



Rapid detection of IMP, NDM, VIM, KPC and OXA-48-like carbapenemases from Enterobacteriales and Gram-negative non-fermenter bacteria by real-time PCR and melt-curve analysis

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Abstract

Carbapenemase-producing microorganisms are increasingly isolated and often associated with treatment failures and outbreaks. The need for reliable and timely detection and/or confirmation of carbapenemase production is paramount; therefore, a real-time PCR assay targeting IMP, NDM, VIM, KPC and OXA-48-like carbapenemases was designed and validated. All available allele variants of the above carbapenemases were downloaded from the Beta-Lactamase DataBase (<http://bldb.eu/>), aligned with Clustal Omega and primers designed using Primer-BLAST. Real-time PCR monoplexes were optimized for the QuantStudio 6-Flex (Applied Biosystems) using the PowerUp SYBR Green Master Mix (Life Technologies) and validated using a panel of 204 characterised strains carrying a wide range of beta-lactamases, sometimes in combination. Melt-curve analysis was used to confirm positive results. The *in silico* approach allowed primers to be designed in conserved regions of the KPC and NDM alignments, while three primer sets for IMP and two for VIM were necessary to ensure amplification of the different variants. One primer set was designed for OXA-48-like; however, it is unlikely to detect all variants. Expected results were obtained for all 204 tested strains, with 100% sensitivity and specificity. Melt-curve analysis showed consistent T_m results for KPC, NDM, and OXA-48-like; differences were instead noted for IMP and VIM as likely consequence of higher variability in the PCR target regions. Inhibition was not observed. The assay is rapid, easy to perform and implement. It enables unequivocal detection of IMP, NDM, VIM, KPC and OXA-48-like carbapenemases even when more than one type is present simultaneously.

Keywords PCR · Detection · Carbapenemase · Enterobacteriales · Non-fermenter

Introduction

Carbapenems are amongst the last line of defence to treat serious bacterial infections. However, carbapenemases (i.e. enzymes able to inactivate carbapenems) are increasingly identified in both Enterobacteriales and non-fermenter Gram-negative isolates. Carbapenemase-

producing organisms (CPO) are frequently associated with treatment failure and outbreaks, with the latter worsened by the fact that carbapenemases are often present on mobile genetic elements and can therefore easily spread between different bacteria [1].

In Wales, IMP, NDM, VIM, KPC and OXA-48-like (known as the “big five”) are the carbapenemases predominantly identified and consistent with those found in the rest of the UK: in particular, IMP, NDM, KPC and OXA-48-like in Enterobacteriales [2] and VIM in *Pseudomonas* species [3]. Phenotypic assays employing inhibitors for the different enzymes are available for the detection of some carbapenemases. For example IMP, NDM and VIM (Class B, metallo- β -lactamase) enzymes are inhibited by chelating agents like ethylenediaminetetraacetic acid (EDTA) and dipicolinic acid (DPA), while KPC (class A β -lactamase) is inhibited by boronic acid;

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an inhibitor for OXA-48-like (class D) β -lactamases has not yet been identified, although temocillin resistance can be used as an indicator of its presence [4]. These phenotypic tests are both sensitive and specific predominantly for Enterobacteriales, while their performance is poor for *Pseudomonas* species [5–7]. Furthermore, these tests require 24-h incubation to completion and can sometimes be difficult to interpret.

Carbapenemase screening in Enterobacteriales is performed in Wales according to EUCAST criteria, i.e. meropenem inhibition zone < 28 mm and/or meropenem MIC > 0.125 mg/mL [4] with isolates flagged as potential CPOs sent to the Specialist Antimicrobial Chemotherapy Unit (SACU), Cardiff (UK) for further investigation. For *Acinetobacter* and *Pseudomonas* species, all carbapenem and carbapenem plus piperacillin/tazobactam resistant isolates are referred accordingly. In SACU, phenotypic confirmation of carbapenem resistance is performed and carbapenemase production investigated using Neo-Sensitabs™ combination disks (ROSCO, Denmark) and MBL IP/IPI (*Pseudomonas* only) and MBL MP/MPI (Enterobacteriales only) double-ended *E* tests (bioMérieux, France), followed by in-house block-based PCR to confirm positive results.

The number of isolates referred to SACU for carbapenemase confirmation doubled from approximately 250 to 500 per year between 2015 and 2018, with an accompanying 100% rise in the number of CPO confirmed per year (from 19 to 38). Nevertheless, the incidence in Wales (population approximately 3,125,000 inhabitants estimated in June 2017 [8]) remains low when compared to data reported from other countries [9]. Referral numbers are predicted to rise further as hospitals undertake more rigorous screening programmes to detect CPO in admission patients as per recommendations [10]. The increase in requests for carbapenemase confirmation plus the importance of rapidly detecting CPO for effective infection control management, demanded a development of the above described confirmatory approach adopted by SACU. These methods are time consuming and labour intensive and involve the use of the toxic and carcinogenic compound, ethidium bromide, to visualise PCR results by gel electrophoresis (although safer intercalating agents are available nowadays). The need for a more rapid and reliable approach has been identified with the aim to reduce the time to issue confirmatory reports and better assist clinicians and infection control teams. Real-time PCR is a well-established methodology for detecting genetic markers in bacteria. It can provide results much faster than block-based PCR and does not normally require the use of high-risk reagents. Therefore, a real-time PCR assay based on SYBR Green chemistry has been designed to detect the “big five” carbapenemases and thoroughly validated using a large panel of previously characterised Gram-negative isolates.

Materials and methods

Assay design

IMP, NDM, VIM, KPC and OXA-48-like allele sequences were downloaded (as of December 2018) from the Beta-Lactamase DataBase [11] and aligned using Clustal Omega [12]. Alleles with less than 90% sequence identity to the rest of the alignment were excluded, and separate primers were designed where a strain carrying them was available to the authors for in vitro testing. Ten different primer sets per target were designed using Primer-BLAST [13] and then compared to the relevant alignment to identify the pair that at least in silico was able to amplify the highest number of alleles. Where necessary, degenerate bases (a maximum of 2 per primer) were added to cover non-conserved positions. Primer sequences and amplicon sizes are detailed in Table 1.

Bacterial strains

A total of 204 previously characterised Gram-negative isolates from 19 different species isolated world-wide were selected from the Authors', Public Health England, NCTC and ATCC collections (Supplementary data). One hundred and thirteen carried one of the “big five” carbapenemases while 22 carried two different markers simultaneously. The remaining 69 were negative for “big five” carbapenemases; however, some carried genes for other β -lactamases (such as AmpC, CTX-M, GES, IMI, L1 and L2, OXA-10, OXA-23, OXA-51, OXA-58, TEM, SHV, SME, SPM and VEB). The 135 “big five” CPOs carried a total of 40 IMPs (including IMP-1, IMP-4, IMP-6, IMP-7, IMP-8, IMP-10, IMP-11, IMP-13, IMP-14, IMP-29 and IMP-62), 27 VIMs (including VIM-1, VIM-2, VIM-4, VIM-7, VIM-10, VIM-19 and VIM-29), 31 NDMs (NDM-1, NDM-3, NDM-4, NDM-5, NDM-7), 26 KPCs (including KPC-2, KPC-3, KPC-4 and KPC-23) and 33 OXA-48-like markers (including OXA-48, OXA-181, OXA-204, OXA-232, OXA-244 and OXA-245).

After overnight aerobic growth on blood agar at 35 ± 1 °C, bacterial growth approximately equivalent to a third of a loopful (10 μ L loop) was re-suspended in 250 μ L of nuclease-free water and heat killed at 100 °C for 10 min. Supernatant was separated by centrifugation at 12,000g for 2 min and diluted 1:20 in nuclease-free water prior to testing. An extraction control (i.e. 250 μ L of nuclease-free water) was always included to discount cross contamination. A panel of seven strains was used as positive control in every experiment, namely *Escherichia coli* NCTC 13476 (IMP_a), *Serratia marcescens* SACU 1212 (IMP_b), *Pseudomonas aeruginosa* SACU 1205 (IMP_c), *Klebsiella pneumoniae* NCTC 13440 (VIM), *Klebsiella pneumoniae* NCTC 13443 (NDM), *Klebsiella pneumoniae* NCTC 13438 (KPC) and *Klebsiella pneumoniae* NCTC 13442 (OXA-48).

Table 1 Summary of primer sets used in this study (FP = Forward Primer; RP = Reverse Primer; ambiguities are underlined; *VIM and VIM-7 tested in the same tube)

Primer set	Target	Name	Sequence (5' → 3')	Amplicon (bp)	Reference
1	IMP(a)	IMP _a _FP IMP _a _RP	TGACGCAAAT <u>D</u> TAGAAGCTTGGC C <u>R</u> TCTCCAR <u>C</u> TTCACCTGTGAC	101	This study
2	IMP(b)	IMP _b _FP IMP _b _RP	GAYGCCTATCTRATTGACACTCC TAT <u>A</u> RCCGCGC <u>T</u> MACAAACCA	79	This study
3	IMP(c)	IMP _c _FP IMP _c _RP	<u>K</u> GAYGCAAATTTAGAAGCTTGGCCA C <u>C</u> CTTTAACAGCCTGYTCCCA	142	This study
4	NDM	NDM_FP NDM_RP	CAACTTTGGCCCGCTCAAGG GCAGCCACCAAAAAGCGATGT	100	This study
5*	VIM	VIM_FP VIM_RP	CGAAAAACACAGCGGCM <u>C</u> TTCT GTGGAGACTGCACGCGT <u>T</u> AC	73	This study
	VIM-7	VIM-7_FP VIM-7_RP	GGTGGCTGTGCAGTTCATGAG ACGACCTCTGCTCCGGATAC	122	This study
6	KPC	KPC_FP KPC_RP	CCACTGGGCGCGCACCTATT TGTTAGGCGCCCGGTGTAG	51	This study
7	OXA-48-like	OXA-48_FP OXA-48_RP	CTGGTGGGTYGGTTGGGTTGA GCAGCCCTAAACCATCCGATGT	89	This study
8	GFP	GFP_FP GFP_RP	CCTGTCTTTTACCAGACAACCA GGTCTCTCTTTTCGTTGGGATCT	76	[14]

Internal process control

An assay detecting a 76 bp fragment of the *green fluorescent protein*, *gfp* from *Aequorea victoria* [14] was included to discount PCR inhibition. A custom-made plasmid (Eurofins, Germany) containing the entire *gfp* sequence (Genbank Accession: M62653) was diluted to a working concentration of 1 pmol/μL before being added to the GFP reaction mix.

Real-time PCR

Monoplex PCR assays were optimized for the QuantStudio 6-Flex (Applied Biosystems) using the PowerUp SYBR Green MasterMix (Life Technologies) and Microamp Fast Optical 96-Well Reaction Plate 0.1 mL (Thermo-Fisher Scientific). Briefly, reactions were performed in a final volume of 10 μL containing 5 μL of MasterMix, 2.5 μL of template, 2 μL of PCR grade water and 0.5 μL of relevant primer mix. The final concentration of each primer is listed in Table 2. The GFP reaction mix also contained 0.5 μL per reaction of pGFP (1 pmol/μL), with 1.5 μL of PCR grade water to make 10 μL final volume. After an initial uracil-DNA-glycosylase step at 50 °C for 2 min, the Dual-Lock™ DNA polymerase was activated at 95 °C for 2 min followed by 35 cycles of denaturation at 95 °C for 1 s and annealing/extension at 60 °C for 20 s. Amplification results were analysed with the threshold set at 0.5 ΔRn for all targets, and the baseline set between 5 and 15 cycles

only for the GFP target. Melting-curve analysis was performed as follows: 95 °C for 15 s (ramp rate = 1.6 °C/s), 60 °C for 1 min (ramp rate = 1.6 °C/s) and 95 °C for 15 s (ramp rate = 0.15 °C/s) with fluorescence fluctuation analysed during the latter.

Table 2 Final concentration of primers used in this study (*VIM and VIM-7 tested in the same tube)

Primer set	Target	Primer name	Final Conc. [nM]
1	IMP _a	IMP(a)_FP IMP(a)_RP	500 500
2	IMP _b	IMP(b)_FP IMP(b)_RP	500 500
3	IMP _c	IMP(c)_FP IMP(c)_RP	500 500
4	NDM	NDM_FP NDM_RP	300 300
5*	VIM	VIM_FP VIM_RP	400 400
	VIM-7	VIM7_FP VIM7_RP	100 100
6	KPC	KPC_FP KPC_RP	500 500
7	OXA-48-like	OXA-48_FP OXA-48_RP	400 400
8	GFP	GFP_FP GFP_RP	300 300

Results

In silico analysis

The in silico approach allowed primers to be designed within 100% conserved regions of the KPC and NDM alignments. For the remaining carbapenemases, a single primer set able to amplify all alleles, was not identified. Three primer sets (tested separately) were necessary to detect IMP variants and two sets (tested in the same tube) for VIM variants. One primer set was designed for the OXA-48-like group; however, despite detecting the most common variants, it is unlikely to detect OXA-54, OXA-436 and OXA-535 due the suboptimal sequence identity (i.e. <90%) to the rest of the group. Clustal alignments of PCR fragments with primers binding sites highlighted are available in the Supplementary data.

Thirty-seven KPC variants were listed on the Beta-Lactamase DataBase; however, two sets (i.e. KPC-1 & KPC-2 and KPC-9 & KPC-23) were identical while KPC-20 was “assigned” but no sequence was available. Specific primers were designed in a conserved region of the remaining 34 KPC alleles. Primer binding sites were 100% conserved, and no single nucleotide polymorphisms (SNPs) were identified in the region between the primers.

A specific primer set was designed in a conserved region of the alignment of all available 24 NDM variants, with no exclusion. Primer binding sites were 100% conserved, and only one SNP (found in NDM-10) was identified in the region between the primers.

Among the 79 described IMP variants, six (i.e. IMP-36, IMP-39, IMP-46, IMP-50, IMP-57 and IMP-65) appeared as “assigned” but no sequence was available. Moreover, IMP-8 and IMP-47 share identical sequence; consequently, the actual number of analysed variants was 72. Clustal analysis showed considerable sequence variability; therefore, it was not possible to identify a single primer set able to detect all alleles. The Clustal generated tree was arbitrarily split in three sections (Fig. 1), and a set of primers designed for each section (i.e. IMPa, IMPb and IMPc). Degenerate bases had to be inserted in all six primer sequences to ensure amplification of different variants.

Among the 60 described VIM variants, VIM-21, VIM-22 and VIM-55 were “assigned” but no sequence was available. VIM-7 showed low sequence identity with the rest of the alleles (e.g. 81% identity with VIM-1); consequently, it was excluded from the alignment. Specific primers were designed in a conserved region of the remaining 56 VIM alleles, and one degenerate base was introduced in the forward primer. As previously mentioned, a separate set of primers was also designed specifically for VIM-7 as this variant was available to the authors for in vitro testing.

Only OXA-48-like variants with a definitive assignment by NCBI (30 in total) were downloaded from the Beta-Lactamase DataBase (i.e. OXA-48, OXA-54, OXA-162, OXA-163, OXA-

181, OXA-199, OXA-204, OXA-232, OXA-244, OXA-245, OXA-247, OXA-252, OXA-370, OXA-405, OXA-416, OXA-436, OXA-438, OXA-439, OXA-484, OXA-505, OXA-514, OXA-515, OXA-517, OXA-519, OXA-535, OXA-538, OXA-546, OXA-547, OXA-566 and OXA-657). After Clustal analysis, OXA-54, OXA-436 and OXA-535 were excluded from the alignment due to low sequence identity (84%, 84% and 85% respectively with OXA-48). In this instance, specific primers were not designed as they were not available to the authors for in vitro testing. Primers for the remaining 27 OXA-48-like variants were designed in a conserved region with one ambiguity introduced within the forward primer while the binding site of the reverse primer was 100% conserved.

In vitro analysis

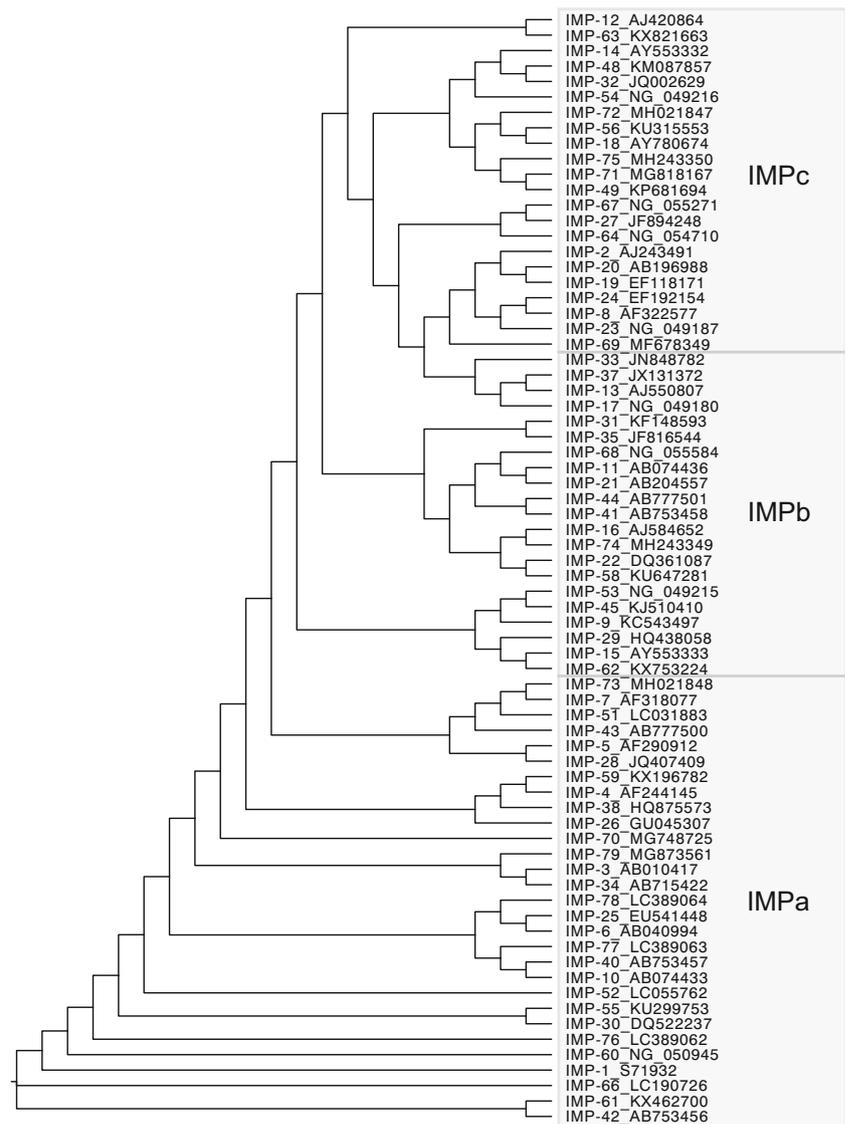
The eight multiplex real-time PCR assays (i.e. IMPa, IMPb, IMPc, NDM, VIM, KPC, OXA-48 and GFP) were performed in 96-well plates with PCR mixes added in rows; DNA extracts were tested in column 1 to 10, while column 11 and 12 were used to test extraction and positive controls respectively. The time necessary to complete PCR amplification and melt-curve analysis was approx. 40 min. Testing of undiluted DNA extracts resulted in strong PCR inhibition (as revealed by absence of- or delayed GFP amplification); consequently, 1:20 dilutions were prepared prior to testing. Formation of primer dimers was observed with the NDM assay; therefore, oligonucleotide sequences were reviewed in silico and concentrations decreased in vitro to improve results (Table 2).

DNA extracts of *Escherichia coli* NCTC 13476 (IMP), *Klebsiella pneumoniae* NCTC 13440 (VIM-1), *Klebsiella pneumoniae* NCTC 13443 (NDM-1), *Klebsiella pneumoniae* NCTC 13438 (KPC-3) and *Klebsiella pneumoniae* NCTC 13442 (OXA-48) were mixed to generate all possible target combinations (for simplicity only IMPa among the three IMP primer sets was included in this analysis). In all cases, the assay successfully detected all the carbapenemases present in the reaction mix, regardless of if only one or all five were present simultaneously (Supplementary data).

Melt-curve analysis was used to confirm positive results by comparing dissociation curves to that of the relevant positive control. Minor T_m variations were observed for NDM, VIM, KPC, OXA-48-like and GFP ($0.15 < \text{St Dev} < 0.30$), while greater differences were noted with the three IMP multiplexes ($0.49 < \text{St Dev} < 0.62$).

The expected result was initially obtained for 203 of the 204 previously characterised isolates. *Klebsiella pneumoniae* SACU 27698 was meant to be negative for the “big five” carbapenemases, instead, it produced unequivocal amplification with IMPa ($C_t = 17.49$) and IMPb ($C_t = 30.49$) primer sets and melting curves consistent with those of *E. coli* NCTC 13476 and *S. marcescens* SACU 1212 (i.e. IMPa and IMPb positive controls). Further analysis with in-house block-

Fig. 1 Clustal Omega generated tree of the IMP alleles available from the Beta-Lactamase DataBase



based PCR confirmed presence of IMP metallo- β -lactamase, while whole genome sequencing (WGS) by MiSeq (Illumina) characterised it as IMP-4 (data not shown). Indeed, the newly designed assay provided the expected result for all 204 tested isolates (100% sensitivity and specificity) including those carrying two “big five” carbapenemases simultaneously. Cross-reaction with the other resistance markers present in the above mentioned isolates was not observed.

Overall, amplification results produced mean Ct values of ca. 16 and Standard Deviation (SD) values between 0.88 and 1.45 (Table 3). Among the 40 isolates carrying IMP markers, 36 gave positive results with two of the three IMP primer sets used (i.e. a strong result in the expected Ct range and a weak result with Ct > 25 respectively). IMP alleles from part A of the Clustal generated tree gave strong IMPa results and weak IMPb results, alleles in part B gave strong IMPb results and weak IMPc results, while alleles in part C of the tree gave IMPc

strong results and weaker IMPb results (Supplementary data). Four IMPs, of which three IMP-13, were only amplified by one set of primers.

Discussion

We describe here the design and validation of an array of monoplex real-time PCRs optimised for the QuantStudio 6-flex platform (ThermoFischer Scientific) to rapidly detect and differentiate the “big five” carbapenemases, (i.e. IMP, NDM, VIM, KPC and OXA-48) from Enterobacteriales and non-fermenter Gram-negative isolates. A rational approach that took into account all the relevant allele sequences available from the Beta-Lactamase Database (as of December 2018) was applied in silico to design specific primers and to then predict whether they would also detect those allele variants that were not

Table 3 Summary of cycle threshold (Ct) and melting temperature (Tm) results for the primer sets used in this study (*VIM and VIM-7 tested in the same tube; **Only one strain containing VIM-7 was available for testing, consequently min, max and SD were not calculated)

Primer set	Target	Ct				Tm (°C)			
		Min	Mean	Max	SD	Min	Mean	Max	SD
1	IMPa	14.67	16.73	20.35	1.43	76.92	77.74	78.47	0.49
2	IMPb	14.43	16.66	18.94	1.45	75.13	76.31	77.21	0.77
3	IMPc	14.88	16.06	16.98	0.88	76.92	77.51	78.06	0.62
4	NDM	13.73	16.41	18.83	0.99	84.61	84.86	85.58	0.21
5*	VIM	14.11	16.09	18.23	0.95	80.43	80.73	81.07	0.15
	VIM-7**	–	15.49	–	–	–	84.12	–	–
6	KPC	13.52	16.81	18.50	1.13	82.90	83.40	83.83	0.30
7	OXA-48-like	13.63	16.16	18.60	1.21	78.05	78.26	78.78	0.18
8	GFP	21.36	23.36	24.28	0.44	77.51	77.77	78.83	0.20

available to the authors for in vitro testing. A wide collection of previously characterised Gram-negative isolates was then tested in vitro to fully validate the newly designed monoplexes. An assay targeting the *gfp* [14] was simultaneously tested as an internal control to discount inhibition.

As resistance markers (especially IMP in this case) evolve rapidly causing emergence of new allele variants, SYBR Green chemistry combined with melting-curve analysis in monoplex PCR reactions was chosen over multiplexing with primers and probes. Newly described SNPs in primers and/or probe binding sites would potentially result in assays having to be redesigned and then revalidated. This is time consuming and costly. The absence of probes in this assay reduces the number of binding sites from three to two and consequently the likelihood that a newly described SNP falls into them. If indeed a new SNP is identified in either of the two primer binding sites and it is decided that they need to be redesigned, the use of separate monoplexes allows to limit the revalidation to just the affected monoplex instead of having to perform a major revalidation like when a multiplex approach is used. Furthermore, the use of separate monoplexes provides greater flexibility to combine testing of different panels of targets if the need arises: one or more of the monoplexes described here could be quickly replaced with others validated separately to detect different resistance markers (e.g. GIM, SIM, SPM, IMI) without the need to perform any further validation on the entire assay panel.

The in silico analysis showed that this assay should be able to detect all the IMP, NDM, VIM and KPC variants described as of December 2018. Among the OXA-48-like group, OXA-54 and OXA-535, described in the chromosome of *Shewanella species* [15, 16] and OXA-436 identified on a plasmid in *Enterobacter species*, *Citrobacter species* and *K. pneumoniae* in Denmark [17] are unlikely to be detected.

The in vitro experiments proved the assay to be 100% sensitive and specific on a large panel of previously characterised isolates available to the authors. As stated by Lund et al. [18], assays are often validated using a limited

selection of target variants that are available locally; furthermore, testing high numbers of unsequenced isolates might simply result in redundant analysis of a small number of variants which then provides little indication about the actual sensitivity and specificity of a particular assay. These issues were addressed in this study by applying a robust in silico approach to confidently predict amplification of those variants that were not available for in vitro testing and by then including (where possible) isolates where the “big five” allele variant had previously been characterised (i.e. by Sanger sequencing and/or by WGS).

Interpretation of melting profiles can be problematic when dissociation curves do not overlap with that of the positive control. This was often observed with isolates carrying IMP genes as a likely consequence of high sequence variability of the IMP PCR products. Nevertheless, when an IMP allele was present, more than one primer set was often able to detect it (usually two primer sets, one producing a strong result with Ct between 14 and 18, and another producing Ct > 18) allowing confident identification of true positives. It is noteworthy that variations in Tm results were observed also for those PCR products that were not meant to contain any SNP (e.g. KPC and GFP); therefore, it seems that the actual Tm value cannot be reproducibly obtained by the PCR platform between different PCR runs. A Tm standard deviation of 0.20 was calculated for the GFP amplified fragment (which is identical in every PCR run) and this value could be considered as an indication of the Tm uncertainty of measurement intrinsic to this procedure. Different Tm values were also noted for VIM alleles; however, in this case, it was due to VIM-7 being quite different (only 81% nucleotide identity with VIM-1), with a Tm of approx. 84 °C compared to Tm of approx. 81 °C for the remaining VIM alleles. This was consistently observed and was actually helpful to differentiate between VIM-7 and the other VIM alleles.

In at least one instance, the assay provided more sensitive and reliable results than standard phenotypic analysis: *K. pneumoniae* SACU 27698 previously characterised as

negative for the “big five” carbapenemases, was instead found to be IMP positive and later characterised by WGS to carry IMP-4. This result triggered an investigation that identified the above isolate as part of a cluster involving five patients (data not shown) which clearly proves the added value of the here described real-time PCR assay. Retrospective analysis on the isolate showed that combination disks did not to show metallo- β -lactamase activity (i.e. only 2 mm difference between the meropenem and the meropenem/DPA disks) while the MP/MPI double-ended strip provided a weakly positive result (MIC ratio = 12). With this in mind, it was decided to modify the SACU approach for investigation of carbapenemases. The real-time PCR assay described here became the first-line method to investigate presence of the “big five” carbapenemases. Positive PCR results are reported immediately without performing further analysis; however, as negative PCR results cannot completely exclude presence of a carbapenemase, further investigations need to be performed. As already mentioned, new “big five” allele variants might not be detected by this assay or a carbapenemase not included in this assay (e.g. GIM, SIM, SPM) could be present. Finally, novel carbapenemases, not known as yet, would equally not be detected. Therefore, all PCR negative isolates are tested with combination disks and double-ended strips to phenotypically exclude both carbapenemase and extended spectrum β -lactamase (ESBL) activity before negative results are reported. In those cases where carbapenemase activity is observed despite a negative PCR results, alternative methods (such as sequence analysis) would be applied to investigate the cause of the resistant phenotype.

In certain cases, “big five” variants detected by this assay might actually confer either weak or undetectable level of carbapenemase resistance. Indeed, KPC-14 and KPC-28 have been demonstrated to have reduced carbapenemase activity [19] while OXA-163, OXA-247 and OXA-405 have been shown to have no carbapenemase activity [20, 21] due to amino acid deletions in the active site. Isolates carrying these variants are likely to generate discrepant PCR and phenotypic results; thus, further testing (e.g. sequence analysis of the “big 5” variant) should be performed. In particular, KPC-28 has also been characterised to have an amino acid substitution (i.e. H274Y) causing a 50-fold increase in ceftazidime hydrolysis and consequently high MIC to ceftazidime/avibactam, an effective antimicrobial option for KPC-producing bacteria [19].

The assay described herein allows testing of ten isolates at a time (plus extraction control and positive control) using 96-well plates. Given the short PCR running time (ca. 40 min), DNA could be extracted simultaneously from a greater number of isolates to allow a quick second PCR experiment to be prepared while the first is running; up to 20 isolates could be then tested in less than 90 min. Alternatively, for high through put 384-well plates may be used, allowing up to 46 strains (plus controls) to be tested simultaneously. The assay was deemed easy to perform by members of staff with little or no experience with real-time PCR and melt-curve analysis.

Importantly, the real-time PCR assay allowed unequivocal result interpretation even when more than one “big five” carbapenemase resistance marker was present. Finally, the new algorithm improved the reference service by reducing the time necessary to report positive results and at the same time reducing the risk of reporting false-negative results.

In summary, the assay was easily implemented, allowed faster and more reliable positive results than previously obtained by SACU to be available for clinicians and infection control specialists. The potential wider benefits of the assay include reducing costs to the hospital from keeping potential positive patients in side rooms, inappropriate therapy of positive patients and increased screening costs because of delays in positive results.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Not required for this study.

Informed consent Not required for this study.

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