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High Genetic Diversity Revealed by Variable-Number Tandem Repeat Genotyping and Analysis of hsp65 Gene Polymorphism in a Large Collection of “Mycobacterium canettii” Strains Indicates that the M. tuberculosis Complex Is a Recently Emerged Clone of “M. canettii”

Michel Fabre,1 Jean-Louis Koeck,2 Philippe Le Flèche,3 Fabrice Simon,4† Vincent Hervé,1 Gilles Vergnaud,3 and Christine Pourcel⃣,6*

Laboratoire de Mycobactériologie, HIA Percy, 92140 Clamart,1 HIA Val de Grâce, 75005 Paris,2 Centre d’Etude du Bouchet, 91710 Vert le Petit,3 Génome, Polymorphisme et Minisatellites (GPMS), Institut de Génétique et Microbiologie, Université Paris XI, 91405 Orsay Cedex,5 and Institut Pasteur, 75015 Paris,6 France, and CHA Bouffiou, Djibouti, Republic of Djibouti4

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We have analyzed, using complementary molecular methods, the diversity of 43 strains of “Mycobacterium canettii” originating from the Republic of Djibouti, on the Horn of Africa, from 1998 to 2003. Genotyping by multiple-locus variable-number tandem repeat analysis shows that all the strains belong to a single but very distant group when compared to strains of the Mycobacterium tuberculosis complex (MTBC). Thirty-one strains cluster into one large group with little variability and five strains form another group, whereas the other seven are more diverged. In total, 14 genotypes are observed. The DR locus analysis reveals additional variability, some strains being devoid of a direct repeat locus and others having unique spacers. The hsp65 gene polymorphism was investigated by restriction enzyme analysis and sequencing of PCR amplicons. Four new single nucleotide polymorphisms were discovered. One strain was characterized by three nucleotide changes in 441 bp, creating new restriction enzyme polymorphisms. As no sequence variability was found for hsp65 in the whole MTBC, and as a single point mutation separates M. tuberculosis from the closest “M. canettii” strains, this diversity within “M. canettii” subspecies strongly suggests that it is the most probable source species of the MTBC rather than just another branch of the MTBC.

The Mycobacterium tuberculosis complex (MTBC) includes M. tuberculosis, M. africanum, M. bovis, and M. microti. Using molecular data, van Soolingen et al. recently proposed to consider “M. tuberculosis subspp. canettii” as a new subspecies of the MTBC, although its colonies are eugonous and have a smooth appearance in contrast to the other bacteria of the MTBC (25).

The first such strain was isolated by Georges Canetti in 1969. About 20 years later, two additional strains were isolated from patients with tuberculosis (TB) lymphadenitis (16, 25). In 2002 Milten et al. described the characteristics of two new strains of “M. canettii” isolated from two French patients with pulmonary TB (14). Considering the very small number of “M. canettii” infections reported to date, no difference with the classical M. tuberculosis infection can be identified. Nonetheless, some authors suggest that “M. canettii” could induce milder pneumonia than classical TB (12, 14).

Studies by Brosch et al. and Marmiesse et al. of 20 regions where insertion-deletion events took place in the genome of M. tuberculosis suggested that “M. canettii” diverged first from the rest of the MTBC (1, 13). The “M. canettii” taxon can also be easily differentiated from the other members of the MTBC on the basis of a restriction site polymorphism in the hsp65 gene (8).

All the described “M. canettii” strains show only two bands by spoligotyping (25), corresponding to spacers 30 and 36, which indicates that the direct repeat (DR) locus in “M. canettii” is very different from that of the other members of the MTBC. By sequencing, van Embden et al. showed the existence of at least 26 spacers that appear to be unique to “M. canettii” (24).

Fromingham et al. (7) and Supply et al. (21) were the first to describe the use of polymorphic tandem repeat loci for genotyping MTBC strains. Variable-number tandem repeat (VNTR) analysis is a very promising approach, since it successfully discriminates low-copy-number IS6110 strains (2), which are poorly resolved by the otherwise quite efficient IS6110 typing (23). In addition, tandem repeat typing can be standardized, and common databases are easily set up (3, 10). However, typing by multiple methods is still required to attain maximum specificity and more importantly to correlate multiple-locus VNTR analysis (MLVA)-derived data sets with data based on previous methods. One reason for this is that mutation rates and evolution of tandem repeat loci in bacteria are not yet fully understood, so that MLVA data interpretation is still to some extent a research area.

Based upon the available genomic sequences for M. tuberculosis, the genetic diversity of “M. canettii” subspecies strongly suggests that it is the most probable source species of the MTBC rather than just another branch of the MTBC.
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culosis, we previously selected and analyzed a larger collection of VNTRs, giving rise to a high-resolution MLVA typing assay (10). Using a selection of 21 VNTRs we have typed 43 smooth variants of M. tuberculosis and compared their genotype with one of the previously described “M. canetti” strains and with the collection of MTBC strains described by Le Flèche et al. (10).

MATERIALS AND METHODS

Strains. The 43 smooth strains investigated in this study were all naiacin negative, nitrate reductase positive, urease positive, and thiopen-2-carboxylic acid hydrazide positive. They were isolated from sputum, gastric fluid, lymph node, or ascites fluid.

Most patients were Djiboutian, and the others were expatriated patients living in Djibouti. No epidemiological link could be established between the patients. The detailed description of the clinical features of the cases will be published elsewhere (J.-L. Koeck et al., unpublished data). DNA from “M. canetti” strain CIPT4010060 (referred to in this work as CIPT060) was kindly provided by Véronique Vincent, percy8 (see Fig. 1) is the same as strain 990161 in reference 13. The reference strain M. tuberculosis H37Rv was used as a control in the MLVA (10).

VNTR analysis. PCR amplification of 21 VNTR loci and electrophoresis of products on agarose gels were carried out as described in reference 10. MIRU26 (22) was used instead of Mtub38, which is difficult to type because of the presence of repeats of different unit length at this locus (10).

Data management and analyses. Gel images were analyzed using a bionumerics software package (version 3.5; Applied-Maths, Sint-Martens-Latem, Belgium) as previously described (10). The number of repeats in each allele was deduced from the amplicon size. The resulting data were analyzed with bionumerics as a character data set. Clustering analysis was done using the categorical data sets (5). The resulting tree minimizes the summed cation of 21 VNTR loci and electrophoresis of products on agarose gels were carried out as described in reference 10. MIRU26 (22) was used instead of Mtub38, which is difficult to type because of the presence of repeats of different unit length at this locus (10).

Analysis of the DR locus by PCR amplification and characterization of new spacers. PCR amplification was performed using primers selected in the spacers described by van Embden et al. (24): primer pair Mcan80For (5'-TACGCGGGACGGAAAC) were used to amplify the DR region as formerly described (8) using primers DRa (5'-TTGCAAGCCGGCACCGG) and DRb (5'-CGGACGCGAAGCGATCG) of reference 10 should be increased by 1 when compared to reference 10 is coded 6 in the present report to avoid the ambiguous code 0 in percy79 (consequently, the Mtub39 values indicated in reference 10 should be increased by 1 when comparing the two data sets). Such new “zero repeat unit” alleles (which are not PCR amplification failures) are observed (Table 1) at loci MIRU02 (genotype 4, strain percy79) and MIRU27 (genotype 14, strain percy65). In a dendrogram produced with the MLVA data and some previously obtained M. tuberculosis and M. bovis data, all the smooth strains, including the previously characterized “M. canetti” strain CIPT060, cluster into a very distant and separate group (not shown). When a dendrogram is produced with the smooth strains and the H37Rv control alone (Fig. 1), one group (group A) comprising 31 strains has a quite-homogenous genotype (genotypes 1 to 3; one or two differences), whereas the remaining 13 strains (including the previously described “M. canetti” strain CIPT060) display more diversity. Among the latter, five strains are clustered into a second group (group B). The diversity is shown for example with markers ETR-C and Mtub30, which possess only one allele in group A strains and, respectively, six and four different alleles in the remaining strains (Table 1).

As a complement, a minimum spanning tree analysis was performed (Fig. 2). This kind of analysis is applicable to categorical data sets (5). The resulting tree minimizes the summed distance of all branches of the tree (the distance between two strains being the number of markers by which they differ). The group A strains (genotypes 1 to 3, light blue, Fig. 2) are closely related and are grouped into a single complex. Genotype 2, which includes 28 isolates, is the center of this cluster. Group B strains (genotypes 5 to 7) are similarly clustered. The eight remaining genotypes are very loosely connected to each other, suggesting a very high diversity. The CIPT060 “M. canetti” strain is genotype 12.

DR typing. van Embden et al. sequenced the DR locus in one “M. canetti” strain, strain SO93 (25), and described the existence of 26 new spacers (spacers 69 to 94) which were absent from all the M. tuberculosis tested. We first tested for the presence of this particular DR by PCR and sequencing using primers flanking the locus and primers corresponding to spacers 80 and 83 (McanFor plus Mcan38Rev and Mcan80For plus McanRev) (data not shown). The result suggested that the locus was present only in a subset of “M. canetti” strains and that two strains, percy32 and CIPT060, had additional spacers. We further investigated the locus by choosing two pairs of primers in spacers 80 and 83 and in spacers 73 and 76 and performing a PCR on all the smooth strains (Fig. 3 shows the result for a subset of strains). PCR using primers Mcan80For and Mcan83Rev produced an ampiclon of the expected size (202 bp) in all the group A strains and in the reference strain CIPT060 and strain percy32 (Fig. 3A). The same result was obtained with primers Mcan73For and Mcan76Rev (expected ampiclon size, 213 bp) except for the two strains CIPT060 and percy32 (lanes 16 and 20). The larger amplicon (505 bp) obtained in these two strains was sequenced, leading to the identification of the same four (and previously unknown) spacers (Fig. 3B). In 11 strains this approach failed to detect any spacer (Fig. 1).
To check whether a DR locus with unknown spacers might be present in some of the strains, we performed a PCR amplification with primers DRa and DRb localized in the constant region of the DR. No amplification was observed in 10 strains, confirming the complete absence of DR structure in these strains (Fig. 1). In contrast an amplification product in the form of a ladder was obtained with strain percy79 (Fig. 4A). We purified amplicons of a size ranging between 100 and 600 bp and cloned them into a plasmid vector (Fig. 4B and C). Sequencing of the insert from eight clones led to the identification of 20 spacers, all of them previously unknown.

When analyzing the polymorphism of the hsp65 gene by PCR restriction analysis (PRA) using HhaI, we found that 43 of the 44 smooth strains studied (including CIPT060) had the same specific “M. canettii” profile formerly described by Goh et al. (8) and different from that of the MTBC strains. Figure 5A shows the constant pattern observed in representative strains from the MTBC. In H37Rv, M. africanum type I, M.

### Table 1. Genotyping data obtained by MLVA in this study

| Genotype | ETR-A | ETR-B | ETR-C | ETR-D | ETR-E | MIRU-02 | MIRU-10 | MIRU-16 | MIRU-23 | MIRU-40 | MIRU-49 | MIRU-50 | MIRU-51 | MIRU-52 | MIRU-53 | MIRU-54 | MIRU-55 | MIRU-56 | Qub1 1a |
|----------|-------|-------|-------|-------|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| ETR-A    | ETR-B | ETR-C | ETR-D | ETR-E | MIRU-02 | MIRU-10 | MIRU-16 | MIRU-23 | MIRU-40 | MIRU-49 | MIRU-50 | MIRU-51 | MIRU-52 | MIRU-53 | MIRU-54 | MIRU-55 | MIRU-56 | Qub1 1a |
| ETR-A    | ETR-B | ETR-C | ETR-D | ETR-E | MIRU-02 | MIRU-10 | MIRU-16 | MIRU-23 | MIRU-40 | MIRU-49 | MIRU-50 | MIRU-51 | MIRU-52 | MIRU-53 | MIRU-54 | MIRU-55 | MIRU-56 | Qub1 1a |
| ETR-A    | ETR-B | ETR-C | ETR-D | ETR-E | MIRU-02 | MIRU-10 | MIRU-16 | MIRU-23 | MIRU-40 | MIRU-49 | MIRU-50 | MIRU-51 | MIRU-52 | MIRU-53 | MIRU-54 | MIRU-55 | MIRU-56 | Qub1 1a |
| ETR-A    | ETR-B | ETR-C | ETR-D | ETR-E | MIRU-02 | MIRU-10 | MIRU-16 | MIRU-23 | MIRU-40 | MIRU-49 | MIRU-50 | MIRU-51 | MIRU-52 | MIRU-53 | MIRU-54 | MIRU-55 | MIRU-56 | Qub1 1a |

**FIG. 1.** MLVA cluster analysis. Clustering analysis was done using the categorical and unweighted pair group method with arithmetic averages options. From left to right, the columns designate the strains names, the genotype number (geno), the result obtained for the PCR amplification of part of the DR locus using “canettii-specific” spacers 73 to 76 or 80 to 83 (24), and the hsp65 profile. The asterisks indicate that sequencing data have been produced. The hsp65 fragment has been sequenced in at least one strain from each genotype (SNPs 2 and 3 [Fig. 5] are not detected by PCR-restriction fragment length polymorphism analysis). Strains H37Rv and CIPT060 are underlined.
africanum type II, M. bovis, and M. microti, the characteristic restriction fragments are 186, 103, 72, and 63 bp (and a non-visible 17-bp fragment) (Fig. 5A, lanes 2 to 6, and B, lane 11). In all but one “M. canettii” strain, the 186- and 72-bp fragments are absent, replaced by a 258-bp fragment because one HhaI site is lacking (Fig. 5A, lane 7, and B). In strain percy65 the 258-bp fragment is absent and presumably replaced by a 235-bp fragment (Fig. 5B, lane 3). In order to further analyze the hsp65 polymorphism we sequenced the PCR product of 16 “M. canettii” strains representing all 14 different genotypes and compared the sequences to that of H37Rv (Fig. 5D; a representative set of sequences is shown). All the strains showed the expected C-to-T nucleotide change compared to H37Rv (Fig. 5D; a representative set of sequences is shown). All the strains showed the expected C-to-T nucleotide change compared to H37Rv, leading to the absence of an HhaI site (Fig. 5D; single nucleotide polymorphism [SNP] 4). A second C-to-T transition was observed in eight strains, percy26b, percy258, percy94, percy89, percy214, percy79, percy25, and percy99b (SNP 3, Fig. 1; the corresponding genotypes are shown in green in Fig. 2). In strain percy65, three other nucleotide differences were observed. An A-to-G change created a new HhaI site (SNP 1), explaining the appearance of the 235-bp fragment upon HhaI digestion (Fig. 5B). A C-to-T transition created a DdeI site (SNP 5). The existence of this predicted DdeI site was checked by digestion of the PCR amplicons. Two fragments of the expected size (330 and 111 bp) were indeed observed in strain percy65 (Fig. 5C, lane 3), whereas neither the representative MTBC strains (Fig. 5A, lanes 9 to 13) nor the other “M. canettii” strains possessed a DdeI site. The last change in strain percy65 was a G-to-A change (SNP 2).

DISCUSSION

In the last few years, an exceptional collection of 43 smooth strain variants of M. tuberculosis, originating from the Republic of Djibouti, has been constituted. The very rare instances of such strains reported before have been estimated to be sufficiently different from the other MTBC species and sufficiently similar to one another to be given a specific name, “M. canettii.” We have investigated this extended collection together with one previously identified “M. canettii” strain, using three complementary molecular tools, MLVA, DR locus investigations, and hsp65 partial gene sequencing (and/or SNP typing). The results obtained clearly demonstrate that this strain collection represents a genetically homogeneous group, quite distinct from the MTBC. The observed relative homogeneity indicates that all these strains should indeed be considered as “M. canettii” strains. However, and very interestingly, this overall homogeneity does cover a diversity of genotypes and sequences which appears to be much larger than those observed across the whole MTBC. This is all the more remarkable in view of the very restricted geographic area from which all
strains investigated originate, the Republic of Djibouti, on the Horn of Africa. We review here the present findings.

The 43 smooth variants of *M. tuberculosis* have characteristics in common with the representative "*M. canettii*" strain analyzed, such as a specific polymorphism of the *hsp65* gene, but can be separated into several groups on the basis of the other molecular tests: (i) clustering by MLVA genotyping (Table 1; Fig. 1 and 2), (ii) the presence of a DR region in one

FIG. 3. Structure of the DR locus. PCR using primers Mean80For and Mean83Rev (A) or Mean73For and Mean76Rev (B) on 24 smooth strains and H37Rv. The 100-bp ruler is used as size marker (lanes 1, 11, 19, and 28). No amplicon is observed in H37Rv (lane 2) and in seven smooth strains (lanes 9, 12, 21, 23, 24, 25, and 27). (B) Strains percy32 and CIPT060 have four additional new spacers as shown by the presence of a 505-bp amplicon and by sequencing.

FIG. 4. Cloning of new spacers from strain percy79. (A) PCR amplification was performed using primers DRa and DRb on 16 "*M. canettii*" strains. Amplification product from strain percy79 was purified and cloned into the pGEM-T Easy vector (B), and inserts were analyzed by PCR amplification (C). Lanes 1, 10, and 19 in panels A and C contain 100-bp ruler DNA size markers.
group containing a collection of unique spacers (Fig. 3 and 4), (iii) the absence of DR in the second group (Fig. 2 to 4), and (iv) additional polymorphism in the hsp65 gene (Fig. 5).

MLVA places the 44 strains together in a separate group compared to almost 200 strains of the MTBC similarly analyzed (10; unpublished data). For several markers, some alleles are unique to "M. canettii," such as ETR-A (allele 10), ETR-C (alleles 6 and 10), MIRU-02 (allele 3), MIRU-40 (allele 8), and Mtub29 (allele 5). Two markers are monomorphic in this collection, ETR-A and Mtub01. In contrast, ETR-A was found to be highly polymorphic in the MTBC (19). Here a unique "M. canettii"-specific allele is observed.

The strains percy32 and CIP060, which possess a DR locus with additional spacers compared to those described by van Embden et al. (24), constitute a branch more closely related to group A strains than to the rest. Ten strains lacking a DR locus are loosely connected (Fig. 1 and 2). Analysis of the PCR amplification product obtained with primers corresponding to the conserved repeat of the DR locus shows that strain percy79 possesses a not previously described set of spacers. Previous work (24) suggested that a common ancestor bearing a large number of units has evolved by the interstitial deletion of motifs to explain the hundreds of different combinations seen in contemporary MTBC strains (6). The fact that strains which lack a DR locus have highly diverged genotypes (here, for instance, strain percy65, [Fig. 2] and the genotypes 5 to 10 and 13) suggests that the deletion occurred at least twice independently in the different strains. Further molecular work such as spoligotyping and sequencing across the "missing DR" might improve the understanding of the origin and history of the DR locus. Considering the genome microdeletions that occurred during the MTBC evolution and separated M. bovis from M. tuberculosis, Brosch et al. (1) concluded that M. canettii is the species closest to the common ancestor. This analysis was based on the investigation of five "M. canettii" strains, which were shown to be devoid of the set of deletions which differentiate the other members of the MTBC. The relatively very high variability of the MTBC in terms of microdeletion events is quite interesting and probably reflects a sudden change of environment and selection pressure (some parts of the genome then becoming dispensable) rather than true evolutionary distance.

Our investigation on a relatively large collection of smooth strains, recruited in a very limited geographic area (the Republic of Djibouti), demonstrates that the genetic heterogene-

FIG. 5. PCR-restriction fragment length polymorphism analysis of the hsp65 locus. (A) hsp65 PRA patterns of representative strains from the MTBC after digestion with HhaI (left) or DdeI (right). The representative "M. canettii" strain CIP060 shows a different pattern with HhaI as expected (lane 7) but not with DdeI (lane 14). (B) Fifteen smooth strains and H37Rv upon digestion of the 441-bp amplicon with HhaI. (C) Same as panel B, using DdeI instead of HhaI. A 100-bp ruler is used as size marker. Strain percy65 has a unique digestion pattern as exemplified. (D) Multiple alignments using the CLUSTALW algorithm of the 180-bp portion of the hsp65 gene in H37Rv and smooth strains showing five single nucleotide changes, numbered 1 to 5. The SNP described by Goh et al. (8) is SNP 4.
ity (not taking into account deletions) within “M. canetti” is much larger than within the whole MTBC. This is suggested first by the MLVA data (Fig. 1 and 2). In spite of the suspicion that tandem repeat loci may be under variable and specific evolutionary pressures, the clustering of strains by MLVA does make sense (15, 17). This is illustrated by a growing number of studies, not only of M. tuberculosis, in which MLVA clustering data have been compared to previous knowledge (3, 11) and which validate this approach as a clinical epidemiologic tool (19). In the present investigation, percy32 and CIPT060, for which validate this approach as a clinical epidemiologic tool data have been compared to previous knowledge (3, 11) and studies, not only of make sense (15, 17). This is illustrated by a growing number of M. tuberculosis AF2122, emerged subspecies of the available data strongly suggest that the MTBC is a recently diverged. In contrast, no sequence difference at this locus is seen between the three sequenced genomes, diverged. In contrast, no sequence difference at this locus is seen between the three sequenced genomes, M. bovis strain AF2122, M. tuberculosis strains H37Rv, and CDC1551. Not a single SNP was observed among either the 267 strains representing the MTBC diversity (and including M. microti, M. africanum, M. bovis) or the M. bovis BCG strains (20). In addition only one SNP separates any member of the MTBC investigated so far from the closest “M. canetti” sequence (Fig. 5D), whereas four different SNPs have been identified within the present collection of “M. canetti.” This implies that the “M. canetti” group is much older than the MTBC. In other words, the available data strongly suggest that the MTBC is a recently emerged subspecies of “M. canetti.” Furthermore, all the “M. canetti” strains investigated originate from the Republic of Djibouti, i.e., a very limited geographic area, and were collected over a short time period, so that the diversity detected probably underestimates the true diversity of the species.

This finding clearly raises a number of interesting questions. Smooth M. tuberculosis strains have not been detected elsewhere in spite of the fact that they show a very remarkable colonial morphology and spoligotype (25) and could not have been missed. It is tempting to speculate that the MTBC originates from East Africa. One successful clone spread, whereas the rest of the progenitor species, “M. canetti,” remained in East Africa. It may be relevant in this view to recall that the group of ancestral M. tuberculosis strains without deletions of TbD1 (13) is associated with the East African Indian type of strains (19).

Finally, a reservoir must exist. In spite of the lack of epidemiological link between the different patients, we show here that one clone (genotype 2) is responsible for a large proportion of cases. Field investigations would be of great interest in trying to find this reservoir.

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