Multilocus sequence typing (MLST) analysis of Vibrio cholerae O1 El Tor isolates from Mozambique that harbour the classical CTX prophage

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INTRODUCTION

Vibrio cholerae is a Gram-negative pathogenic bacterium that causes severe dehydrating diarrhoeal disease (Faruque et al., 1998; Kaper et al., 1995; Mekalanos et al., 1997). The serogroup of V. cholerae is determined by the LPS structure. While over 206 different serogroups are currently recognized (Li et al., 2002), only the O1 and O139 serogroups have been linked to epidemic and pandemic cholera in humans. The O1 serogroup is classified into two biotypes, classical and El Tor, which can be distinguished by a number of phenotypic traits (Kaper et al., 1995). The pathogenesis of cholera is related mainly to the production of cholera toxin, encoded by the ctxAB genes. The cholera toxin genes ctxAB are located on the genome of a filamentous lysogenic phage designated CTXΦ (Waldor & Mekalanos, 1996). CTXΦ is integrated in the large chromosome of the El Tor biotype, or at two different sites of both chromosomes of the classical biotype (Davis et al., 2000). Various arrays of the CTX prophage and the related genetic element RS1 have been reported on the genomes of the O1 El Tor biotype and the O139 serogroup (Davis et al., 1999; Davis & Waldor, 2000; Heidelberg et al., 2000). The CTX phage and RS1 both contain the genes rstR, rstA and rstB. The phage-encoded protein RstA is required for phage genome replication, and RstB is required for phage genome integration. RstR is a repressor that down-regulates the rstA promoter. While there are genes of the phage core region on the CTX prophage genome, RS1 contains rstC instead. RstC is an anti-repressor of RstR, and promotes transmission of RS1 and CTXΦ (Davis et al., 2002). While solitary or truncated prophages are generally integrated into both chromosomes of classical biotype strains, classical biotype strains
containing multiple-copy CTX prophages have also been documented (Basu et al., 2000; Davis et al., 2000). The CTX prophages found in El Tor and classical biotypes have a major difference in rstr, a repressor of rsta that is required for replication of CTXφ (Kimsey & Waldor, 1998). Recently, genetic hybrids of V. cholerae O1 strains possessing both classical and El Tor biotypes were found in Bangladesh (Nair et al., 2002; Nusrin et al., 2004), which may imply that rstr is not biotype specific. V. cholerae O1 El Tor strain harbouring the classical CTX prophage was isolated in Beira, Mozambique, in 2004 (Ansaruzzaman et al., 2004). We further analysed the genetic relationship of these isolates by using a multilocus sequence typing (MLST) approach. MLST analysis of nine loci showed that the isolates from Mozambique and O1 El Tor strain N16961 (for which the whole genome sequence is known) have the same unique sequence type. We could also amplify the ctxB-rstr-rsta-rstB-phs-cep fragment from these isolates, which suggests that there is a tandem repeat of the classical prophage in the genome of the isolates from Mozambique.

METHODS

Bacterial strains and growth conditions. Forty V. cholerae isolates collected at the Cholera Treatment Centre, Beira, Mozambique, were analysed at the International Vaccine Institute (IVI) in Korea. For the comparison of sequences, five isolates each of V. cholerae O1 El Tor biotype (strain numbers 2201969, AR-17384, AR-11698, AR-17379 and AR-11585), classical biotype (strain numbers C-19385, F-2427, H-18, X-19850 and Y8661) and O139 (strain numbers AR196157, AR-18096, 2206945, 2206252 and AR-9954) were analysed at the International Vaccine Institute (IVI) in Korea. For the comparison of sequences, five isolates each of V. cholerae O1 Ogawa serotype, as described previously (Ansaruzzaman et al., 2004). All isolates agglutinated with chicken cell erythrocytes, were positive for El Tor-type haemolysin by the modified tube agglutination method, yielded a positive Voges–Proskauer reaction, and were resistant to polymixin B. They were sensitive to Merkerjee El Tor phage 5 but resistant to the classical phage IV (Table 1). The isolates were therefore classified as El Tor biotype.

RESULTS AND DISCUSSION

Subtyping of Mozambique isolates

All 40 Mozambican isolates were identified as V. cholerae O1 Ogawa serotype, as described previously (Ansaruzzaman et al., 2004). All isolates agglutinated with chicken cell erythrocytes, were positive for El Tor-type haemolysin by the modified tube agglutination method, yielded a positive Voges–Proskauer reaction, and were resistant to polymixin B. They were sensitive to Merkerjee El Tor phage 5 but resistant to the classical phage IV (Table 1). The isolates were therefore classified as El Tor biotype.

Sequence type (ST) of V. cholerae isolates from Mozambique

Though a number of MLST studies have been conducted on V. cholerae, most have focused on O139 strains, and only a few O1 strains have been analysed with a limited number of loci for MLST analysis (Garg et al., 2003; Kotetishvili et al., 2003). We applied the MLST analysis method of Garg et al. (2003) to O1 El Tor and classical biotypes. Among 40 Mozambique V. cholerae O1 isolates transported to IVI, 23 were fully sequenced at nine MLST loci, and all 23 had identical DNA sequences at the loci. The remaining 17 isolates were sequenced at six to eight MLST loci, and each sequenced locus was identical to that of the other isolates. We therefore concluded that the Mozambican isolates belonged to one ST. When the sequence of each allele in our study was identical to previously reported allele sequences, the allele type number was denoted with the same number. The allele types and ST results are summarized in Table 2. We found one new allele type in rsta, recA and chu loci in all five classical biotype strains, and one new rsta allele type in the O139 strains. We also compared the DNA sequence of nine loci of the Mozambican isolates with those of the El Tor N16961 strain, for which the whole genome sequence is available (Heidelberg et al., 2000). As shown in Table 2, the ST of the Mozambique isolates was identical to that of V. cholerae O1 El Tor N16961. The allele profile of O1 El Tor N16961 and Mozambique isolates is 1, 1, 1, 2, 1, 1, 1, 1, 1 (in the order dnaE, lap, rsta, gmd, recA, pgm, gyrB, cat and chu).
This allele profile does not match any of the O139 strains previously reported (Table 2; Garg et al., 2003). As this MLST method can be applied to O1 El Tor and classical biotypes, we propose further MLST analyses of O1 strains.

Based on allele profiles of *V. cholerae*, allele profile similarities were calculated and divided into four groups. The highest similarity value was found between *V. cholerae* Mozambique and *V. cholerae* O1 El Tor. After determining the *V. cholerae* allele profiles, we constructed a dendrogram using unweighted pair grouping with mathematical averaging (UPGMA) (Fig. 1). The Mozambique isolates were closely related to *V. cholerae* O1 El Tor compared to strains O139 and O1 classical biotype. When all sequences of the nine loci were used to calculate sequence similarity, the *V. cholerae* isolates from Mozambique and *V. cholerae* O1 El Tor strains were the most similar. On the basis of the allele profile, the dendrogram and the sequence similarities, we concluded that *V. cholerae* isolates from Mozambique are closely related to *V. cholerae* O1 El Tor.

**CTX prophage of Mozambique *V. cholerae* isolates**

A 1447 nt DNA fragment, encompassing the first 288 (of 336) nt of classical *rstR*, ig-2, and the first 1032 nt of *rstA*, was amplified only from classical strains and Mozambique isolates using primer set 4. The DNA sequence of Mozambique isolates showed 100% homology with that of the classical biotype *rstR* and ig-2. With primer set 1, a 1460 nt fragment was amplified from all five O1 El Tor strains and all five O139 strains; however, there was no amplification of this DNA fragment in classical strains or in the Mozambique isolates. From these results, we concluded that only the classical *rstR* was present in the CTX prophage of *V. cholerae* isolates from Mozambique.

The DNA sequence of the 618 nt *rstA* internal fragment for MLST analysis (from nt 415 to 1032, out of 1083 nt of the full-length *rstA*) of Mozambique isolates was identical to that of the most common allele type of O139 and O1 El Tor N16961 (allele type 1). However, the rest of the *rstA* of the Mozambique isolates was different from *rstA* of El Tor N16961. When we compared the full-length sequences of *rstA* of Mozambique isolates to those of other *V. cholerae* strains, we found an overall sequence similarity of over 99%. We identified 10 polymorphic sites (Fig. 2). The first four variable sites (27, 162, 183 and 258) of Mozambique isolates were identical to those of the classical biotype, and the last six variable sites that belong to the internal fragment used for the MLST analysis were the same as those of the El Tor biotype. The positions of all polymorphic-site nucleotides within their codons were third positions, and all differences were synonymous changes when translated. Although the *rstA* of the Mozambique isolates seems to be a

**Table 1.** Biotype characterization of *V. cholerae* O1 isolated from Beira, Mozambique

<table>
<thead>
<tr>
<th>Test</th>
<th>Mozambique strain (<em>n</em> = 40)</th>
<th>Classical reference strain</th>
<th>El Tor reference strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicken erythrocyte agglutination</td>
<td>+</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Voges–Proskauer reaction</td>
<td>+</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Sensitivity to:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymyxin B (50 i.u.)</td>
<td>R</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Mukerjee classical phage IV</td>
<td>R</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Mukerjee El Tor phage 5</td>
<td>S</td>
<td>R</td>
<td>S</td>
</tr>
</tbody>
</table>

| r, Resistant; S, sensitive. |

<table>
<thead>
<tr>
<th>Test</th>
<th>Mozambique</th>
<th>Classical</th>
<th>El Tor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicken erythrocyte agglutination</td>
<td>+</td>
<td>−</td>
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<td>Voges–Proskauer reaction</td>
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<td>+</td>
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<tr>
<td>Polymyxin B (50 i.u.)</td>
<td>R</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Mukerjee classical phage IV</td>
<td>R</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Mukerjee El Tor phage 5</td>
<td>S</td>
<td>R</td>
<td>S</td>
</tr>
</tbody>
</table>

**Table 2.** Allele profiles of *V. cholerae* O1 classical, O1 El Tor and O139 strains, and Mozambique isolates of this study

Numbers are previously reported allele profile numbers (Garg et al., 2003). N, New allele type identified in this study.

<table>
<thead>
<tr>
<th>Strain or isolate</th>
<th>Locus</th>
<th>dnaE</th>
<th>lap</th>
<th>rstA</th>
<th>gmd</th>
<th>recA</th>
<th>pgm</th>
<th>gyrB</th>
<th>cat</th>
<th>chi</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1 El Tor</td>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>O1 classical</td>
<td></td>
<td>1</td>
<td>1</td>
<td>12 (N)</td>
<td>2</td>
<td>3 (N)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>6 (N)</td>
</tr>
<tr>
<td>O139</td>
<td></td>
<td>1</td>
<td>1</td>
<td>13 (N)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mozambique</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>O1 El Tor N16961</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Fig. 1.** Dendrogram of *V. cholerae* strains based on allele profiles created by using unweighted pair grouping with mathematical averaging (UPGMA). *V. cholerae* isolates from Mozambique were closely related to *V. cholerae* O1 El Tor strains.
hybrid of classical biotype and El Tor biotype, the generation mechanisms of this mosaic structure would be quite complicated. Therefore, we propose the presence of a classical CTX phage with the same variable sites in those of the Mozambique isolates.

Given that the ST of the Mozambique isolates is identical to that of El Tor strain N16961 and that the CTX prophage of the Mozambique isolates is the classical type, it is likely that the Mozambique strain originated from the El Tor biotype. One possible (and the simplest) mechanism for the generation of this strain is the infection of the El Tor biotype strain by the classical CTX phage that has the Mozambique rstA. This classical CTXΦ either integrated into an O1 El Tor biotype strain that had lost the existing El Tor prophage or replaced the existing El Tor prophage. Since the classical CTX phage particle, along with the classical biotype strains of V. cholerae, is believed to have been extinct from 1994 onwards (Nair et al., 2002; Safa et al., 2005), the acquisition of the classical CTX phage genome by the El Tor biotype remains an open question. Epidemic cholera in Mozambique, caused by V. cholerae O1, Ogawa, biotype El Tor strains, was first reported in 1997 (Folgos et al., 2001). Those strains contained two copies of CTX prophage, and were resistant to sulphonamides and trimethoprim, characteristics similar to those of the Mozambique isolates. The relationship between the isolates from the 1997 and 2004 epidemics can be established with the methods presented here. Further studies will be needed to understand the origin of the Mozambique strains, since no classical biotype strains have reached the African continent during the past 30 years of the seventh cholera pandemic. The investigation of the pathogenicity of this hybrid strain and the intensity of symptoms in patients should also be investigated, because the O1 El Tor and classical biotype strains differ in these aspects.

**CTX prophage array in the genome of Mozambique V. cholerae isolates**

We examined the CTX prophage array of the Mozambique isolates with respect to two aspects: 1) the presence of the RS1 element or the truncated prophage, and 2) the presence of the tandem repeat of the CTX prophage. To see the presence of the RS1 element or 3′ truncated CTX on the 5′ region of the prophage, we used primer set 2, designed to amplify the fragment between rstB and rstA, as shown in Fig. 3. The same primer set produced a different size DNA fragment from the classical biotype and El Tor biotype strains. A 1962 nt fragment was amplified from the classical biotype strains C-19385, F-2427, H-18, X-19850 and Y-8661, which implies that there are truncated CTX prophages in these strains, as shown in Fig. 3. From all five El Tor strains and from three O139 strains (AR-196157, AR-18096 and AR-9954), a 2543 nt fragment was amplified, showing the presence of the RS1-CTX prophage array. No DNA fragment was amplified from the Mozambique isolates with the same primer set, indicating that no RS1 element is present upstream of the CTX prophage, or the CTX′ truncated prophage. We confirmed the absence of the RS1 element in the Mozambique isolates with an rstC primer set. No DNA amplification was obtained from Mozambique isolates, but a 173 nt fragment was amplified from all O1 El Tor and O139 strains (data not shown).

We used primer set 3 to evaluate the presence of the tandem repeat of the CTX prophage on the genome of the Mozambique isolates. The PCR product encompassing ctxB-ig2-rstR-ig2-rstB-psl-cep can be amplified only from a tandem repeat of the CTX prophage. As expected, there was no amplification from classical biotype strains (data not shown). This DNA fragment was PCR-amplified from only one O1 El Tor strain (2201969) and two O139 strains (AR196157 and 2206945). The DNA sequence of the fragment from the O139 isolates showed that these strains had a similar genetic structure to that of strain O139 AS207, which contains one El Tor prophage followed by a tandem repeat of a new-type prophage, CTX Calcutta, as shown in Fig. 3 (Davis et al., 1999). A DNA fragment of similar size was amplified from most Mozambique isolates, and we analysed the DNA sequence of this fragment (GenBank accession no. DQ012295). Mozambique isolates contain an ig-1 that is homologous to that of the CTX Calcutta prophage (18 nt different out of 730 nt), followed by a classical biotype rstR instead of the Calcutta type rstR. The potential genetic structure and the array of CTX prophages of the Mozambique isolate are shown in Fig. 3. Since the infectious CTX virion particles (CTXΦ) can be produced from the tandem repeat prophage array (Davis et al., 2000), we expect that this tandem-repeat classical prophage array can yield classical CTX phage particles.

The CTX prophage integration site on the large chromosome is well defined (Heidelberg et al., 2000), and we could detect the integration site on the large chromosome of O1 El

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**Fig. 2.** Variable sites of the rstA gene among O1 classical and O1 El Tor (strain N16961) biotypes, O139 strains, and Mozambique isolates. The vertical numbers indicate the positions of variable sites, numbered from the first nucleotide of rstA. The first four variable sequences (bases 27, 162, 183 and 258) of rstA of the Mozambique isolates are identical to those of O1 classical biotype, but six variable sites (from base 345 to base 774) are identical to those of O1 El Tor N16961. However, variations similar to those of the Mozambique isolates were also present in O139 isolates. The accession nos of O139 strains at the NCBI database are: O139 9803, AF302794; O139 AS207, AF110029 (Davis et al., 1999); O139 86015, AF220606.
Tor, classical and O139 strains by using PCR primer pairs that straddled both ends of the prophage. However, we could not define the integration site of the CTX prophage of the Mozambique strains with the same primers (data not shown). Identification of the CTX prophage location and full sequencing of the tandem repeat prophage are planned.

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