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Comparative genomic analysis of European and Middle Eastern community-associated methicillin-resistant *Staphylococcus aureus* (CC80:ST80-IV) isolates by high-density microarray

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Abstract

Infections as a result of community-associated methicillin-resistant *Staphylococcus aureus* (CA-MRSA) are an issue of increasing global healthcare concern. In Europe, this principally involves strains of multi-locus sequence type clonal complex 80 sequence type 80 with methicillin resistance in a staphylococcal chromosomal cassette (SCC*mec*) type IV arrangement (CC80:ST80-IV). As with other CA-MRSA strains, CC80:ST80-IV isolates tend to appear uniform when analysed by common molecular typing methods (e.g. pulsed field gel electrophoresis, multi-locus sequence type, SCC*mec*). To explore whether DNA sequence-based differences exist, we compared the genetic composition of six CC80:ST80-IV isolates of diverse chronological and geographic origin (i.e. Denmark and the Middle East) using an Affymetrix high-density microarray that was previously used to analyse CA-MRSA USA300 isolates. The results revealed a high degree of homology despite the diversity in isolation date and origin, with isolate differences primarily in conserved hypothetical open reading frames and intergenic sequences, but also including regions of known function. This included the confirmed loss of SCC*mec* recombinase genes in two Danish isolates representing potentially new SCC*mec* types. Microarray analysis grouped the six isolates into three relatedness pairs, also identified by pulsed field gel electrophoresis, which were consistent with both the clinical and molecular data.

Keywords

Community; microarray; ST80; *Staphylococcus aureus*

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Transparency Declaration
The authors declare that they have no conflicting interests in relation to this work.

Introduction

Although healthcare-associated (HA) methicillin-resistant *Staphylococcus aureus* (MRSA) have been a subject of longstanding clinical concern, infections as a result of community-associated (CA) MRSA have now become an intense focus of interest and investigation [1–3]. Although CA-MRSA are globally distributed, specific strains continue to exhibit geographic predominance. In the USA, this is typified by isolates that are multi-locus sequence type (MLST) clonal complex 8, sequence type 8, staphylococcal cassette chromosome (SCC*mec*) type IV (CC8:ST8-IV), exhibiting the USA300 pulsed-field gel electrophoresis (PFGE) profile [4,5]. In Europe, the most common CA-MRSA strain is CC80:ST80-IV [6,7]. In Denmark, CC80:ST80-IV isolates are the predominant cause of CA-MRSA infections, with epidemiological studies [7,8] showing a large proportion of patients with family relationships in the Middle East. Individuals colonized when traveling abroad or visiting such high endemic areas have been suspected as likely sources of CC80:ST80-IV importation because the overall proportion of MRSA in Denmark is very low (approximately 0.1%) [7,9]. However, establishing direct transmission routes is challenging because of the conserved nature of CC80:ST80-IV genomic (e.g. PFGE) profiles [7], similar to other CA-MRSA, such as USA300 [4,10]. Although at least 17 PFGE subtypes have been identified in the Danish CC80:ST80-IV collection, there has been no specific association between specific subtypes and infections acquired domestically vs. those most likely acquired abroad [7]. Concern regarding the increased incidence of infections as a result of CA-MRSA has prompted investigations regarding their genetic composition, to better understand their potential for virulence and epidemic spread. In this context, microarrays have been a powerful tool for assessing the genomic presence or absence of important loci (e.g. regulatory, resistance, virulence or adhesion). For example, analysis of USA300 (ST8) in comparison to CA-MRSA USA400 (ST1) and HA-MRSA USA100 (ST5) and 500 (ST8) using a high-density microarray (i.e. 7775 loci) revealed a high degree of relatedness, especially between USA300 and USA500, with a set of 20 known or hypothetical genes unique to USA300 [4].

Past microarray analysis of CC80:ST80-IV by Monecke *et al.* [11,12] used 100 and 87 probes, respectively (e.g. genes for resistance and virulence) to compare isolates (12 from Germany, five from the UK and two from Switzerland) with a variety of *S. aureus* strains encoding the Panton–Valentine leukocidin (PVL), including the sequenced *S. aureus* USA400 strain MW2. These analyses revealed a diverse origin for pandemic PVL-positive strains but differences between CC80:ST80-IV isolates in only four plasmid-born antibiotic-resistance loci. Similarly, a recent study by Monecke *et al.* [13] comparing eight German CC80:ST80-IV isolates using 157 probes for resistance and virulence revealed differences only for plasmid-associated antibiotic resistance genes.

The *S. aureus* Affymetrix high-density microarray represents a powerful tool for genomic comparison because the 7775 loci include not only resistance determinants, toxins, virulence regulators and cell surface factors, but also hypothetical genes and intergenic sequences from the published *S. aureus* N315, Mu50, COL and NCTC8325 genomes [4,14]. Sung *et al.* [15] noted the importance of mobile genetic elements (e.g. plasmids, transposable elements and bacteriophages) in strain differentiation. In addition, as our understanding of microbial genomic organization, gene structure and function increases, sequences initially considered to be unimportant are finding new significance (e.g. phenol-soluble modulins) [16,17]. Thus, the present study aimed to use the *S. aureus* Affymetrix high-density microarray to investigate inter-relationships between six CC80:ST80-IV isolates obtained from 1997–2003, including one of the earliest (i.e. ‘ancestral’) entries in the Danish database, as well as isolates with possible ties to the Middle East (Lebanon and Egypt).

Materials and Methods

Bacterial isolates and susceptibility testing

Subsequent to 1988, Danish regional clinical microbiology departments have systematically referred all MRSA isolates to Statens Serum Institut. Based on hospital discharge summaries or notes from outpatient clinics and physicians, all patients with MRSA infections were evaluated for the potential origin of infection according to previously described criteria [9,18]. A total of 294 CC80:ST80-IV cases were registered (1988–2004), most of which were CA originating in Denmark. However, a large proportion of cases had family relationships in the Middle East [7]. For array investigation, six isolates spanning a 6-year period were chosen including an isolate from a patient infected during hospitalization in Egypt and one from a patient born in Lebanon. Four isolates caused CA infections (1198, 1200, 1202 and 1209) and one caused a health care-associated community-onset infection (1201). The remaining isolate (1199) was a surveillance culture (1199) from a patient transferred to Denmark from an Egyptian hospital with no record of earlier hospitalization for approximately 2 years. The isolates were unrelated as determined by epidemiological information. Susceptibility to cefoxitin, penicillin, streptomycin, tetracycline, erythromycin, clindamycin, fusidic acid, norfloxacin, kanamycin, rifampicin and linezolid was assessed using Neosensitabs® (Rosco, Taastrup, Denmark) on Danish Blood agar (SSI, Copenhagen, Denmark) [9]. Suspected methicillin/oxacillin resistance, predicted by cefoxitin test results, and fusidic acid resistance, was confirmed by detecting the *mecA* and *fusB* genes, respectively [19,20].

PFGE and PCR

Molecular characterization by PFGE and PCR analysis for the presence of the PVL genes, protein A gene (*spa*), accessory global regulator (*agr*), SCC*mec* and MLST were performed as described previously [7]. SCC*mec* typing was primarily conducted using the multiplex PCR method of Oliveira and de Lencastre [19] with additional *ccr* recombinase and *mec* typing as outlined by Kondo *et al.* [21] and Milheirico [22].

Microarray analysis

The *S. aureus* CC80:ST80-IV isolates were analysed using a commercially available *S. aureus* Affymetrix GeneChip® (Affymetrix, Santa Clara, CA, USA) as described previously [4,14]. Chromosomal DNA was interrogated for the presence or absence of the 7775 loci on the GeneChip®, which included resistance determinants, exoenzymes, exo- or enterotoxins and a variety of virulence regulators and cell surface factors from the *S. aureus* N315, Mu50, COL and NCTC8325 published genomes. Chromosomal DNA was purified from each of the CC80:ST80-IV isolates, fragmented, and biotinylated at the 3′ end [4,14]. Labelled DNA (1.5 µg) was hybridized to a GeneChip® and adjusted ‘present’ and ‘absent’ determinations were made for each array locus with an average of 20 probe sets per open reading frame (ORF) or intergenic region [4,14]. For adjusted calls, raw values were log transformed and normalized by dividing each value by the chip mean. Cut-off values for *p* calls were ≤0.89 = absent; ≥0.981 = present; and 0.9–0.98 = marginal.

Results

As shown in Table 1, the CC80:ST80-IV isolates were primarily associated with skin and soft tissue infections and were chosen to represent differences in year of isolation, potential geographic origin and antimicrobial susceptibility. Initial genotypic characterization (Fig. 1) revealed the expected homogeneity for *spa*, MLST, SCC*mec* (see below), PVL and *agr* type. Minor variations (>90% similarity) in PFGE patterns were consistent with published CC80:ST80-IV profiles. However, PFGE identified three subgroup pairs (approximately

96% relatedness) that linked the two Middle East isolates (1199 and 1200) cultured in 2001, Danish isolates 1201 and 1202 (cultured in 2003 and 2001, respectively) and Danish isolates 1198 and 1209, which were isolated in 1997 (i.e, one of the earliest CC80:ST80-IV in the database) and 2001, respectively.

Overall, when analysed on the *S. aureus* Affymetrix Gene-Chip, DNA from the isolates hybridized to an average of 58% of the 7775 loci (i.e. 4489 ± 174). As shown in Fig. 2, although 95% related, the isolates appeared to group in pairs (i.e. 1199/1200, 1201/1202 and 1198/1209) similar to that seen by PFGE. Differences were primarily in conserved hypothetical ORFs and intergenic sequences as seen by pairwise analysis (Table 2), indicating the number of the 7775 queried loci present in one isolate but absent from another. This comparison confirmed that isolates 1199 and 1200 were the most similar, with only 73 instances (18 plus 55) where a locus found in one isolate was absent from the other. Isolate pairs 1201/1202 and 1198/1209 had 354 and 326 instances of nonshared loci, respectively. The inter-relationships were even more clearly seen with intergenic sequences removed from the analysis. As shown in Table 2, isolate pairs 1199/1200 shared all remaining 3514 ORFs, followed by isolate pair 1198/1209 with only 15 instances of nonshared loci. Isolate pair 1201 /1202 was more distantly related but lacked the SCC*mec*-associated recombinase (*ccr*) genes but retained *mecA* (see below).

A summary of differences between the CC80:ST80-IV isolates (not including intergenic regions) is shown for 82 representative loci in Table 3. In many instances, these appeared to relate to variation in bacteriophage carriage. For example, the isolates were identical for 20 of 21 probes associated with PVL-encoding bacteriophages, with most being similar to the Mu50 array sequences. However, only 1198 and 1209 contained the bacteriophage-associated SA1789 sequence. Isolate 1198 contained at least one bacteriophage and various hypothetical genes not found in isolates 1199 and 1200. Isolate 1198 did not contain the epidermin immunity factor (*epiG*) gene or hypothetical protein SA0848, found in all other isolates. Isolate 1201 lacked hypothetical protein SA0406, the SAA0001 replication initiation protein *repC*, the SA0002 tetracycline resistance protein, the SAA0003 plasmid recombination-mobilization protein *pre*, and uniquely contained hypothetical protein SA2487. Isolate 1202 contained a unique set of bacteriophage-associated adjacent genes (COL SA1573–1586) encoding replication protein, integrase and various hypothetical ORFs. Isolate 1209, most similar to isolate 1198, was unique in lacking virulence genes *sdrD* and *sdrE* and hypothetical proteins SA0397, SA0753 and SA1346. As noted above, although initially characterized as SCC*mec* IV based on the Oliveira and de Lencastre multiplex PCR protocol [19], further SCC*mec* subtyping using the strategy of Kondo *et al.* [21] and Milheirico [22] revealed that isolates 1201 and 1202 lacked the SCC*mec* recombinase (*ccr*), whereas all isolates contained the SCC*mec* IVc J1 sequence (data not shown). All isolates were positive for *mecA*, ΔmecR1, and ΨIS*1272* SCC*mec* IV probes. Within loci that varied among the CC80:ST80-IV (Table 4), the unique adjacent genes (COL SA1573–1586) in isolate 1202, as mentioned above, were also found in USA300 (CC8:ST8-IV). Of the 57 most variable loci (i.e. either present or absent in two to three of the six isolates), the majority (37/57; 65%) were absent in both USA300 and USA400 (Table 3) [4]. For loci of known function, CC80:ST80-IV isolates were generally similar to USA300 and USA400. However, for 19 loci of known function that varied between USA300 and USA400 [4], the CC80:ST80-IV isolates were more similar to USA400. These differences included *agr*, capsule type, the presence in USA300 of a complete *ebh* gene, fosfomycin resistance, and assorted extracellular virulence determinants (e.g. exotoxin 3) not found in USA400 or CC80:ST80-IV (data not shown).

Discussion

As noted above, CA-MRSA strains are generally characterized by phenotypic and genotypic homogeneity which, coupled with their ability to spread, complicates the epidemiological picture. Currently, there is no accurate way to determine whether the multiple isolates that one wishes to compare represent the spread of a single or limited number of organisms vs. introduction from multiple independent sources. This dilemma is potentially more problematic with a higher MRSA prevalence. Because Denmark represents an environment of low MRSA prevalence, we were interested in comparatively analysing CC80:ST80-IV isolates chosen to represent different years of isolation and the probability of different geographic origin.

Although genetic exchange is known to occur between *S. aureus* strains, the high degree of genomic relatedness (95%) among the CC80:ST80-IV examined in the present study supports a model of clonal expansion leading to genomic uniformity, despite differences in time and geography. However, upon closer examination, subtle differences were observed, leading to potentially interesting 'sub-type' inter-relationships. For example, the most similar isolates were from outside of Denmark (1199 and 1200), both cultured in 2001 but from different locations (i.e. Lebanon and Egypt). Because of the small number of isolates examined, it is unclear whether clustering of the Lebanese and Egyptian isolates apart from the isolates of Danish origin is significant, as are the conclusions regarding possible transmission from the Middle East to Denmark. However, CC80:ST80-IV was recently shown to constitute 55% of all MRSA in a large hospital in Lebanon, which may support this hypothesis (Tokajian, *et al.*, 13th International Symposium on Staphylococci and Staphylococcal Infections, 2008, abstract P655). In addition, Denmark is a country of low MRSA endemicity (approximately 0.1%) [23], with only a single case of CC80:ST80-IV hospital transmission being documented to date [7]. Therefore, the acquisition of MRSA in these two patients before leaving Denmark for Lebanon and Egypt would appear to be unlikely. Interesting inter-relationships were also noted among the Danish isolates. Although cultured over a 4-year time span (1997 vs. 2001), isolates 1198 and 1209 were the second most highly related pair. The final pair of isolates (1201 and 1202), found in Denmark over a 2-year period, were somewhat more distantly related but shared the interesting loss of SCC*mec*-associated recombinase genes at the same times as retaining *mecA*, ΔmecR1 and ΨIS*1272*, and the SCC*mec* IVc specific J1 region. Recent studies have reported both *S. aureus* [24] and *Staphylococcus epidermidis* [25] isolates positive for *mecA* but negative for *ccr* by PCR analysis. However, whether this is a result of the absence of *ccr* or sequence divergence influencing primer recognition remains unknown. Thus, to our knowledge, this is the first report of such a deletion that would clearly affect the mobility/excision of SCC*mec* in these isolates. The multi-year observation of these isolates suggests that they may represent a stable CC80:ST80-IV subpopulation (e.g. a SCC*mec* IV variant or potentially new type), the frequency and significance of which is currently unknown. Regarding PVL, two recent studies [26,27] reported interesting sequence differences related to specific MRSA strains and geography. Microarray analysis indicated that all six CC80:ST80-IV isolates appeared to carry the same PVL-associated bacteriophage, similar to that of *S. aureus* strain Mu50. As with issues related to SCC*mec* differences, additional sequence-based studies of PVL could provide potentially interesting information regarding possible isolate sub-type inter-relationships.

It is reassuring to note that both PFGE and microarray analysis identified the same relatedness pairs, which fit well with the overall clinical and molecular data, grouping the Middle East and *ccr*-deleted pairs from the remaining Danish isolates. This suggests that minor differences in both PFGE and microarray analysis of genomically uniform strains such as CC80:ST80-IV may have the potential for clinical and epidemiological significance.

However, conclusions regarding these observations must be tempered by the small number of isolates analysed. As with other CA-MRSA, the conserved nature of CC80:ST80-IV isolates has limited the usefulness of current molecular approaches for epidemiological investigation. Nevertheless, as with recent USA300 genomic analyses [28,29], the data obtained in the present study suggest that differences such as single-nucleotide polymorphisms and divergence in hypothetical ORFs and intergenic regions may ultimately provide a useful sequence-based foundation for discerning epidemiologically meaningful inter-relationships. This is further supported by the recently demonstrated ability of a small number of single-nucleotide polymorphisms to provide meaningful typing data in the highly conserved genomic background of *Bacillus anthracis* [30]. However, the potential usefulness of microarray data for the epidemiological analysis of CC80:ST80-IV clearly requires further evaluation with isolates of known relatedness. Although microarray analysis revealed differences between the CC80:ST80-IV isolates primarily in conserved hypothetical ORFs and intergenic sequences, these differences are worth noting because the unknown function of such loci does not automatically equate with unimportance. For example, approximately 80% of the USA300 genome represents a coding sequence that includes numerous conserved hypothetical proteins whose role is yet to be determined [28]. In *S. epidermidis*, phenol-soluble modulins, now known to be important virulence factors [16], were initially poorly annotated in genomic sequences [17]. Thus, sequence-based comparisons (i.e. differences and similarities) of CA-MRSA strains such as CC80:ST80-IV hold potential promise as a means of uncovering relevant and important information that will hopefully lead to a better understanding of both the pathogenicity and epidemiology of these increasingly important pathogens.

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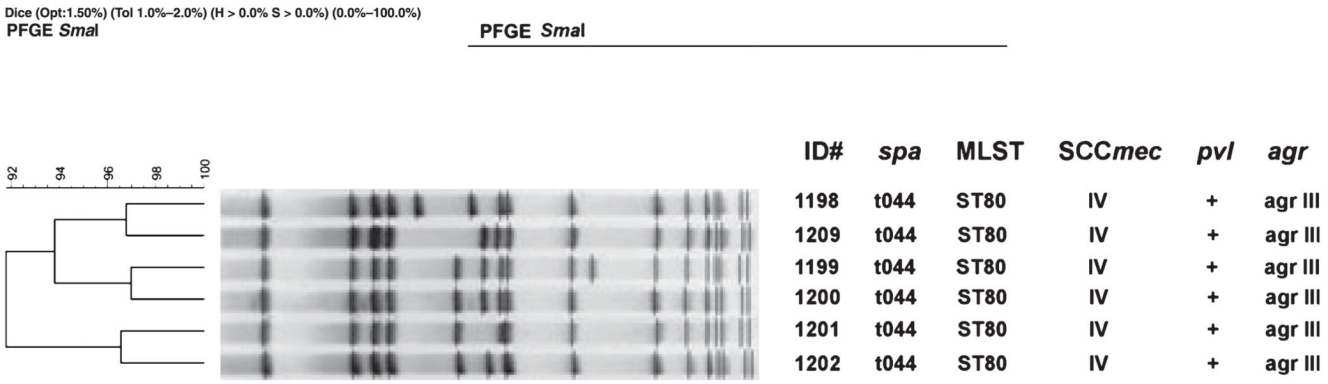

FIG. 1.

A summary of CC80:ST80-IV isolate molecular characteristics by pulsed-field gel electrophoresis (PFGE) and analysis by PCR for *spa*, MLST, SCC*mec*, *pvl*, and *agr*.

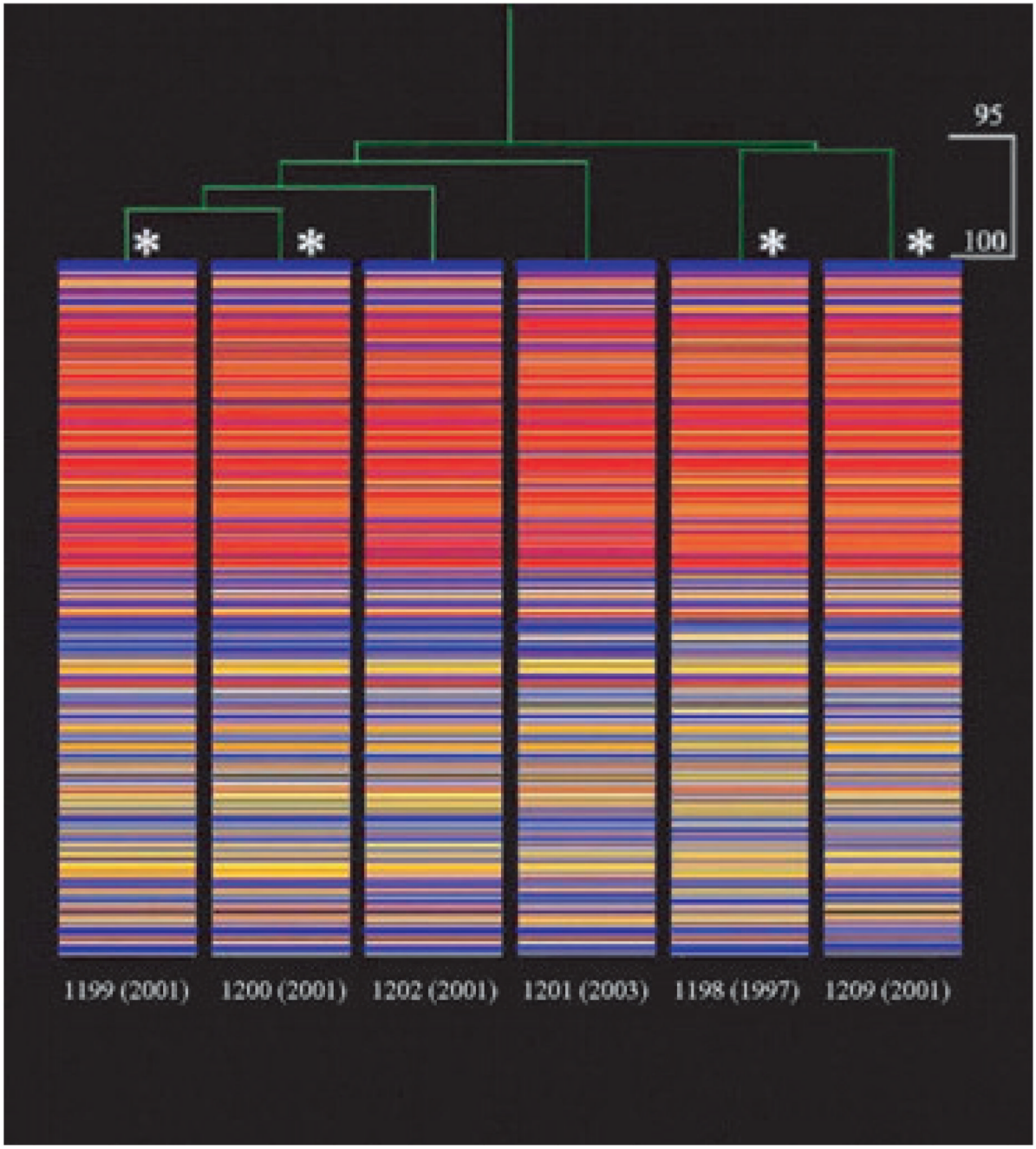

FIG. 2.

Dendrogram (top) with heat map (beneath) for all loci that were analysed in each isolate. The dendrogram illustrates relatedness based on the signal intensity of each locus across all isolates. Within the heat map, each locus (total = 7775) is shown vertically for each strain. Red indicates high signal intensity; yellow indicates marginal signal intensity, and blue indicates low signal intensity. The order of loci is identical for all strains. For adjusted calls, raw values were log transformed and normalized by dividing each value by the chip mean. Cut-off values for *p* calls were ≤0.89 = absent; ≥0.981 = present; and 0.9–0.98 = marginal. Asterisks indicate isolates that especially clustered together by pairwise comparison (Table 2).

TABLE 1

CC80:ST80-IV isolates examined

Isolate number	Year of isolation	Presumed country of origin	Age of patient (years)	Infection/screening[a]	Antibiotic resistance pattern[b]
1198	1997	Denmark	21	Skin and soft tissue infection (CA)	Ox, P, K, F
1199	2001	Egypt	43	Screening in Denmark after heart attack abroad (S)	Ox, P, S, T, K, F
1200	2001	Lebanon	5	Scratches infected during vacation in Lebanon (CA)	Ox, P, S, T, K, F
1201	2003	Denmark	20	Folliculitis at thigh, knee, and eyelid (HACO)	Ox, P, T, E, Cli, F
1202	2001	Denmark	19	Inflammation in axilla (CA)	Ox, P, T, F
1209	2001	Denmark	10	Skin abscesses (CA)	Ox, P, S, T, K, F

[a] CA, community-associated; S, surveillance; HACO, healthcare-associated community-onset.

[b] antibiotic resistance detected against: Ox, oxacillin; P, penicillin; S, streptomycin; T, tetracycline; E, erythromycin; Cli, clindamycin; F, fusidic acid; K, kanamycin.

TABLE 2

Pairwise comparison of CC80:ST80-IV isolates for the number of 7775 queried loci and the 3514 open reading frames (total loci minus intergenic sequences; shown in parentheses) that were present in one isolate but absent from another

	Loci present					
Loci absent	**1199**	**1200**	**1202**	**1201**	**1198**	**1209**
1199	0 (0)	55 (0)	63 (16)	99 (3)	145 (47)	142 (46)
1200	18 (0)	0 (0)	44 (17)	80 (3)	125 (47)	130 (44)
1202	65 (11)	79 (11)	0 (0)	79 (3)	145 (59)	146 (58)
1201	275 (22)	337 (22)	275 (23)	0 (0)	206 (64)	211 (63)
1198	366 (17)	449 (17)	383 (28)	239 (10)	0 (0)	175 (7)
1209	364 (18)	425 (19)	364 (38)	204 (10)	151 (8)	0 (0)

TABLE 3

GeneChip® loci which varied between the CC80:ST80-IV isolates

Genes	ORF no.	Description[a]	Results for: 1198	1199	1200	1201	1202	1209	Comments
	MW1419	Conserved hypothetical protein (MSSA476, MRSA252, MW2)	+	−	−	−	−	+	USA300− USA400−
	SAR395a	Conserved hypothetical protein (MRSA252)	−	+	+	+	+	−	USA300+ USA400−
	SAV0876	Conserved hypothetical protein similar to phage phi ETA protein (MU50)	+	−	−	−	−	+	USA300− USA400+
	SAV0880	Hypothetical protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0884	Phage phi 11-like int gene activator protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0884	Phage phi 11-like int gene activator protein (MU50)	−	−	−	−	−	−	USA300− USA400−
	SAV0885	Phage phi 11-like terminase protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0886	Similar to phage terminase large subunit (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0887	Phage phi MU50B/phi11-like portal protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0888	Phage phi MU50B/phi11-like head protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0890	Hypothetical phage phi MU50B/phi11-like protein (MU50)	−	−	−	−	−	−	USA300− USA400−
	SAV0890	Hypothetical phage phi MU50B/phi11-like protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0891	Hypothetical phage phi11 head protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0892	Phage phi MU50B/phi11-like head protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0893	Phage phi MU50B/phi11-like protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0894	Phage phi MU50B/phi11-like protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0896	Phage phi MU50B/phi11-like protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0897	Phage phi MU50B/phi11-like protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0898	Similar to phage phi MU50 tail protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0899	Hypothetical phage phi11 protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0900	Hypothetical phage phi 11 protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0901	Hypothetical phage minor tail subunit protein (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0902	Conserved phi ETA orf 54-like protein (Mu50)	+	−	−	−	−	+	USA300− USA400−
	SAV0903	Conserved phi ETA orf 55-like protein (Mu50)	+	−	−	−	−	+	USA300− USA400−
	SAV0904	phi ETA orf 56-like protein (Mu50)	+	−	−	−	−	+	USA300− USA400−
	SAV0905	phiETA ORF57-like protein (Mu50)	+	−	−	−	−	+	USA300− USA400−
	SAV0906	phiETA ORF58-like protein (Mu50)	+	−	−	−	−	+	USA300− USA400−

Genes	ORF no.	Description[a]	Results for: 1198	1199	1200	1201	1202	1209	Comments
	SAV0907	Conserved phage phiETA ORF59-like protein (Mu50)	+	−	−	−	−	+	USA300− USA400−
	SAV0909	Phage phi11 cell wall hydrolyase (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0910	Phage phi11 tail fiber (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV0913	Amidase (MU50)	+	−	−	−	−	+	USA300− USA400−
	SAV1977	phi PV83-like protein (Mu50)	+	−	−	−	−	+	USA300+ USA400−
	SAS1087	Conserved hypothetical protein (MSSA476)	−	+	+	+	+	−	USA300+ USA400+
	SA0043	Hypothetical protein pathogenicity island SaPIn1	+	+	+	−	−	+	USA300+ USA400+
	SA0044	Conserved hypothetical protein	+	+	+	−	−	+	USA300− USA400−
	SA0022	Hypothetical protein (N315)	+	−	−	+	−	+	USA300− USA400−
ccrB	SA0057	Cassette chromosome recombinase B (N315)	+	+	+	−	−	+	USA300+ USA400+
ccrA	SA0058	Cassette chromosome recombinase A (N315)	+	+	+	−	−	+	USA300+ USA400+
	SA0059	Putative membrane protein (N315)	+	+	+	−	−	+	USA300+ USA400+
	SA0061	Hypothetical protein (N315)	+	+	+	−	−	+	USA300− USA400−
	SA1591	Arsenical resistance operon repressor homologue (N315)	+	−	−	−	−	+	USA300− USA400−
	SA0321	Prophage L54a, Cro-related protein	+	−	−	−	−	+	USA300− USA400−
	SA0322	Putative prophage L54a repressor protein	+	−	−	−	−	+	USA300− USA400−
	SA0331	Hypothetical protein	−	+	+	−	+	−	USA300− USA400−
	SA0359	Hypothetical protein	+	−	−	−	−	+	USA300− USA400−
	SA0360	Conserved hypothetical protein	+	−	−	−	−	+	USA300− USA400−
	SA0397	Conserved hypothetical protein	+	+	+	+	+	−	USA300− USA400−
	SA0406	Hypothetical protein	+	+	+	−	+	+	USA300+ USA400−
sdrD	SA0520	Virulence gene (N315)	+	+	+	+	+	−	USA300+ USA400+
sdrE	SA0610	Virulence gene	+	+	+	+	+	−	USA300+ USA400+
	SA0753	Conserved hypothetical protein	+	+	+	+	+	−	USA300+ USA400+
	SA0848	Hypothetical protein	−	+	+	+	+	+	USA300+ USA400−
	SA0865	Hypothetical protein	−	+	+	−	+	−	USA300+ USA400+
	SA0871	Putatative acetyltransferase	−	+	+	−	+	−	USA300+ USA400+
	SA0881	Putative thioredoxin	−	+	+	+	+	−	USA300+ USA400+
	SA0984	Conserved hypothetical protein	−	+	+	−	+	−	USA300+ USA400+
	SA1345	Hypothetical protein	−	+	+	−	−	+	USA300+ USA400−

Genes	ORF no.	Description[a]	Results for: 1198	1199	1200	1201	1202	1209	Comments
	SA1346	Conserved hypothetical protein	+	+	+	+	+	−	USA300+ USA400+
	SA1527	Conserved hypothetical protein	+	−	−	+	−	−	USA300+ USA400−
	SA1573	Integrase/recombinase/transposase (phage)	−	−	−	−	+	−	USA300+ USA400−
	SA1575	Hypothetical protein	−	−	−	−	+	−	USA300+ USA400−
	SA1576	Hypothetical protein, similar to secretory antigen precursor SsaA	−	−	−	−	+	−	USA300+ USA400−
	SA1577	Conserved hypothetical protein	−	−	−	−	+	−	USA300+ USA400−
FtsK/SpoIIIE	SA1578	Cell division protein	−	−	−	−	+	−	USA300+ USA400−
	SA1579	Conserved putative conjugative transposon protein	−	−	−	−	+	−	USA300+ USA400−
	SA1580	Hypothetical protein	−	−	−	−	+	−	USA300+ USA400−
	SA1581	Conserved hypothetical protein	−	−	−	−	+	−	USA300+ USA400−
	SA1582	Conserved hypothetical protein	−	−	−	−	+	−	USA300+ USA400−
	SA1583	Replication initiation protein (transposon)	−	−	−	−	+	−	USA300+ USA400−
	SA1584	Hypothetical protein	−	−	−	−	+	−	USA300+ USA400−
	SA1585	Conserved hypothetical protein	−	−	−	−	+	−	USA300+ USA400−
	SA1586	Hypothetical protein	−	−	−	−	+	−	USA300+ USA400−
	SA1598	Conserved hypothetical protein (competence)	−	+	+	−	+	−	USA300+ USA400+
	SA1789	Hypothetical protein phage phi PVL	+	−	−	−	−	+	USA300− USA400−
	SA1829	Hypothetical protein	−	+	+	−	+	−	USA300+ USA400+
	SA1839	IS200-like transposase	−	+	+	−	+	−	USA300+ USA400+
epiG	SA1871	Epidermin immunity protein F	−	+	+	+	+	+	USA300+ USA400+
	SA2307	Hypothetical protein	−	+	+	−	+	−	USA300+ USA400+
	SA2327	Hypothetical protein (N315)	−	+	+	+	+	−	USA300+ USA400+
	SA2338	Hypothetical protein	−	+	+	+	+	+	USA300+ USA400+
	SA2487	Conserved hypothetical protein	−	−	−	+	−	−	USA300+ USA400+
repC	SAA0001	Replication initiation protein	−	+	+	−	+	+	USA300+ USA400+
tetR	SAA0002	Tetracycline resistance protein	+	+	+	−	+	+	USA300+ USA400+
pre	SAA0003	Plasmid recombination/mobilization protein	+	+	+	−	+	+	USA300+ USA400+

[a]Unless otherwise noted, poen reading frame (ORF) numbers and descriptions refer to *Staphylococcus aureus* strain COL. Hypothetical proteins are sequences lacking a homologue in the National Center for Biotechnology Information NR database; conserved hypothetical proteins have a homologue, although of no known function.