

Prevalence of Transmitted HIV-1 Drug Resistance Among Treatment-naive Individuals in China, 2000-2016

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Abstract

HIV with transmitted drug-resistance (TDR) limits the therapeutic options available for treatment-naive HIV patients. This study aimed to further our understanding of the prevalence and transmission characteristics of HIV with TDR for the application of first-line antiretroviral regimens. A total of 6578 HIV-1 protease/reverse-transcriptase sequences from treatment-naive individuals in China between 2000 and 2016, were obtained from the Los Alamos HIV Sequence Database and were analyzed for TDR. Transmission networks were constructed to determine genetic relationships. The spreading routes of large TDR clusters were identified using a Bayesian phylogeographic framework. TDR mutations were detected in 274 (4.51%) individuals, with 1.40% harboring TDR to nucleoside reverse transcriptase inhibitors, 1.52% to non-nucleoside reverse transcriptase inhibitors, and 1.87% to protease inhibitors. The most frequent mutation was M46L (58, 0.89%), followed by K103N (36, 0.55%), M46I (36, 0.55%), and M184V (26, 0.40%). The prevalence of total TDR initially decreased between 2000 and 2010 (OR = 0.83, 95% CI 0.73–0.95), and then increased thereafter (OR = 1.50, 95% CI 1.13–1.97). The proportion of sequences in a cluster (clustering rate) among HIV with TDR sequences was lower than that of sequences without TDR (40.5% vs. 48.8%, $P = 0.023$) and increased from 27.3% in 2005–2006 to 63.6% in 2015–2016 ($P < 0.001$). While most TDR mutations were associated with reduced relative transmission fitness, mutation M46I was associated with higher relative transmission fitness than the wild-type strain. This study identified a low-level prevalence of TDR HIV in China during the last two decades. However, the increasing TDR HIV rate since 2010, the persistent circulation of drug resistance mutations, and the expansion of self-sustaining drug resistance reservoirs may compromise the efficacy of antiretroviral therapy programs.

Introduction

The global scale-up of antiretroviral therapy (ART) for HIV-1 infections has resulted in considerable reductions in HIV/AIDS-related morbidity and mortality [1-3]. However, drug resistance can hamper virological suppression in patients who receive treatment. After decades of ART scale-up, the increasing HIV drug resistance in low- and middle-income countries, such as China, poses a growing threat [4].

The Chinese government officially launched the National Free Antiretroviral Treatment Program (NFATP) in 2003. By the end of 2015, approximately 70% of individuals in this country living with HIV/AIDS received ART [5]. Nearly half of ART failures in China are reported to be associated with drug resistance-associated mutations (DRMs) [6,7]. Primary infection with transmitted drug resistant (TDR) HIV strains limits a newly-diagnosed patient's treatment options and is associated with treatment failure. Previous studies have shown that China had a prevalence of HIV with TDR of approximately 3.6% in ART-naive patients in 2015 [8,9], which was lower than that in Western countries [10-13]. However, given the large number of HIV-infected people and the persistent circulation of HIV in China, the number of patients for whom ART failed because of drug resistance is considerably high in this country.

To achieve the UNAIDS's goal of ending the AIDS pandemic by 2030, ever-increasing numbers of people will be enrolled in the ART program in the coming years. Thus, with the quick scale-up of treatment and the passage of time, drug resistance will require more attention. Little is known about the temporal trend of HIV with TDR or its transmission characteristics in China.

In this study, we examined the changing prevalence of HIV with TDR from 2000 to 2016 in ART-naive patients in China, utilizing *pol* gene sequences of HIV extracted from the Los Alamos HIV Sequence Database. We performed comprehensive phylogenetic analyses to explore the transmission characteristics of HIV with TDR strains. In addition, we explored the evolutionary characteristics of the largest transmission clusters by applying Bayesian coalescent-based methods.

Materials And Methods

Data collection

We retrieved all available records of HIV-1 sequences containing the *pol* gene region from China from the Los Alamos HIV Sequence Database (<http://www.hiv.lanl.gov>). A total of 12447 sequences were obtained along with basic information, including the GenBank accession number, subtype, sampling location, collection date, and ART status, if provided. For sequences without a denoted ART status, we collected information for each sequence from the original source publication. The *pol* gene region was extracted from these data according to the annotation information, with all sequences < 500 bp or for which the ART status was "yes" or "unknown" removed. For patients with multiple sequences, only the earliest sequence was retained.

Sequences were aligned using MAFFT (version 7) [14] and manually checked and edited with MEGA (version 7) [15]. All the sequences were manually selected to maximize the length and the number of segments for analysis. Segments spanning 1053 bp of the *pol* gene, including the entire protease (PR) and partial reverse transcriptase (RT) regions (HXB2 nucleotide coordinates 2253–3305), were finally selected.

Drug resistance mutation analysis

The Stanford Calibrated Population Resistance Tool version 7.0 (<https://hivdb.stanford.edu/>) was used to screen the *pol* sequences for surveillance drug resistance mutations (SDRMs), according to the World Health Organization (WHO)-recommended surveillance drug resistance mutation list, which was updated in 2009 for nucleoside reverse transcriptase inhibitors (NRTIs), nonnucleoside reverse transcriptase inhibitors (NNRTIs), and protease inhibitors (PIs). HIV with TDR was defined as the detection of at least one of the standard surveillance drug resistance mutations listed by the WHO.

Transmission clusters and network construction

The transmission network was built as previously described [16]. Briefly, an approximately-maximum likelihood phylogenetic tree was estimated for all sequences using the GTR + G + I nucleotide substitution

model in FastTree 2 [17] after excising 43 codons associated with drug resistance from the alignment. The Tamura-Nei 93 (TN93) pairwise genetic distances (PGDs) were calculated for all pairs of sequences to identify potential transmission partners. Transmission clusters (TCs) were defined as sequences for which the bootstrap support value > 0.9 and the PGD $< 3.0\%$, which was employed to detect longer-term transmission events. TCs were extracted from the phylogenetic tree using Cluster Picker [18]. A minimum genetic distance algorithm [19], which selected the best tree that minimized the sum of the edge weights (TN93 PGDs) among all undirected trees that built with the TN93 PGD, was used to define the network structure of a cluster. To visualize and analyze networks, the network data were processed in the R software package utilizing the *ape* (version 5.4-1) [20] and *qgraph* packages (version 1.6.5) [21].

Bayesian phylogeographic inference

We used BEAST (Bayesian evolutionary analysis sampling trees, version 1.10.4) [22] to conduct the Bayesian phylogeographic inference for large HIV with TDR clusters after removing all the drug-resistance-associated sites from the alignment. All the clusters were analyzed using a suitable nucleotide substitution model (HKY for M46L clusters, JC for M46I clusters), which were selected by jModelTest (version 2.1.10) [23]. We used a strict molecular clock model to infer the timescale of HIV evolution. A Bayesian skygrid coalescent tree was used to estimate the effective infection population size. A continuous time Markov chain (CTMC) model was used to estimate the transition rates between each pair of locations, and the Bayesian stochastic search variable selection (BSSVS) procedure was applied to identify well-supported transitions and infer the location state of the ancestral nodes of the trees.

Markov chain Monte Carlo (MCMC) analyses were run for 100 million generations, with parameter values sampled every 10,000 steps. The resulting log files were imported into the program TRACER v1.7.1 and the first 10% of the output was used as burn-in. The convergence of the estimates was evaluated with generation vs. log probability plots in TRACER using an effective sample size >200 . The Bayes factor (BF) was calculated using Spread3 [24] to identify well-supported transitions by applying a cutoff of 3.0. TreeAnnotator was used to generate a summary maximum clade credibility (MCC) tree from the posterior distribution of the trees (after removal of the MCMC burn-in of 10%).

Statistical analysis

The temporal trends of the prevalence of HIV with TDR were evaluated with odds ratios (ORs) and 95% confidence intervals (CIs) using a logistic regression model. An OR > 1 indicates an increase in the prevalence of HIV with TDR over time, and an OR < 1 indicates a decrease over time. Furthermore, we examined the trend in a smaller window size using a local weighted regression model with the reciprocal of the standard error of prevalence set as the weight. Fischer's exact test was used for the analysis of differences between proportions, and Student's t-test was used for the analysis of differences between means. Transmission fitness was defined as the ability of a pathogen to be transmitted and cause secondary cases of the disease as means to describe the fitness of the virus at the population level [25]. To evaluate the transmission fitness of each TDR mutation, we calculated the ORs and 95% CIs from the clustering frequency by comparison with wild-type strains using a logistic regression model. An OR > 1

indicates positive fitness, and an OR < 1 indicates negative fitness. Statistical significance was defined as a p value < 0.05. All analyses were carried out with the R program (version 3.5.3) [26].

Results

Characteristics of the study dataset

Ultimately, a total of 6578 HIV-1 *pol* gene sequences from treatment-naive patients from 24 provinces in China between 2000 and 2016 were obtained. Of these patients, 5155 were male (78.37%) and 313 were female (4.76%). The patient characteristics are shown in Table 1. The largest group of patients (3067, 46.6%) were infected with CRF01_AE, followed by CRF07_BC (2013, 30.6%) and subtype B (836, 12.7%) (Table 2). The remaining patients were infected with other pure subtypes or circulating recombinant forms (CRFs, 662, 10.1%). Subtype B infections decreased from 34.1% to 11.2% from 2000 to 2016 ($p < 0.001$). CRF01_AE and CRF07_BC infections increased over time (29.5% to 47.1%, $p < 0.001$; 11.4% to 31.6%, $p = 0.0229$) (Fig. 1). The composition of the risk behaviors was 4414 (67.1%) men having sex with men (MSM), 654 (9.9%) heterosexual sex, 622 (9.5%) injected drug use (IDU), and 888 (13.5%) other risk behaviors or data unrecorded (Table 2).

Prevalence and temporal trend of transmitted drug resistance

HIV with TDR was demonstrated in 274 (4.51%) patients in the period from 2000 and 2016. Table S1 shows information for all the HIV-1 sequences with TDR mutations. Mutations conferring resistance to NRTIs, NNRTIs, PIs, and multiclass drugs were found in 92 (1.40%), 100 (1.52%), 123 (1.87%), and 37 (0.56%) patients, respectively. The prevalence of TDR in both CRF01_AE (5.31%) and subtype B (6.58%) was higher than that in the other subtypes (Table 2). Among subtypes, CRF01_AE had the highest prevalence of PI-TDR, while subtype B had the highest prevalence of NRTI- and NNRTI-associated TDR. Among the different risk behavior populations, the prevalence of HIV with TDR in heterosexual individuals was relatively high (7.34%). MSM had the highest prevalence of PI-TDR among the risk groups, while the prevalence of NNRTI-TDR in heterosexuals was higher than that in IDU and MSM groups (Table 2).

The prevalence of drug-resistance mutations in all sequences is shown in Table 3. Overall, the most frequent mutation was M46L, which was found in 0.89% ($n = 58$) of patients, followed by K103N (0.55%, $n = 36$), M46I (0.55%, $n = 36$), and M184V (0.40%, $n = 26$). Furthermore, in patients infected with strain CRF01_AE, the most frequent mutation was M46L (1.76%), followed by M46I (1.04%), M184V (0.46%), and K103N (0.39%). The most frequent TDR mutation in patients infected with CRF07_BC was M184V (0.39%), followed by T215S (0.20%) and Y181C (0.15%). The most frequent TDR mutation in subtype B was K103N (2.27%), followed by G190A (0.96%), Y181C/Y188L/M41L/D67N (0.84%), and M184V (0.72%). The prevalence of TDR mutations in each HIV-1 subtype is shown in Fig. 2.

The prevalence of HIV with TDR varied throughout the study period, it was 2.73% in 2011–2012 and 9.09% in 2000–2003, with no clear trend observed (OR = 0.94, 95% CI 0.86–1.04, $p = 0.233$). The prevalence of NRTI (OR = 0.76, 95% CI 0.66–0.89, $p < 0.001$) and NNRTI-associated (OR = 0.84, 95% CI

0.73–0.98, $p = 0.020$) TDR slightly decreased from 2000 to 2016, while the prevalence of PI-associated (OR = 1.09, 95% CI 0.95–1.27, $p = 0.233$) TDR was stable during the same period.

However, when we examined the trends in a smaller window, the prevalence of total TDR was found to decrease from 2000 to 2010 (OR = 0.83, 95% CI 0.73–0.95, $p = 0.006$), but it increased after 2010 (OR = 1.50, 95% CI 1.13–1.97, $p = 0.004$). The prevalence of NNRTI-associated TDR decreased from 2000 to 2010 (OR = 0.77, 95% CI 0.64–0.94, $p = 0.007$), and increased after 2010 (OR = 1.91, 95% CI 1.13–3.18, $p = 0.014$). PI-associated TDR was found to slightly increase after 2006, with no statistical significance, but it increased after 2010, with marginal significance (OR = 1.44, 95% CI 0.99–2.09, $p = 0.055$) (Fig. 3).

Clusters and transmission fitness of TDR mutations

Finally, Cluster Picker identified 788 transmission clusters containing 3189 of 6578 patients (48.4%). Strains CRF01_AE and CRF07_BC had higher rates of phylogenetic clustering than the other subtypes, while the rate of clustering was higher in MSMs than in the other risk groups (Table 2).

Of these 788 clusters, 69 had one or more sequences with TDR mutations, comprising 111 of 274 (40.5%) TDR sequences. The network construction of these 69 transmission clusters is shown in Fig. S1. The clustering rate of sequences with TDR increased annually from 27.3% in 2005–2006 to 63.6% in 2015–2016 ($p < 0.001$). Of these 69 TDR clusters, 52 had only one TDR sequence, 10 had two TDR sequences, and seven had three or more TDR sequences. Among the 17 clusters with at least two TDR sequences, 15 had the same TDR mutation, seven of which were M46L, followed by M46I ($n = 2$).

Overall, the sequences with TDR were less likely to form phylogenetic clusters than the sequences not resulting in TDR, even after adjusting for subtype and at-risk populations (40.5% vs. 48.8%, $p = 0.023$). The clustering rates of NNRTI- and NRTI-associated TDR mutations were significantly lower than those of the wild-type sequences (Table 3). Mutation M46L had the highest frequency in the clusters ($n = 32$), followed by M46I ($n = 26$), L210W ($n = 7$), M184V ($n = 7$), T215S ($n = 5$), and K103N ($n = 4$).

Of the 58 TDR mutations, seven had clustering frequencies that deviated significantly from the neutral expectation, most of which resulted in a significant reduction in transmission fitness (NNRTI and NRTI mutations: K103N, G190A, Y181C, K101E). Conversely, M46I had a relative fitness significantly greater than 1.0 (Table 3).

The spatiotemporal origins and epidemic dynamics of large TDR clusters

There were four large HIV with TDR clusters containing ≥ 5 sequences. All these sequences were from patients infected with strain CRF01_AE in the MSM risk group. We extracted the two largest clusters containing mutants M46I (cluster 300) and M46L (cluster 67) to implement Bayesian phylogeographic inference. The most recent common ancestors (tMRCAs) of clusters 67 and 300 were 2007.2 (95% HPD 2004.1–2008.5) and 2006.9 (95% HPD 2004.1–2008.5), respectively. The evolutionary rates of clusters 67 and 300 were 2.144×10^{-3} (95% HPD 1.075×10^{-3} – 3.213×10^{-3}) and 2.933×10^{-3} (95% HPD 1.385×10^{-3} –

4.873×10^{-3}), respectively. From the phylogeographical analysis, the potential transmission source locations for clusters 67 and 300 were Beijing [posterior probability (PP) = 0.80] and Liaoning (PP = 0.69), respectively (Fig. 4).

Interestingly, two other clusters, 65 and 68, together with clusters 62, 63, and 69, were adjacent to cluster 67 in the phylogenetic tree, and most of them shared the same TDR mutation, M46L. Analysis of the sequences from these clusters found that the TN93 pairwise genetic distances were < 3.0% for the majority of the sequences (Fig. S2). Therefore, we applied the same analyses to these taxa with the tMRCA estimated at 2002.9 (95% HPD 2000.4–2004.8) and its evolutionary rate estimated at 2.087×10^{-3} (1.467×10^{-3} – 2.818×10^{-3}) while Beijing was estimated as the source location with the highest support (PP = 0.99) (Fig. 4). Analysis of the geographical migration as estimated from the Bayes factors indicated that the migration pathways, from Beijing to Hebei, Hubei, Hunan, and Guangdong, and from Hubei to Hunan and Shanghai, were all well supported for the M46L taxa, while in the large M46L cluster, viral migration from Beijing to Liaoning was well supported. Table 4 illustrates the best-supported pathway of migration of the M46L/L large clusters in China.

Discussion

In the present study, we identified transmitted-drug resistant HIV among ART-naive HIV-1-infected individuals in China. The overall prevalence of HIV with TDR was 4.51%, which is comparable to that reported by Zhao *et al.* and Su *et al.* (3%–5%) [8,9]. It is not surprising that the prevalence of HIV with TDR in China was lower than that in Europe (9.4%) and North America (11.5%), in which ART was initiated much earlier [27].

The prevalence of HIV with TDR varied throughout the study period and ranged from 2.73% in 2011–2012 to 9.09% in 2000–2003. The higher HIV with TDR prevalence in the earlier phase of the NFATP may be due to the widespread use of generic agents, including zidovudine, didanosine, and nevirapine [28]. The decreasing trend in HIV with TDR from 2000 to 2010 mainly contributed to the decrease in NRTI-related resistance mutations (Figure 3B). We speculate that the decline of the prevalence of HIV with TDR could be partially attributed to the antiretroviral drugs newly available after 2004, such as lamivudine and efavirenz. The toxicity and side effects of lamivudine are lower than those of didanosine, which improved patient compliance and providing better therapeutic effects [29]. Accordingly, lamivudine was replaced in the following years [30]. In addition, to guide the national free ART Program, four editions of the China Free ART Manual were released from 2004 to 2016. Because of standardized treatment guidance, increased availability of effective drugs, and improved patient compliance to the NFATP, the virological suppression rate increased from 78% in 2004–2005 to 90% in 2013[8]. Therefore, the prevalence of HIV with TDR declined accordingly.

However, after 2010, a slight increase in HIV with TDR prevalence was observed in our study. A similar trend between 2009 and 2012 was also observed by Su *et al.* [9]. The authors attributed this phenomenon to the broad expansion of access to ART during this time period and/or to the cumulative increase in

prevalence of drug strains in HIV-infected patients on therapy. However, when we looked closely at the factors driving the increase, we found that the PI-resistant strain was the main contributor to the growth trend since 2010. Furthermore, both in Su *et al.*'s study and in this study, one noteworthy finding was the elevated prevalence of PI-specific TDR among the MSM group. MSM have become the most predominant risk group for HIV-1 infection in the last decade[31]. Accordingly, the high prevalence and an increasing trend of PI-resistance in this population will pose a significant challenge to the prevention and control efforts in a large number of HIV-infected MSM in China.

The most frequent TDR mutation was M46I/L in China, whereas, in Europe and North America, it was K103N [32-34,12]. This difference might largely be attributed to the dominant HIV-1 subtypes that circulate between regions. In China, the predominant subtype of HIV-1 is CRF01_AE, in which most M46I/L substitutions were observed. In Europe and North America, subtype B HIV-1 is the most prevalent. The second most frequent TDR mutation was K103N, which represents the most frequent TDR mutation in subtype B, consistent with that of European and North American isolates. Furthermore, the TDR rates overall and in NRTI/NNRTI in subtype B were higher than those in other subtypes. Subtype B was the predominant strain of the early HIV epidemic in China [35]. Therefore, it had a more prolonged exposure to ART and consequently accumulated drug resistance mutations, leading to this relatively high TDR prevalence.

In this study, we found that TDR mutations are associated with reduced transmission clustering rate, suggesting that TDR strains have weaker fitness effects than their wild-type strains. Drug-resistance mutations can revert to wild-type and wild-type strains can then outcompete strains with the DRMs. In addition, viral competition experiments have demonstrated that DRMs generally reduce the replication rate of HIV (i.e., replicative fitness). When transmission occurs, systemic infection is typically established by a single genetic variant, and founder virus selection is biased toward certain genetic characteristics[36]. This genetic bottleneck could limit the transmission of DRMs. In the absence of antiretroviral therapy, strains containing DRMs commonly have reduced fitness compared with the wild-type strain within the population [3]. Therefore, TDR-associated strains are likely to be less active in onward transmission. This transmission disadvantage could explain the reduced clustering rate of TDR strains compared with wild-type strains. Despite this negative impact of TDR on transmission, the clustering rate of TDR strains remained at 40.5%, showing that the transmission clusters had a significant contribution to the spread of TDR. More importantly, we found that the clustering rate of TDR strains increased annually after 2004, indicating that the contribution of transmission clusters to the spread of TDR has been increasing.

In contrast, people infected with the virus containing mutation M46I were involved in increased rates of transmission. The enhanced transmission of M46I strains is noteworthy, as it has implications for second-line regimens containing lopinavir or atazanavir in resource-limited countries [37]. Another mutation at the same site, M46L, is also noteworthy as it had the highest prevalence in the study with a high rate of clustering. Using Bayesian phylogeographic models, we found that Beijing was a critical transmission location for the source of M46I/L. Interestingly, all the sequences of M46I/L were derived

from CRF01_AE-infected MSM patients. Considering the high prevalence of CRF01_AE in China and the increasing proportion of newly diagnosed HIV-infected patients within MSM populations [31], concern about the rapid onward transmission of the M46I/L variant within the Chinese MSM community is warranted. Given that M46I/L is one of the most commonly transmitted PI mutations globally, especially in South/Southeast Asia [27], there is an urgent need to better understand its clinical impact on the efficacy of current second-line therapy, as well as its effects combined with other mutations.

Some limitations should be noted here. First, because data on the infection history and disease progression were limited, a proportion of individuals might not have been recently infected. The overall trend of many TDR-associated mutations is toward a gradual reversion to the wild type in the years following the initial infection. Therefore, the drug-resistant strains in plasma would become minor quasi-species after a period of infection. Accordingly, the prevalence of HIV with TDR in chronically-infected individuals is generally lower than that in acutely-infected individuals, which will impact the estimated TDR rate determined in this study. Second, like all genetic clustering studies, we were unable to determine whether the genetic linkage results were due to direct or indirect transmissions.

In conclusion, the overall prevalence of HIV with TDR among pretreatment HIV-infected individuals in China has remained at a low level during the last two decades. However, the onwards transmission of drug resistance mutations may compromise the efficacy of ART programs. We also found the existence of self-sustaining reservoirs of TDR mutations among transmission networks that may have important implications for the success of ART programs. We thus suggest that effective measures are still needed to strengthen monitoring and guide ART usage, such as drug-resistance testing for patients enrolling in ART programs.

Declarations

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no competing interests.

Ethical approval This study did not include experiments with human participants or animals performed by any of the authors.

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Tables

Table 1 Characteristics of HIV-1 sequences in the study

Characteristics		Sequence number (N=6578)	Percentage (%)
Gender			
Male		5155	78.37
Female		313	4.76
Unknown		1110	16.87
Sampling year			
Befor 2003		44	0.67
2003-2004		71	1.08
2005-2006		179	2.72
2007-2008		743	11.30
2009-2010		1864	28.34
2011-2012		1865	28.35
2013-2014		1606	24.41
2015-2016		206	3.13
Sampling province			
Central	Henan	373	5.67
	Hubei	153	2.33
	Hunan	54	0.82
East	Anhui	207	3.15
	Jiangsu	72	1.09
	Shandong	50	0.76
	Shanghai	1317	20.02
	Zhejiang	335	5.09
	Fujian	21	0.32
North	Beijing	972	14.78
	Hebei	100	1.52
	Shannxi	1	0.02
	Tianjin	1	0.02
Northeast	Jilin	5	0.08

	Liaoning	113	1.72
Northwest	Ningxia	1	0.02
	Xinjiang	51	0.78
South	Guangdong	1552	23.59
	Guangxi	347	5.28
	Hainan	73	1.11
Southwest	Chongqing	96	1.46
	Guizhou	84	1.28
	Sichuan	335	5.09

Table 2 Transmitted drug resistance and rates of phylogenetic clustering in subtypes and risk groups

	Total	Any TDR (%)	PI (%)	NRTI (%)	NNRTI (%)	Clustering (%)
Subtype						
CRF01_AE	3067	163 (5.31) ^b	97 (3.16) ^{bcd}	41 (1.34) ^c	39 (1.27) ^{bc}	1553 (50.64) ^{cd}
CRF07_BC	2013	32 (1.59) ^{acd}	6 (0.3) ^{ad}	19 (0.94) ^c	9 (0.45) ^{ad}	1070 (53.15) ^{cd}
Subtype B	836	55 (6.58) ^{bd}	10 (1.2) ^{ad}	28 (3.35) ^{ab}	41 (4.9) ^{ad}	317 (37.92) ^{ab}
Other subtypes	662	24 (3.63) ^{bc}	10 (1.51) ^{abc}	4 (0.60)	11 (1.66) ^{bc}	249 (37.61) ^{ab}
Risk behavior						
Heterosexual	654	48 (7.34) ^{fg}	13 (1.99)	18 (2.75) ^g	28 (4.28) ^{fg}	245 (37.46) ^{gh}
Injected drug user	622	20 (3.22) ^{eh}	5 (0.8) ^g	8 (1.29) ^h	9 (1.45) ^e	212 (34.08) ^{gh}
Men sex with men	4414	157 (3.56) ^{eh}	96 (2.17) ^{fh}	39 (0.88) ^{eh}	35 (0.79) ^{eh}	2467 (55.89) ^{efh}
Other/Unknown	888	49 (5.52) ^{fg}	9 (1.01) ^g	27 (3.04) ^{fg}	28 (3.15) ^g	165 (18.58) ^{efg}

TDR, transmitted drug-resistance; NNRTI, nonnucleoside reverse transcriptase inhibitor associated drug resistance; NRTI, nucleoside reverse transcriptase inhibitor associated drug resistance; PI, protease inhibitor associated drug resistance; ^a Statistical significance observed when compared with CRF01_AE; ^b Statistical significance observed when compared with CRF07_BC; ^c Statistical significance observed when compared with subtype B; ^d Statistical significance observed when compared with other subtypes; ^e Statistical significance observed when compared with heterosexual; ^f Statistical significance observed when compared with injected drug user; ^g Statistical significance observed when compared with men sex with men; ^h Statistical significance observed when compared with other/unknown risk groups.

Table 3 Frequency, clustering rate and relative fitness of transmitted drug resistance mutations in treatment-naive patients

Mutation	Number (%)	Clustering number (%)	Fitness OR (95%CI)	Fitness OR _a (95%CI)	P _a
NNRI	100 (1.52)	16 (16.00)	0.200 (0.113, 0.332)	0.230 (0.129, 0.384)	<0.001
K103N	36 (0.55)	4 (11.11)	0.131 (0.039, 0.331)	0.157 (0.047, 0.399)	<0.001
G190A	21 (0.32)	1 (4.76)	0.052 (0.003, 0.251)	0.058 (0.003, 0.277)	0.005
Y181C	20 (0.3)	3 (15)	0.185 (0.043, 0.551)	0.215 (0.05, 0.646)	0.015
K101E	15 (0.23)	2 (13.33)	0.161 (0.025, 0.584)	0.191 (0.03, 0.698)	0.030
Y188L	11 (0.17)	2 (18.18)	0.233 (0.035, 0.905)	0.281 (0.043, 1.101)	0.106
V106M	8 (0.12)	2 (25)	0.349 (0.051, 1.512)	0.354 (0.052, 1.550)	0.206
NRTI	92 (1.40)	29 (31.52)	0.482 (0.306, 0.744)	0.510 (0.322, 0.789)	0.0012
M184V	26 (0.4)	7 (26.92)	0.386 (0.151, 0.880)	0.385 (0.150, 0.880)	0.032
L210W	14 (0.21)	7 (50)	1.048 (0.358, 3.065)	1.127 (0.383, 3.322)	0.824
D67N	13 (0.2)	2 (15.38)	0.191 (0.029, 0.710)	0.217 (0.033, 0.816)	0.048
M41L	12 (0.18)	0			0.931
T215S	10 (0.15)	5 (50)	1.048 (0.291, 3.772)	1.120 (0.308, 4.072)	0.860
K65R	8 (0.12)	1 (12.5)	0.150 (0.008, 0.842)	0.179 (0.009, 1.024)	0.109
M184I	7 (0.11)	1 (14.29)	0.175 (0.009, 1.023)	0.208 (0.011, 1.231)	0.147
T215F	6 (0.09)	0			0.925
T215I	6 (0.09)	1 (16.67)	0.210 (0.011, 1.301)	0.201 (0.010, 1.252)	0.143
K70R	6 (0.09)	1 (16.67)	0.210 (0.011, 1.301)	0.253 (0.013, 1.593)	0.212
PI	123 (1.87)	67 (54.47)	1.254 (0.877, 1.799)	1.251 (0.873, 1.801)	0.216

M46L	58 (0.88)	32 (55.17)	1.290 (0.768, 2.186)	1.215 (0.722, 2.064)	0.465
M46I	36 (0.55)	26 (72.22)	2.725 (1.353, 5.941)	2.749 (1.357, 6.025)	0.007
L90M	8 (0.12)	1 (12.5)	0.150 (0.008, 0.842)	0.190 (0.010, 1.082)	0.122

OR, crude odds ratio calculated with logistic regression modelling result; OR_a, odds ratio adjusted by subtype and risk behavior; P_a, *p* value adjusted for subtype and risk behavior; bold indicates statistical significance; only mutations presenting at less 5 individuals were showed in the table.

Table 4 The best supported pathway of migration of the M46I/L large clusters in China

Mutation	Pathway start	Pathway end	Bayes factor	Posterior probability
M46L	Beijing	Hebei	97.94	0.98
	Beijing	Hubei	12.69	0.86
	Beijing	Hunan	6.93	0.76
	Beijing	Guangdong	3.46	0.62
	Hubei	Hunan	13.46	0.86
	Hubei	Shanghai	4.12	0.66
M46I	Beijing	Liaoning	4.84	0.98

Figures

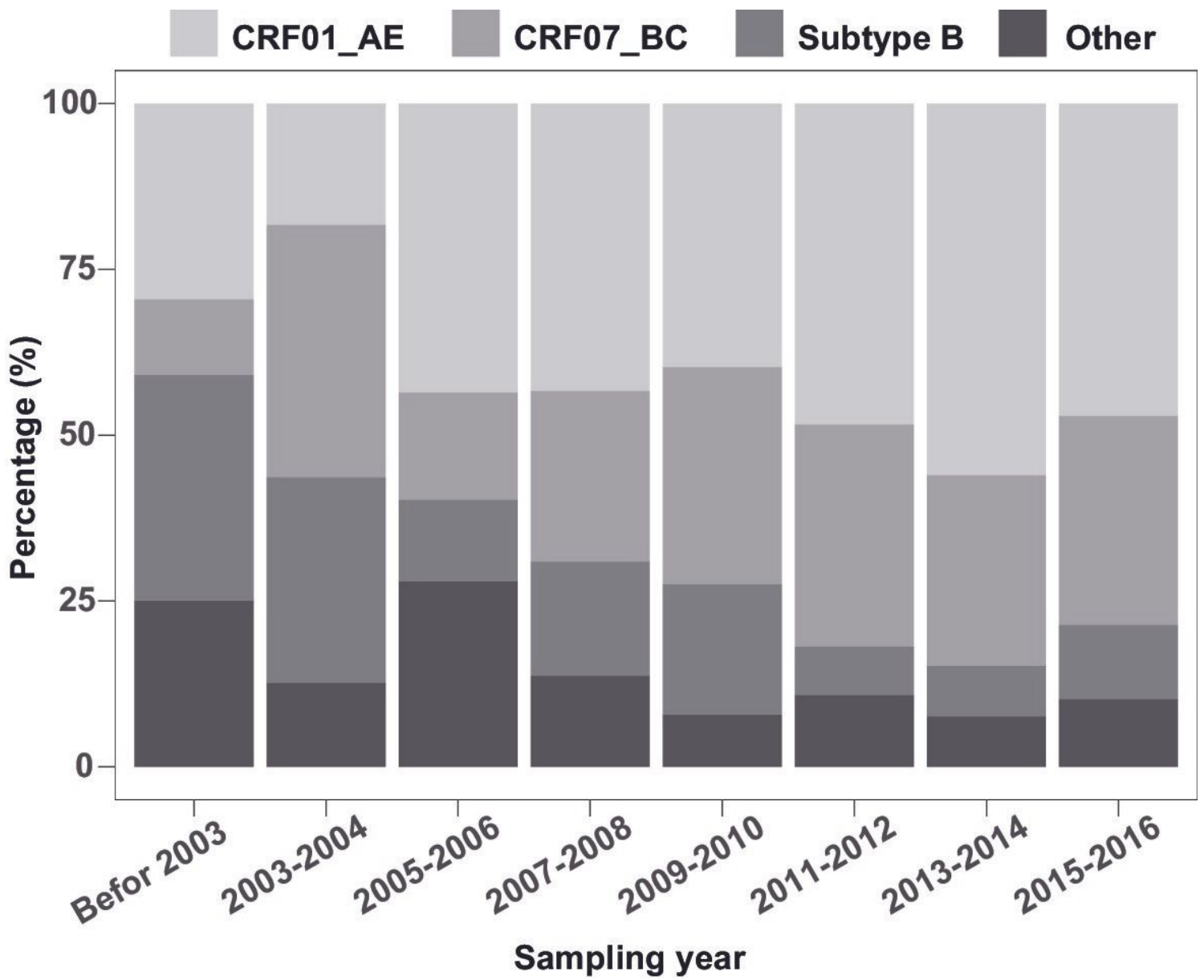


Figure 1

Yearly proportional change in HIV-1 subtypes from 2000 to 2016.

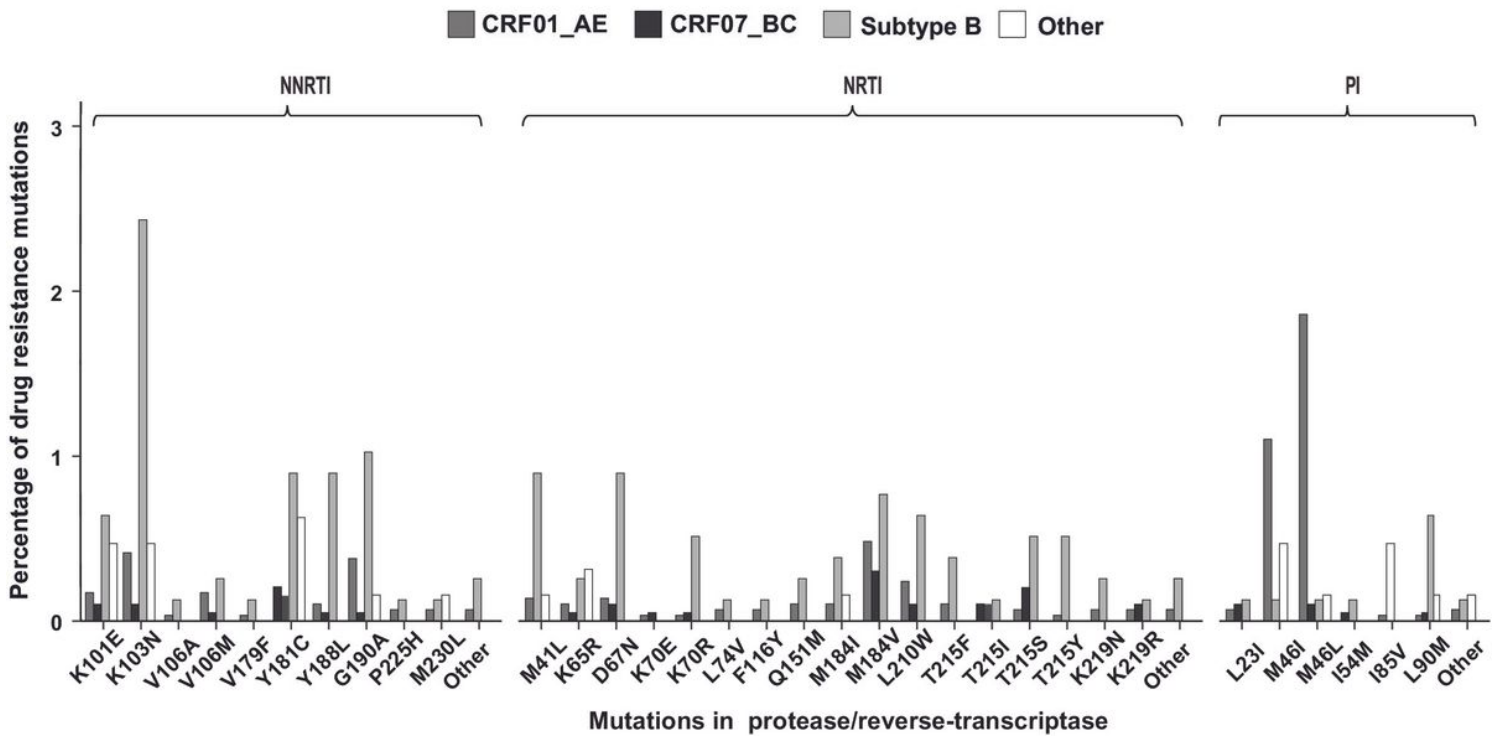


Figure 2

Prevalence of transmitted drug-resistance mutations in HIV-1 subtypes according to drug class.

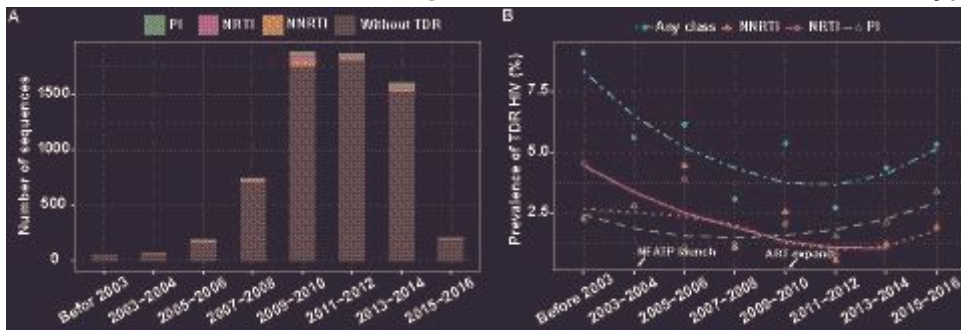


Figure 3

Number distribution (A) and temporal trends in the yearly proportion (B) of individuals with transmitted HIV drug resistance by drug class. Note, that a local weighted regression was applied to the prevalence to smooth the curves. Abbreviations: NNRTI, nonnucleoside reverse transcriptase inhibitor associated drug resistance; NRTI, nucleoside reverse transcriptase inhibitor associated drug resistance; PI, protease inhibitor associated drug resistance; Any class, any class of transmitted drug resistance.

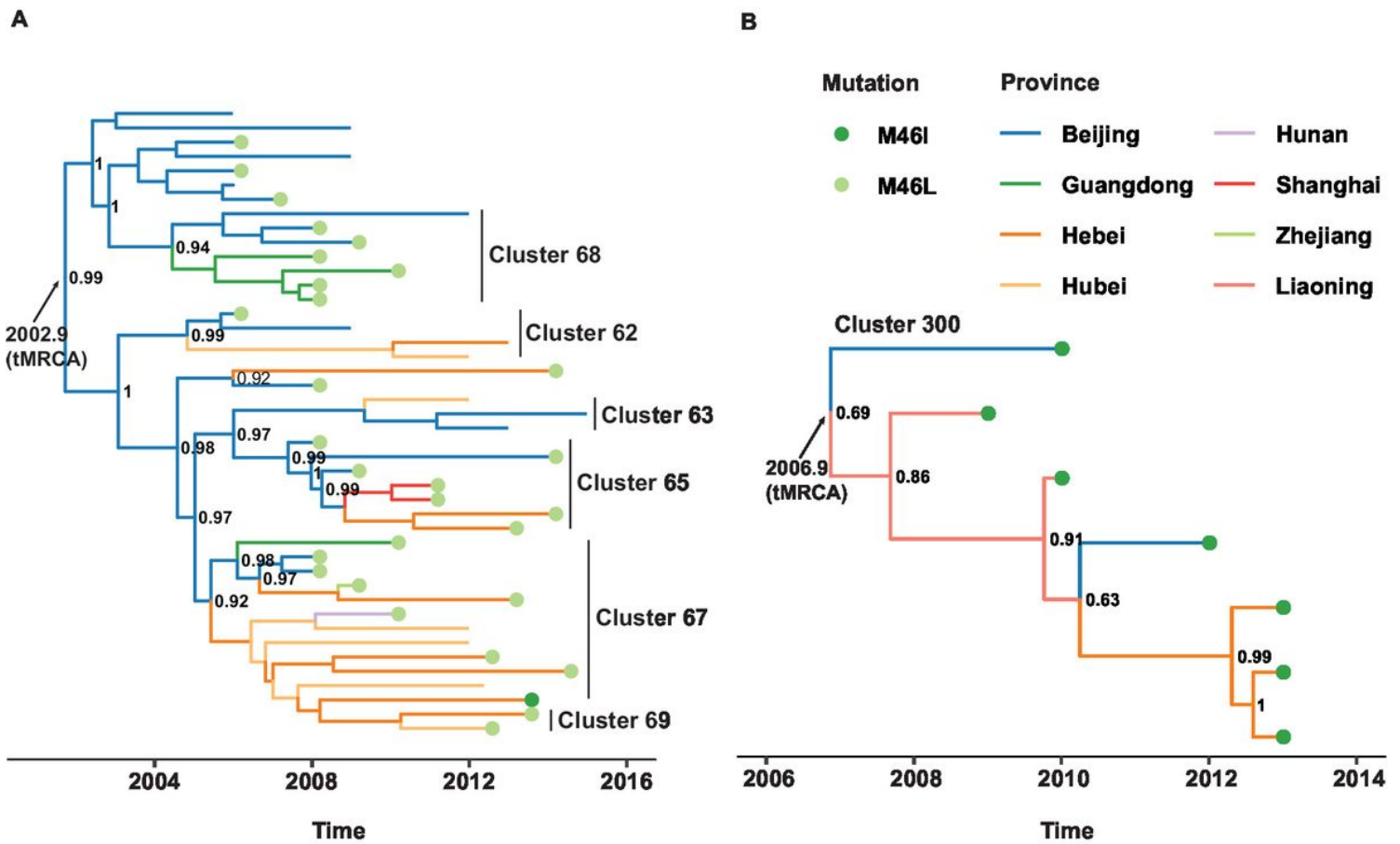


Figure 4

Molecular dating analysis of large HIV-1 clusters with evidence of transmitted drug resistance. The phylogenies of the (A) M46L and (B) M46I clusters are colored according to the sampling location. The posterior probabilities of the potential transmission sources of taxa are annotated on the right of the node.

Supplementary Files

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