Molecular characterisation of the first New Delhi metallo-\(\beta\)-lactamase 1-producing *Acinetobacter baumannii* from Tanzania

Sabrina J. Moyo\(^a\), Joel Manyah\(^a\), Alasdair T. M. Hubbard\(^c\), Rachel L. Byrne\(^c\), Nahya Salim Masoud\(^d\), Said Aboud\(^b\), Karim Manji\(^d\), Bjørn Blomberg\(^e\), Nina Langeland\(^e\), and Adam P. Roberts\(^c\)

\(^a\)Department of Clinical Science, University of Bergen, Norway; \(^b\)Department of Microbiology and Immunology, Muhimbili University of Health and Allied Sciences, MUHAS, Dar es Salaam, Tanzania; \(^c\)Department of Tropical Disease Biology, Liverpool School of Tropical Medicine, Liverpool, L3 5QA, UK; \(^d\)Department of Paediatrics and Child Health, Muhimbili University of Health and Allied Sciences, MUHAS, Dar es Salaam, Tanzania; \(^e\)Norwegian National Advisory Unit for Tropical Infectious Diseases, Haukeland University Hospital, Bergen, Norway

\(^*\)Corresponding author: Tel: +44 744 4244 537; E-mail: sabrina.moyo@uib.no

Received 3 September 2020; revised 1 December 2020; editorial decision 8 December 2020; accepted 22 December 2020

**Background:** We aimed to characterise the genetic determinants and context of two meropenem-resistant clinical isolates of *Acinetobacter baumannii* isolated from children hospitalised with bloodstream infections in Dar es Salaam, Tanzania.

**Methods:** Antimicrobial susceptibility was determined by disc diffusion E-test and broth microdilution. Genomes were completed using a hybrid assembly of Illumina and Oxford Nanopore Technologies sequencing reads and characterisation of the genetic context of resistance genes, multi-locus sequence types (STs) and phylogenetic analysis was determined bioinformatically.

**Results:** Twelve *A. baumannii* were isolated from 2226 blood cultures, two of which were meropenem-resistant. The two meropenem-resistant isolates, belonging to distinct STs, ST374 and ST239, were found to harbour \(^bla\)NDM-1, which was chromosomally located in isolate DT0544 and plasmid-located in isolate DT01139. The genetic environment of \(^bla\)NDM-1 shows the association of insertion sequence ISAba\(^{125}\) with \(^bla\)NDM-1 in both isolates. Both isolates also harboured genes conferring resistance to other \(\beta\)-lactams, aminoglycosides and cotrimoxazole.

**Conclusions:** This is the first report of New Delhi metallo-\(\beta\)-lactamase-producing isolates of *A. baumannii* from Tanzania. The genetic context of \(^bla\)NDM-1 provides further evidence of the importance of ISAba\(^{125}\) in the spread of \(^bla\)NDM-1 in *A. baumannii*. Local surveillance should be strengthened to keep clinicians updated on the incidence of these and other multidrug-resistant and difficult-to-treat bacteria.

**Keywords:** *Acinetobacter baumannii*, antimicrobial resistance mechanisms, bloodstream infections, New Delhi metallo-\(\beta\)-lactamase 1, Tanzania

**Introduction**

*Acinetobacter baumannii* is a Gram-negative, opportunistic pathogen that can cause infections of multiple body sites, including the bloodstream, lungs and urinary tract.\(^3\) *Acinetobacter baumannii* infections are often difficult to treat because of intrinsic and acquired resistance mechanisms and are associated with poor clinical outcomes.\(^2\) Carbapenems are indispensable last-resort antibiotics for severe infections caused by multidrug-resistant bacteria, although they are expensive and largely unavailable in low-income settings. The clinically important \(\beta\)-lactamase New Delhi metallo-\(\beta\)-lactamase 1 (NDM-1), which confers resistance to carbapenems, was first reported in *A. baumannii* in India\(^a\) and NDM-1-producing *A. baumannii* have since been reported from northern and eastern Africa (Algeria, Libya, Egypt, Tunisia, Kenya and Ethiopia) and South Africa.\(^5\) To the best of our knowledge, NDM-1-producing *A. baumannii* has not yet been reported in Tanzania. As *bla*NDM-1- carrying bacteria are often multidrug-resistant, infections due to NDM-1-producing *A. baumannii* may increase the risk of poor clinical outcomes due to a lack of therapeutic options. Therefore,
there is a need to report the detection, spread and molecular epidemiology of multi-drug resistant *A. baumannii*-producing NDM-1 in resource-limited settings.

In a large-scale study to determine the causes of bloodstream infections in children in Dar es Salaam, Tanzania, we detected two carbapenem-resistant isolates of *A. baumannii* in blood cultures from febrile Tanzanian children. This study was conducted to determine the mechanisms responsible for carbapenem resistance. Using whole genome sequencing (WGS) we predicted the resistance genes present in the two *A. baumannii* isolates and compared them with the corresponding phenotypic resistance. Furthermore, we characterised the genetic context of *bla*NDM-1, determined the sequence types (STs) of both isolates and placed them within the phylogenetic context of other *A. baumannii*-carrying *bla*NDM-1 previously sequenced.

### Materials and methods

#### Study population, bacteria isolation and identification

A cross-sectional study was conducted from March 2017 to July 2018. We obtained blood cultures from 2226 children aged <5 y hospitalised because of fever at Amana, Temekte and Mwananyamala Regional hospitals and Muhimbili National Hospital (MNH), Dar es Salaam, Tanzania. Blood was cultured using BACTEC FX40 system (Becton-Dickinson, Sparks, MD, USA) and the bacteria isolated were identified by Matrix-Assisted Laser Desorption/Ionization-Time Of Flight (MALDI-TOF) mass spectrometry (MS), using the Microflex LT instrument and MALDI BioTyper 3.1 software (Bruker Daltonics, Bremen, Germany).

#### Antimicrobial susceptibility testing

Antimicrobial susceptibility was determined by disk diffusion on Mueller-Hinton agar plates at 35°C and incubated for 16–18 h according to Clinical and Laboratory Standards Institute (CLSI) guidelines. Antibiotic discs included were piperacillin/tazobactam (TZP), ceftazidime, cefotaxime, meropenem, imipenem, ciprofloxacin, sulphamethoxazole/trimethoprim, gentamicin tetracycline and doxycycline (Oxoid, UK). The minimum inhibitory concentrations (MICs) for TZP, ceftazidime, cefotaxime, meropenem, imipenem, ciprofloxacin, sulphamethoxazole/trimethoprim, gentamicin tetracycline and doxycycline were determined by E-test (bioMérieux, Marcy-l’Etoile, France) following CLSI guidelines.

The MIC of colistin was determined by broth microdilution in cation-adjusted Mueller-Hinton broth according to CLSI guidelines.

#### WGS and analysis

WGS was performed using HiSeq X10 (Illumina, San Diego, CA, USA) by Microbes NG (UK), who also performed quality filtering and sequencing read trimming and MinION (Oxford Nanopore Technologies [ONT], Oxford, UK) platforms. ONT long reads were de-multiplexed with Porechop (v. 0.2.4; https://github.com/rwick/Porechop) and filtered with a quality score of 30 using Filtlong (v. 0.2.0; https://github.com/rwick/Filtlong). Long and short read sequences were assembled using Unicycler (v. 0.4.8.0) and the genome was annotated with Prokka (v. 1.14.6).

The *bla*NDM-1-carrying plasmid from isolate DT01139 and upstream and downstream of *bla*NDM-1 in the chromosome of isolate DT0544 were annotated manually using a combination of Prokka (v. 1.14.6) BLAST (v. 2.11.0), ResFinder (v. 4.1), UniProt and MobileElementFinder (v. 1.0.3) in SnapGene (v. 3.3.4) from GSL Biotech (available at snapgene.com). Comparison of the annotated plasmid from DT01139 with other *bla*NDM-1-carrying plasmids from *A. baumannii* was performed using BRIG (v. 0.95). Comparison of upstream and downstream of *bla*NDM-1 for the isolate DT01139 and DT0544 was produced using EasyFig (v. 2.2.2).

### Identification of resistance genes and multi-locus sequence typing

Prediction of antimicrobial resistance genes and multi-locus sequence typing (MLST) were carried out using ResFinder (v. 4.1) and MLST (v. 2.19.0; https://github.com/tseemann/mlst), which uses the PubMLST database (https://pubmlst.org).

#### Phylogenetic analysis

A single nucleotide polymorphism (SNP)-based phylogenetic tree was created using conserved signature inserts phylogeny server (v. 1.4), comparing the two isolates in this study to 27 published *bla*NDM-1-carrying *A. baumannii* WGS using default parameters. *Acinetobacter baumannii* ab736 [accession number NZ_CP015121] was used as the reference genome for the phylogenetic tree. The phylogenetic tree was annotated using the Interactive Tree of Life (v. 5.6.3).

### Results

#### Characteristics of the two patients with *A. baumannii*-carrying NDM-1 gene

In total, 12 *A. baumannii* isolates were identified, two of which were found to be meropenem-resistant by antimicrobial susceptibility testing and were designated as DT0544 and DT01139. The two meropenem-resistant *A. baumannii* isolates were obtained from blood cultures of neonates. Isolate DT0544 was obtained from a 4-d-old male neonate, admitted as a referral patient from a regional hospital to MNH in October 2017 with a history of fever and convulsions. This patient received ceftriaxone and gentamicin on admission but died the next day. Isolate DT01139 was obtained from a 3-d-old female neonate, admitted from a healthcare centre to Amana Regional Hospital in November 2017 with a history of fever. This patient received amoxicillin-clavulanic and gentamicin on admission, but due to her worsening condition the treatment changed to ceftriaxone and gentamicin. After 7 d she was transferred to another hospital and was lost to follow-up.

#### Antimicrobial susceptibility testing results

Susceptibility testing results identified the two *A. baumannii* isolates were resistant to imipenem and meropenem as well as numerous other antibiotics, including those prescribed to the
patients, and were susceptible to ciprofloxacin and tetracyclines (Table 1). Both isolates were resistant to imipenem with a MIC of 32 \mu g/ml (DT0544) and 8 \mu g/ml (DT01139). Resistance to gentamicin and colistin was also identified in two isolates with a MIC of 128 and 24 \mu g/ml towards gentamicin and colistin was also identified in two isolates with a MIC of 128 and 24 \mu g/ml for DT01139 and DT054, respectively, while both isolates had a MIC of 16 \mu g/ml towards colistin.

**WGS results**

Isolate DT0544 contained two plasmids of approximately 55 and 4 Kb in size, while isolate DT01139 contained three plasmids of 97, 64 and 10 Kb in size. bla\textsubscript{NDM-1} was predicted to be present in both isolates; the \beta-lactamases were chromosomally located in isolate DT0544 while for DT01139 it was plasmid-located (Figure 1A,1B). The \beta-lactamases bla\textsubscript{ADC-25} and bla\textsubscript{CARB-16} were also present in both isolates, while bla\textsubscript{OXA-259}, belonging to bla\textsubscript{OXA-51} type, was present in DT0544; and DT01139 contained bla\textsubscript{OXA-51}. Several other resistance genes were predicted in the genome of DT0544: aadA1 \textit{aph (3)′-Ia} and \textit{ant (2)′-Ia} (aminoglycosides), sul2 (sulphonamides) and \textit{dfrA1} (trimethoprim), all located on a 55 Kb plasmid, while DT01139 was predicted to contain \textit{aac (3)-IId} and \textit{aph (3)′ VI} (aminoglycosides), sul2 (sulphonamides) and \textit{floR} (phenicol), all located on the 64 Kb plasmid with bla\textsubscript{NDM-1}. Predicted resistance genes by WGS were supported by and corresponded to phenotypic susceptibility. However, it is worth noting that no acquired 

**Table 1. Antimicrobial susceptibility results and acquired resistance genes of the two A. baumannii**

| Antimicrobial class | Antimicrobial agent | Disc diffusion | MIC (E-test) \mu g/ml | Acquired resistance genes |
|--------------------|---------------------|----------------|-----------------------|--------------------------|
|                    |                     | DT0544 | DT01139     | DT0544 | DT01139 | DT0544 | DT01139 | DT0544 | DT01139 |
| Fluoroquinolone \(\beta\)-lactams | Ciprofloxacin | S (23 mm) | S (27 mm) | 0.094 | 0.064 | none | none | bla\textsubscript{ARB-25}, bla\textsubscript{CARB-16}, bla\textsubscript{CARB-16} and bla\textsubscript{OXA-259} and bla\textsubscript{NDM-1} and bla\textsubscript{NDM-1} |
|                | Piperacillin/tazobactam | R (13 mm) | R (17 mm) | >256 | 128 | none | none | | |
| Ceftazidime | R (0 mm) | R (0 mm) | >256 | >256 | 32 | 32 | sul2 and dfrA1 | sul2 | |
| Cefotaxime | R (0 mm) | R (0 mm) | 4 | 4 | | | none | none | |
| Meropenem | R (14 mm) | R (16mm) | 4 | 4 | | | none | none | |
| Imipenem | R (11 mm) | R (16 mm) | 8 | 8 | | | none | none | |
| Folate antagonist | Sulphamethoxazole/trimethoprim | R (0 mm) | R (0 mm) | >256 | 4 | sul2 and dfrA1 | sul2 | |
| Tetracyclines | Tetracycline | S (19 mm) | S (21 mm) | 4 | 4 | | | | |
| Doxycycline | S (21 mm) | S (24 mm) | 0.5 | 0.5 | aadA1, \textit{aph (3)′-Ia}, and \textit{ant (2)′-Ia} | aac (3)-IId and \textit{aph (3)′ VI} | none | none | |
| Aminoglycosides | Gentamicin | R (0 mm) | R (0 mm) | 24 | 128 | | | | |
| Polymyxin | Colistin | NA | NA | 16* | 16* | | | | |

Note: NA, test not applicable for that antimicrobial agent; * MIC tested by broth microdilution.

**STs and phylogenetic analysis**

Using the Pasteur MLST scheme, the two isolates were found to belong to two distinct STs, ST374 (DT0544) and ST 239 (DT01139). Figure 1C is a whole genome SNP-based phylogenetic tree containing the two isolates from this study and 27 other 

**Discussion**

While NDM-1-producing 

**Genetic environment of bla\textsubscript{NDM-1} gene**

bla\textsubscript{NDM-1} is located on a composite transposon, Tn125, in DT0544 flanked by two copies of the insertion sequence (IS) ISAb125 ori}
where NDM-1-producing A. baumannii originated from samples obtained from axilla, abscesses, peritoneal swabs and the urinary tract, our isolates originated from bloodstream infections, emphasising their clinical importance. These findings are of significant public health importance as they show that there is ongoing dissemination of NDM-1-type resistance in an African setting.

The fact that the two neonates, only 3 and 4 d old, were transferred from a health centre and a regional hospital, respectively, and that the blaNDM-1-producing A. baumannii isolates were obtained from blood cultures taken on admission at the study hospital, raises concern that they may have acquired these multidrug-resistant bacteria locally at health facilities serving local communities.

The two isolates were susceptible only to ciprofloxacin and tetracyclines, but resistant to all other antibiotics tested. Evidence-based guidelines are vital for the acute management of severe systemic infections before microbiological results are ready. In sub-Saharan Africa, empirical treatment guidelines are even more important, as microbiological laboratory services are impeded by limited infrastructure capacity and funding to perform routine blood cultures and antimicrobial susceptibility
testing. Only major referral hospitals have the capacity to identify specific multidrug-resistant problematic bacteria such as carbapenemase-producing Gram-negatives. The empiric treatment protocol that was used to treat the two patients did not include the antibiotics to which the isolates were sensitive, hence the patients did not receive appropriate treatment, and we know at least one of them died. This highlights the importance of introducing and strengthening antimicrobial resistance surveillance programmes.

Differing antibiograms, resistance gene profiles and STs show the isolates are not clonal. Furthermore, blaNDM-1 was carried on a chromosomally located composite transposon Tn125 in one isolate and on a plasmid with only one ISAba125 in the other and therefore are not representative of an outbreak.

The two neonates and their parents had no history of traveling outside the country and the travel history of their healthcare providers is unknown. Therefore, to understand in depth the origins and extent of NDM-1-producing A. baumannii in the region there is a need for a comprehensive surveillance programme within the healthcare system in the country.

This study has shown further evidence of diversity among the NDM-1-producing A. baumannii in different parts of the world, for example, the two isolates belong to ST374 and ST239 (Pasteur MLST), while in the neighbouring countries Kenya and Ethiopia, NDM-1-producing A. baumannii belong to ST25 and ST957, respectively, and from Tunisia in northern Africa they belong to ST85.26 In European countries (Switzerland, Slovenia, Germany, France and Belgium), the NDM-1-producing isolates of A. baumannii were reported to belong to ST1, ST25, ST85 and ST92.5,26 While ST1, ST25 and ST85 are now widely reported throughout the globe, the two STs (374 and 239) in our study have been rarely reported. Non-NDM-1-producing A. baumannii ST374 isolates have previously been isolated from a wound swab in Kilimanjaro, the northern region of Tanzania (strain KCRI-49 with [accession number GCA_900406775.1]) and from respiratory tract infection in Brazil (strain Ac56 with [accession number WP100000000]). There is one previously reported ST239 A. baumannii isolate, H33 from Japan ([https://pubmlst.org/bigsdb?db=pubmlst_abaumannii_isolates&id=1695]), and other ST239 have been isolated from pets in France.27 In addition to a wide variety of STs among NDM-1-producing A. baumannii, the phylogenetic analysis (Figure 1C) also showed that the strains of A. baumannii-producing NDM-1 are not clonally related between different countries and within one country (e.g. two strains in the current study and three strains from Ethiopia and Thailand). This shows that the spread of NDM-1-producing A. baumannii in Africa is not clonal and likely results from the spread of the NDM-1 gene itself, as reported in Europe.26 A similar situation has been recently reported with NDM-1 in Klebsiella pneumoniae.28

The genetic environment of blaNDM-1 has previously been reported to be on the composite transposon Tn125, flanked by ISAba125.29,30 In A. baumannii DT0544, Tn125 harbouring blaNDM-1 is 100% identical to that found in A. baumannii VB473 (accession number CP050388) isolated from human sputum in India and is up to 99% identical to many other copies of Tn125 from various Acinetobacter spp.30 and other bacteria, including Escherichia coli and K. pneumoniae. The similar genetic organisation of blaNDM-1 on a Tn125 in most A. baumannii and other Acinetobacter spp. is due to the Tn125-linked mobility of blaNDM-1.31 In A. baumannii, DT01139 blaNDM-1 is associated with an upstream copy of ISAba125 in a more complex, plasmid-located arrangement flanked by ISAba14 (Figure 1B).

This is the first report of NDM-1-producing A. baumannii isolated from neonates with bloodstream infections from Tanzania. The genetic context of blaNDM-1 provides further evidence of the importance of ISAba125 in the spread of blaNDM-1 in A. baumannii. These findings shed light on the epidemiology of carbapenem resistance in Africa and calls for continued and strengthened surveillance to guide clinicians treating severe bacterial infections.

Supplementary data
Supplementary data are available at Transactions online.

Authors' contributions: SJM, NL and BB conceived the study. SJM, JM and NSM were involved in data collection. SJM and JM performed the microbiological investigations. SJM, ATMH, RB and APR were involved in WGS and analysis. SJM and APR drafted the manuscript. All the authors contributed to editing the manuscript and they approved the final version.

Acknowledgements: We would like to thank the technical staff at Muhimbili University of Health and Allied Sciences for technical assistance in performing blood cultures. We also thank Helene Heitmann Sandnes from the Department of Clinical Science at the University of Bergen for her support in antimicrobial susceptibility testing.

Funding: This work was supported by the University of Bergen, Bergen, Norway. APR would like to acknowledge funding from the AMR Cross-Council Initiative through a grant from the Medical Research Council, a Council of UK Research and Innovation [grant number MR/S004793/1] the Medical Research Council funded LSTM-Lancaster Doctoral Training Partnership [grant no. MR/N013514/1] for supporting RLB and the National Institute for Health Research [grant number NIHR200632].

Competing interests: APR is a policy advisor (drug resistance) for the RSTMH. All other authors have no conflicts of interest to disclose.

Ethical approval: This study was approved by the Senate Research and Publications Committee of Muhimbili University of Health and Allied Sciences, National Health Research Ethics Committee and by the Regional Committee for Medical and Health Research Ethics in western Norway. Written informed consent was obtained from the parents or guardians on behalf of the children.

Data availability: The chromosomal and plasmid sequences of DT0544 and DT01139 were submitted to GenBank with [accession numbers PRJNA679703 and PRJNA679704], respectively.

References
1 Howard A, O’Donoghue M, Feeney A, et al. Acinetobacter baumannii: an emerging opportunistic pathogen. Virulence. 2012;3(3):243–50.
2 Leao AC, Menezes PR, Oliveira MS, et al. Acinetobacter spp. are associated with a higher mortality in intensive care patients with bacteremia: a survival analysis. BMC Infect Dis. 2016;16:386.
Nordmann P, Poirel L, Toleman MA, et al. Does broad-spectrum beta-lactam resistance due to NDM-1 herald the end of the antibiotic era for treatment of infections caused by Gram-negative bacteria? J Antimicrob Chemother. 2011;66(4):689–92.

Karthikeyan K, Thirunayagan MA, Krishnan P. Coexistence of blaOXA-23 with blaNDM-1 and armA in clinical isolates of Acinetobacter baumannii from India. J Antimicrob Chemother. 2010;65(10):2253–4.

Bogaerts P, Rezende de Castro R, Roisin S, et al. Emergence of NDM-1-producing Acinetobacter baumannii in Belgium. J Antimicrob Chemother. 2012;67(6):1552–3.

Hammerum AM, Larsen AR, Hansen F, et al. Patients transferred from Libya to Denmark carried OXA-48-producing Klebsiella pneumoniae, NDM-1-producing Acinetobacter baumannii and meticillin-resistant Staphylococcus aureus. Int J Antimicrob Agents. 2012;40(2):191–2.

Jaidane N, Naas T, Oueslati S, et al. Whole-genome sequencing of a multidrug-resistant ST85 Acinetobacter baumannii isolate from Tunisia. Int J Antimicrob Agents. 2018;52(6):916–21.

Revathi G, Siu LK, Lu PL, et al. First report of NDM-1-producing Acinetobacter baumannii in East Africa. Int J Infect Dis. 2013;17(12):e1255–8.

Pritsch M, Zeynudin A, Messerer M, et al. First report on blaNDM-1-producing Acinetobacter baumannii in three clinical isolates from Ethiopia. BMC Infect Dis. 2017;17(1):180.

Agbo EE, Govinden U, Peer AK, et al. ISAba1 regulated OXA-23 carbapenem resistance in Acinetobacter baumannii strains in Durban, South Africa. J Antimicrob Chemother. 2018;73(9):2496–503.

Ogbolu DO, Alisi OAT, Oluremi AS, et al. Contribution of NDM and OXA-type carbapenemases to carbapenem resistance in clinical Acinetobacter baumannii from Nigeria. Infect Dis. 2020;1–7.

Moyo SJ, Manyahi J, Blomberg B, et al. Bacteraemia, malaria, and case fatality among children hospitalized with fever in Dar es Salaam, Tanzania. Front Microbiol. 2020;11:2118.

CLS1. Performance standards for antimicrobial susceptibility testing. CLSI supplement M100. Wayne, PA, 2019.

Afgan E, Baker D, Batut B, et al. The Galaxy platform for accessible, reproducible and collaborative biomedical analyses: 2018 update. Nucleic Acids Res. 2018;46(W1):W537–44.

Wick RR, Judd LM, Gorrie CL, et al. Unicycler: Resolving bacterial genome assemblies from short and long sequencing reads. PLoS Comput Biol. 2017;13(6):e1005595.

Seemann T. Prokka: rapid prokaryotic genome annotation. Bioinformatics. 2014;30(14):2068–9.

Altshul SF, Gish W, Miller W, et al. Basic local alignment search tool. J Mol Biol. 1990;215(3):403–10.