibility testing results of these isolates are presented showing the same PFGE pattern, representative isolates (1a and 3a) were chosen for MLST analysis. Multilocus sequence typing (MLST) analysis. We conducted MLST analysis using the Institut Pasteur’s MLST scheme (http://www.pasteur.fr/recherche/genopole/PF8/mlst/Abaumannii.html), as previously described (Diancourt et al., 2010). Among the isolates showing the same PFGE pattern, representative isolates (1a and 3a) were chosen for MLST analysis.

RESULTS

Susceptibility testing

Sixty-three unique isolates of A. baumannii were detected in our clinical microbiology laboratory during the study period. Among these, the isolates from eight patients were AMK-resistant but were initially susceptible to carbapenems regardless of antimicrobial agent use. Carbapenem-resistant strains were, however, isolated later from three patients. Susceptibility testing results of these isolates are presented in Table 1. All isolates were resistant to cephalosporins,

Table 1. Susceptibility tests of A. baumannii isolates

<table>
<thead>
<tr>
<th>Patient</th>
<th>Strain</th>
<th>Date of isolation (dd/mm/yyyy)</th>
<th>Source</th>
<th>PIPC CAZ CZOP CFPM IPM MEPM S/C</th>
<th>GM</th>
<th>AMK TOB</th>
<th>CPFX LVFX MINO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1a</td>
<td>12/07/2010 Sputum</td>
<td></td>
<td>&gt;64 &gt;16 &gt;16 8 16 2 4</td>
<td>≤16 &gt;16 &gt;32 &gt;8 &gt;2 4 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1b</td>
<td>01/09/2010 Sputum</td>
<td></td>
<td>&gt;64 &gt;16 &gt;16 16 4 &gt;8 ≤16 &gt;16 &gt;32 &gt;8 &gt;2 &gt;4 4</td>
<td>GM</td>
<td>AMK TOB</td>
<td>CPFX LVFX MINO</td>
</tr>
<tr>
<td>2</td>
<td>2a</td>
<td>13/12/2010 Central venous catheter</td>
<td></td>
<td>&gt;64 &gt;16 &gt;16 8 16 2 &gt;1 &gt;32 &gt;8 &gt;32 &gt;8 &gt;2 &gt;4 4</td>
<td>GM</td>
<td>AMK TOB</td>
<td>CPFX LVFX MINO</td>
</tr>
<tr>
<td>2</td>
<td>2b</td>
<td>17/01/2011 Sputum</td>
<td></td>
<td>&gt;64 &gt;16 &gt;16 8 &gt;16 4 &gt;8 &gt;32 &gt;8 &gt;32 &gt;8 &gt;2 &gt;4 4</td>
<td>GM</td>
<td>AMK TOB</td>
<td>CPFX LVFX MINO</td>
</tr>
<tr>
<td>3</td>
<td>3a</td>
<td>18/01/2011 Sputum</td>
<td></td>
<td>&gt;64 &gt;16 &gt;16 &gt;16 2 4 &gt;32 &gt;8 &gt;32 &gt;8 &gt;2 &gt;4 4</td>
<td>GM</td>
<td>AMK TOB</td>
<td>CPFX LVFX MINO</td>
</tr>
<tr>
<td>3</td>
<td>3b</td>
<td>08/02/2011 Blood culture</td>
<td></td>
<td>&gt;64 &gt;16 &gt;16 &gt;16 &gt;8 &gt;8 &gt;32 &gt;8 &gt;32 &gt;8 &gt;2 &gt;4 4</td>
<td>GM</td>
<td>AMK TOB</td>
<td>CPFX LVFX MINO</td>
</tr>
</tbody>
</table>

MIC values (mg L⁻¹) are shown. PIPC, piperacillin; CAZ, ceftazidime; CZOP, cefozopran; CFPM, cefepime; IPM, imipenem; MEPM, meropenem; S/C, sulbactam/cefoperazone; GM, gentamicin; AMK, amikacin; TOB, tobramycin; CPFX, ciprofloxacin; LVFX, levofloxacin; MINO, minocycline.
fluoroquinolones and aminoglycosides (gentamicin, AMK, tobramycin). Carbapenem-resistant strains developed from isolates 1b, 2b and 3b. In addition, these strains were negative both for the modified Hodge test and for the confirmatory test using the SMA disk for MBL.

**DNA amplification analysis**

The bla<sub>IMP-1</sub>, bla<sub>IMP-2</sub>, bla<sub>VIP-2</sub>, bla<sub>OXA-23</sub>, bla<sub>OXA-24</sub> and bla<sub>OXA-58</sub> genes were not detected from these six isolates. The bla<sub>OXA-51</sub> gene and ISA<sub>ba1</sub> were positive in all isolates, but ISA<sub>ba1</sub>-bla<sub>OXA-51</sub> was positive only in nos. 1a, 1b and 2b (Table 2). ISA<sub>ba1</sub>-bla<sub>ADC</sub> was positive in all six isolates (Table 2). The arm<sub>A</sub> gene, which confers high resistance to aminoglycosides, was positive in all isolates (Table 2). The carO gene, which encodes an OMP, was positive in these six isolates. However, a PCR amplicon for the carO gene (approx. 1700 bp), which was larger than the expected size of 741 bp, was obtained from one isolate (2b) (Table 2).

**Expression of bla<sub>OXA-51</sub>, bla<sub>ADC</sub> and adeB**

In the first case, both isolates were positive for ISA<sub>ba1</sub>-bla<sub>OXA-51</sub>, but the expression of the bla<sub>ADC</sub> gene was increased 3.1-fold in the carbapenem-resistant isolate of the pair. In the second case, the carbapenem-resistant strain became positive for ISA<sub>ba1</sub>-bla<sub>OXA-51</sub>, resulting in 21.5-fold increased expression of bla<sub>OXA-51</sub> compared to the carbapenem-susceptible strain of the pair. In the third case, the carbapenemase genes remained negative despite the carbapenem resistance, but the expression of the adeB gene was increased 4.6-fold after acquisition of carbapenem resistance (Table 2).

**PFGE and MLST analyses**

Six isolates were classified to type I (isolates 1a and 1b) and type II (isolates 2a, 2b, 3a and 3b) based on the PFGE pattern. Type I and type II were demonstrated to be closely related clones (data not shown).

MLST analysis for two isolates (1a and 2a) of type I and II, showing representative PFGE patterns, demonstrated that both isolates belonged to sequence type 2 (ST2).

**DISCUSSION**

This study investigated the mechanisms by which ArmA methylase-producing A. baumannii developed carbapenem resistance in three isolates. The clones from two patients (cases 2 and 3) were proven to be identical by PFGE analysis, but the mechanisms of carbapenem resistance in the three isolates differed.

The loss of a 29 kDa OMP, also known as CarO, is reportedly associated with carbapenem resistance (Peleg et al., 2008). Efflux pumps such as AdeABC are also reportedly involved in multidrug resistance (Vila et al., 2007). AdeABC, a resistance-nodulation-division (RND) family-type pump, has a three-component structure of AdeA, AdeB and AdeC, which form the inner membrane fusion protein, the transmembrane component and the OMP, respectively. AdeABC is chromosomally encoded and is normally regulated by a two-component system with a sensor kinase (AdeS) and its associated response regulator (AdeR). Overexpression of adeB has been attributed to mutations in the adeS and adeR genes and also to insertion of ISA<sub>ba1</sub> into the adeS gene, thereby resulting in multidrug resistance in A. baumannii (Coyne et al., 2011). However, the reduced permeability alone is not sufficient to cause carbapenem resistance (Peleg et al., 2008).

The insertion sequence element ISA<sub>ba1</sub> provides a promoter in the upstream region of the bla<sub>OXA-51</sub> and bla<sub>ADC</sub> genes. In this study, all strains were positive for ISA<sub>ba1</sub>. Furthermore, in all strains, ISA<sub>ba1</sub> was inserted in the upstream region of bla<sub>ADC</sub>, suggesting potential overproduction of the ADC β-lactamase. The change from carbapenem susceptibility in isolate 1a to carbapenem resistance in isolate 1b was ascribed to an increased expression of ADC β-lactamase (Table 2). In strain 2b, in which ISA<sub>ba1</sub>-bla<sub>OXA-51</sub> was positive, the expression of bla<sub>OXA-51</sub> was increased (Table 2). The carO gene encoding an OMP was positive in these six isolates. However, a PCR amplicon for the carO gene of approximately 1700 bp, which was larger than the expected size of 741 bp, was obtained from strain 2b, suggestive of a CarO OMP defect. Lee et al. (2011) and Lu et al. (2009) reported that the loss of the CarO OMP had only a minor effect on carbapenem resistance in A. baumannii. Brattu et al. (2008) reported that the loss of the CarO OMP did not correlate with carbapenem resistance. However, resistance to

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**Table 2. Epidemiological and genotypic characteristics of A. baumannii isolates**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Strain</th>
<th>PFGE</th>
<th>ArmA</th>
<th>IMP-1</th>
<th>IMP-2</th>
<th>VIM-2</th>
<th>bla&lt;sub&gt;OXA-51&lt;/sub&gt;</th>
<th>ISA&lt;sub&gt;ba1&lt;/sub&gt;-bla&lt;sub&gt;OXA-51&lt;/sub&gt;</th>
<th>ISA&lt;sub&gt;ba1&lt;/sub&gt;-bla&lt;sub&gt;ADC&lt;/sub&gt;</th>
<th>Status of CarO</th>
<th>Relative expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1a</td>
<td>I</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>Intact</td>
<td>adeB 1.0</td>
</tr>
<tr>
<td>1</td>
<td>1b</td>
<td>I</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>Intact</td>
<td>adeB 1.0</td>
</tr>
<tr>
<td>2</td>
<td>2a</td>
<td>II</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>Intact</td>
<td>adeB 0.9</td>
</tr>
<tr>
<td>2</td>
<td>2b</td>
<td>II</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>Lost</td>
<td>adeB Intact</td>
</tr>
<tr>
<td>3</td>
<td>3a</td>
<td>II</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>Intact</td>
<td>adeB 1.0</td>
</tr>
<tr>
<td>3</td>
<td>3b</td>
<td>II</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>Intact</td>
<td>adeB 4.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gene</th>
<th>1a</th>
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<th>2a</th>
<th>2b</th>
<th>3a</th>
<th>3b</th>
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<tr>
<td>adeB</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>bla&lt;sub&gt;ADC&lt;/sub&gt;</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>bla&lt;sub&gt;OXA-51&lt;/sub&gt;</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

**Notes:**
- **Patient Strain:** Classification of the patient strain.
- **PFGE:** Phenotypic fingerprinting by gel electrophoresis.
- **ArmA:** Presence of the armA gene.
- **IMP-1:** Presence of the IMP-1 gene.
- **IMP-2:** Presence of the IMP-2 gene.
- **VIM-2:** Presence of the VIM-2 gene.
- **bla<sub>OXA-51</sub>:** Presence of the bla<sub>OXA-51</sub> gene.
- **ISA<sub>ba1</sub>-bla<sub>OXA-51</sub>:** Presence of the ISA<sub>ba1</sub>-bla<sub>OXA-51</sub> element.
- **ISA<sub>ba1</sub>-bla<sub>ADC</sub>:** Presence of the ISA<sub>ba1</sub>-bla<sub>ADC</sub> element.
- **Status of CarO:** Presence or absence of the carO gene.
- **Relative expression:** Ratio of expression levels compared to the wild type.
carbapenem resistance via mechanisms of various kinds. Furthermore, these isolates acquired susceptibility to carbapenem initially, but acquired carbapenem resistance following exposure to antimicrobial agents, including carbapenem.

The first isolates (1a, 2a and 3a) from our three patients were all resistant to fluoroquinolones and aminoglycosides, but were susceptible to carbapenems based on the criteria of CLSI (2009).

Three carbapenem-resistant strains (1b, 2b and 3b) were isolated after treatment with carbapenems and other antimicrobial agents (data not shown). These results suggested that A. baumannii has the propensity to develop resistance by rapid mutation upon exposure to antimicrobial agents. However, the relations between treatment with carbapenems and the mechanism of carbapenem resistance still needed to be clarified.

Three outbreak clones of multidrug-resistant A. baumannii have been described, namely international clones I, II and III (Diancourt et al., 2010). In this study, the isolated clones were demonstrated to be ST2, which belongs to international clone II. Such ST2 clones have been reported in Italy, Greece (Di Popolo et al., 2011), the Czech Republic (Nemec et al., 2008), the USA (Adams-Haduch et al., 2011) and the UK (Zarrilli et al., 2011). We need to continue observations of the epidemic spread of 16S rRNA methylase-producing A. baumannii infections in a hospital setting.

In summary, ArmA methylase-producing A. baumannii showed susceptibility to carbapenem initially, but acquired multi-antibiotic resistance immediately after the use of antibacterial agents. Furthermore, these isolates acquired carbapenem resistance via mechanisms of various kinds.

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