

Revising mtDNA haplotypes of the ancient Hungarian conquerors with next generation sequencing

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Abstract

As part of the effort to create a high resolution representative sequence database of the medieval Hungarian conquerors we have resequenced the entire mtDNA genome of 24 published ancient samples with Next Generation Sequencing, whose haplotypes had been previously determined with traditional PCR based methods. We show that PCR based methods are prone to erroneous haplotype or haplogroup determination due to ambiguous sequence reads, and many of the resequenced samples had been classified inaccurately. The SNaPshot method applied with published ancient DNA authenticity criteria is the most straightforward and cheapest PCR based approach for testing a large number of coding region SNP-s, which greatly facilitates correct haplogroup determination.

Introduction

Comparing ancient DNA (aDNA) sequences extracted from well dated archaeological remains from different periods and locations provide crucial information about past human population history (reviewed in (Pickrell and Reich, 2014)). Phylogeographic inferences are drawn from phylogenetic and population genetic analyses of sequence variations, the quality of which can be biased by data quantity and quality. Nowadays Next Generation Sequencing technology (NGS) provides a growing number of high quality aDNA sequence data, but until recently the majority of aDNA studies have been restricted to short fragments from the hypervariable region-1 (HVR-I) of the mitochondrial DNA (mtDNA) genome, using PCR based methods. PCR based methods are very sensitive for contamination, as low amounts of exogenous DNA can easily dominate PCR products resulting in the recovery of irrelevant sequences (Richards et al., 1995) (Malmström et al., 2005) (Pilli et al., 2013) (Heupink et al., 2016). As a result, in spite of the applied authenticity criteria (Knapp et al., 2012), many of the published databases may contain unreliable sequences, which distort statistical analyses. This problem is especially relevant for many of the ancient populations, from which only PCR based HVR data are available.

Recently several aDNA studies were published aiming to shed light on the origin of ancient Hungarians, two of these (Tömöry et al., 2007) (Csösz et al., 2016) applied restriction fragment length polymorphism (RFLP) to identify 11 and 14 haplogroup (Hg) specific coding region SNP-s in

addition to HVR sequencing, while another study (Neparáczki et al., 2016) tested 22 coding region SNP-s with multiplex PCR and GenoCoRe22 assay described in (Haak et al., 2010).

Using the NGS method combined with hybridization enrichment, we have sequenced the entire mtDNA genome of 9 samples from the (Tömöry et al., 2007) study, and 15 samples from the (Neparáczki et al., 2016) study, so we could compare the reliability of two different traditional approaches.

Materials and Methods

Archaeological samples:

Bone samples from the Hungarian conquest period used in the study of (Tömöry et al., 2007) are carefully maintained in the anthropological collection at the Department of Biological Anthropology, University of Szeged, Hungary, so we could unambiguously identify and resample these remains. Bone powder remains of samples from the study of (Neparáczki et al., 2016), were saved in the Department of Genetics, University of Szeged, and were reused to build NGS sequencing libraries.

DNA extraction:

Ancient DNA work was performed in the specialized ancient DNA (aDNA) facilities of the Department of Genetics, University of Szeged, Hungary with strict clean-room conditions. 100 mg bone powder from tooth roots or petrous bones was predigested in 1 ml 0,5 M EDTA 100 µg/ml Proteinase K for 30 minutes at 48 °C, to increase the proportion of endogenous DNA (Damgaard et al., 2015), then DNA solubilisation was done overnight, in 1 ml extraction buffer containing 0.45 M EDTA, 250 µg/ml Proteinase K, 1% Triton X-100, and 50 mM DTT. DNA was bound to silica (Rohland and Hofreiter, 2007) adding 6 ml binding buffer (5,83 M GuHCl, 105 mM NaOAc, 46,8% isopropanol, 0,06% Tween-20 and 150 µl silica suspension to the 1 ml extract, and the pH was adjusted between 4-6 with HCl. After 3 hours binding at room temperature silica was pelleted, and washed twice with 80% ethanol, then DNA was eluted in 100 µl TE buffer.

NGS library construction

First 50 µl DNA extract was subjected to partial uracil-DNA-glycosylase (UDG) treatment followed by blunt end repair, as described in (Rohland et al., 2015a). DNA was then purified on MinElute column (Qiagen), and double stranded library was made as described in (Meyer and Kircher, 2010), except that all purifications were done with MinElute columns, and after adapter fill-in libraries were preamplified in 2 x 50 µl reactions containing 800 nM each of IS7 and IS8 primers, 200 µM dNTP mix, 2 mM MgCl₂, 0,02 U/µl GoTaq G2 Hot Start Polymerase (Promega) and 1X GoTaq buffer, followed by MinElute purification. PCR conditions were 96 °C 6 min, 16 cycles of 94 °C 30 sec, 58 °C 30 sec, 72 °C 30 sec, followed by a final extension of 64 °C 10 min. Libraries were eluted from the column in 50 µl 55 °C EB buffer (Qiagen), and concentration was measured with Qubit (Thermo Fisher Scientific). Libraries below 5 ng/µl concentration were reamplified in the same reaction for additional 5-12 cycles, depending on concentration, in order to obtain 50 µl preamplified library with a concentration between 10-50 ng/µl.

50 ng preamplified libraries were double indexed according to (Kircher et al., 2012) in a 50 µl PCR reaction containing 1 x KAPA HiFi HotStart ReadyMix (Kapa Biosystems) and 1000 nM each of P5 and P7 indexing primers. PCR conditions were 98 °C 3 min, 6 cycles of 98 °C 20 sec, 66 °C 10 sec, 72 °C 15 sec followed by a final extension of 72 °C 30sec. Indexed libraries were MinElute purified and their concentration was measured with Qubit, and size distribution was checked on Agilent 2200 TapeStation Genomic DNA ScreenTape.

Control libraries without UDG treatment were also made for assessing the presence of aDNA specific damages in the extract, as well as DNA free negative control libraries, to detect possible contamination during handling or present in materials.

Mitochondrial DNA capture and sequencing:

Biotinilated mtDNA baits were prepared from three overlapping long-range PCR products as described in (Maricic et al., 2010), but using the following primer pairs, L14759-H06378, L10870-H14799, L06363-H10888, described in (Haak et al., 2010).

Capture was done according to (Maricic et al., 2010) with the following modifications: Just four blocking oligos, given below were used in 3 μ M (each) final concentration:

BO1.P5.part1F: AATGATACGGCGACCACCGAGATCTACAC-Phosphate,

BO2.P5.part2F ACACTCTTTCCTACACGACGCTCTTCCGATCT-Phosphate,

BO4.P7.part1 R GTGACTGGAGTTCAGACGTGTGCTCTTCCGATCT-Phosphate,

BO6.P7.part2 R CAAGCAGAAGACGGCATAACGAGAT-Phosphate.

For one capture 300 ng biotinilated bait was used with 30 μ l Dynabeads MyOne Streptavidin C1 magnetic beads (Thermo Fisher Scientific). Double indexed libraries of 20 samples (300 ng each) were mixed and concentrated on MinElute columns, then captured together in a 64 μ l hybridization reaction. When fewer samples were enriched, we used proportionally smaller amounts of baits. After washing, bead-bound enriched libraries were resuspended in 20 μ l water and released from the beads in a 60 μ l PCR reaction containing 1 X KAPA HiFi HotStart ReadyMix and 2000 nM each of IS5- IS6 library primers. PCR conditions were: 98 $^{\circ}$ C 1 min, 10 cycles of 98 $^{\circ}$ C 20 sec, 60 $^{\circ}$ C 30 sec, 72 $^{\circ}$ C 30 sec, followed by a final extension of 72 $^{\circ}$ C 30 sec. The captured and amplified library mix was purified on MinElute column and eluted in 15 μ l EB.

Before sequencing, libraries were quantified with Qubit, and quality checked and Agilent 2200 TapeStation Genomic DNA ScreenTape. Sequencing was done at the SeqOmics Biotechnology Ltd., using MiSeq sequencer with MiSeq Reagent Kit v3 (Illumina, MS-102-3003) generating 2x150bp paired-end sequences.

Data analysis

The adapters of paired-end reads were trimmed with the cutadapt software (<http://dx.doi.org/10.14806/ej.17.1.200>) in paired end mode. Read quality was assessed with FastQC (<http://www.bioinformatics.babraham.ac.uk/projects/fastqc/>). Sequences shorter than 25 nucleotide were removed from this dataset. The resulting analysis-ready reads were mapped to the GRCh37.75 human genome reference sequence using the Burrows Wheeler Aligner (BWA) v0.7.9 software (Li and Durbin, 2009) with the BWA mem algorithm in paired mode and default parameters. Aligning to the GRCh37.75 human reference genome that also contains the mtDNA revised Cambridge Reference Sequence (rCRS, NC_012920.1) (Andrews et al., 1999) helped to avoid the forced false alignment of homologous nuclear mitochondrial sequences (NumtS) to rCRS, though the proportion of NumtS, derived from low copy nuclear genome, is expected to be orders of magnitudes lower than mtDNA in aDNA libraries. Samtools v1.1 (Li et al., 2009) was used for sorting and indexing BAM files. PCR duplicates were removed with Picard Tools v 1.113 (<http://picard.sourceforge.net>). Ancient DNA damage patterns were assessed using MapDamage 2.0 (Jónsson et al., 2013), and read quality scores were modified with the rescale option to account for post-mortem damage. Freebayes v1.02 ([arXiv:1207.3907](https://arxiv.org/abs/1207.3907) [q-bio.GN]) was used to identify variants and generate variant call format (VCF) files with the parameters -q 10 (exclude nucleotids with <10 phred quality) and -P 0.5 (exclude very low probability variants). Each variant call was also inspected manually. From VCF files FASTA format was generated with the Genom Analysis Tool Kit (GATK v3.5) FastaAlternateReferenceMaker walker.

Results and Discussion

NGS sequencing

We have sequenced 24 complete mtDNA genomes of the ancient Hungarians with multiple coverage (Table 2) without gaps and determined the haplotypes of the individuals (Table 1 and Supplementary Table 1). For two samples we have replicated the experiments from two independent extracts, one from bone another from tooth derived from the same individual, and in each case received identical sequence reads. UDG treated and non UDG treated libraries derived from the same extract also gave the same sequence reads. MapDamage profile of our partial UDG treated and control non treated library molecules displayed typical aDNA damage distribution (Supplementary Figure 1), as described in (Rohland et al., 2015b). MapDamage computed proportions of sequence reads with aDNA specific C-to-T and G-to-A transitions at the ends of molecules which remained after partial UDG treatment are shown in Table 2. The average length of the obtained mtDNA fragments ranged from 56 to 85 bp (Table 2), an expected size range for aDNA (Sawyer et al., 2012). These data indicated that the majority of sequences were derived from endogenous DNA molecules. Then we have estimated the percentage of possible contaminating molecules (Table 2) with a similar logic as in (Fu et al., 2013), by calculating the proportion of reads which did not correspond with the diagnostic positions of the consensus sequence given in Supplementary Table 1, which revealed very low contamination levels. Phylogenetic analyses (HaploGrep 2, (Weissensteiner et al., 2016) of all consensus sequences resulted unambiguous classifications without contradictory positions. Consensus sequences were submitted to NCBI GenBank under Accession No: KY083702-KY083725.

In NGS sequence reads typical aDNA sequence alterations, present in individual molecules, are disclosed and excluded by averaging multiple reads. Moreover aDNA specific sequence alterations, primarily C-T and G-A transitions accumulating at the end of molecules, serve as markers to distinguish ancient molecules from contaminating modern DNA. Therefore NGS eliminates most sequencing uncertainties inherent in PCR based methods (reviewed in (Rizzi et al., 2012), resulting in very reliable sequence reads. So we could use our NGS data to reevaluate and compare previous haplotyping strategies used in (Tömöry et al., 2007), (Csősz et al., 2016) and (Neparáczki et al., 2016). For this end, from our NGS data, we collected all SNP-s within the HVR stretches and coding region positions, which had been examined in (Tömöry et al., 2007) and (Neparáczki et al., 2016), then contrasted these with the original dataset (Table 1).

Contrasting NGS and PCR based sequence data

We found that in (Tömöry et al., 2007) haplotypes of 5 out of 9 samples were determined correctly, while in one sample haplogroup was correct with inaccurate haplotype, and in 3 samples NGS detected entirely different haplogroups. In the 15 samples of (Neparáczki et al., 2016) the same haplogroups were assigned from NGS data in all cases, however only 8 haplotypes proved to be correct. In both studies the majority of deviations originated from undetected SNP-s in sequencing reactions of PCR fragments, but (Tömöry et al., 2007) also identified 3 SNP-s erroneously (lined through nucleotide positions in Table 1). These results indicate that haplotypes from both studies were rather unreliable, but haplogroup classification with the approach of (Neparáczki et al., 2016) is more trustworthy than with approach used in (Tömöry et al., 2007).

As multicopy mtDNA is much better best preserved in archaeological remains than low copy nuclear DNA, most ancient sequences are derived from mitochondria (Hofreiter et al., 2001). Within mtDNA, the most polymorphic HVR control region contains outstanding phylogenetic information, therefore HVR sequencing has been the primary method of choice for mtDNA haplotyping. However HVR polymorphisms have a limited reliability for haplogroup determination, therefore in addition several informative coding region SNP-s (CR-SNP) were selected to unambiguously define haplogroups (Behar et al., 2007). At the beginning individual CR-SNP-s were determined with RFLP (Brown, 1980) or direct sequencing of PCR clones, but soon multiplex PCR combined with the

SNaPshot technique (Salas et al., 2005) offered a more straightforward solution for identifying multiple SNP-s simultaneously. Latter method was soon adapted in the ancient DNA field (Bouakaze et al., 2007), (Haak et al., 2010).

Determining individual CR-SNP-s separately is very time consuming and expensive, so it is tempting to test just those CR-SNP-s which are in line with HVR-I data. This is exactly what we read in (Tömöry et al., 2007): “*In cases when haplogroup categorization was not possible on the basis of HVSI motifs alone, analysis of the diagnostic polymorphic sites in the HVSI region and mtDNA coding region was also performed.*” A major problem with this approach is the ambiguity of sequence reads derived from aDNA PCR clones, as amplification typically starts from a mixture of endogenous and contaminating human DNA molecules (Malmström et al., 2005). Erroneous HVR reading will lead to inappropriate CR-SNP selection, and in case of dubious CR-SNP results, false Hg classification. This is the most probable explanation of the 3 incorrectly defined haplogroups in (Tömöry et al., 2007), (Table 1). A major advantage of the GonoCore22 SNaPshot assay is that all Hg specific CR-SNP-s are examined irrespectively of HVR reads. The 22 CR-SNP alleles independently define a certain Hg, which must correspond with that based on HVR sequence. As both HVR and CR-SNP reads may give ambiguous results, this approach provides a double control for correct Hg designation, but is not immune against incorrect HVR haplotype reads. This is the explanation of correct Hg-s and erroneous haplotypes in (Neparáczki et al., 2016), (Table 1).

The problem of ambiguous aDNA sequence reads is demonstrated on Fig. 1. In (Neparáczki et al., 2016) consequently the higher peaks were taken into account, which also matched with the GenoCoRe22 data. However in position 16399 the correct nucleotide is defined by the neglected lower peak (G instead of A, see Table 1.), which resulted in incorrect haplotyping. In contrast in the neighboring double peak (16403 in Fig. 1), the correct nucleotide is defined by the selected higher peak.

Coding region SNP testing with either RFLP, sequencing or SNaPshot method also suffers from the same problem as demonstrated on Fig. 2. After multiplex PCR amplification of 22 mtDNA fragments two separate Single Base Extension (SBE) reactions are performed, and each reveals 11 Hg defining alleles. Both independent SBE reactions shown in Fig. 2 contain several double peaks, and one of each must have derived from contamination. Some of these can be excluded from repeated SNaPshot reactions, for example the lower electropherogram excludes the ancestral *preHV* allele, since it has a single peak (T) in this position. If such exclusion is not possible, the higher peaks are preferably chosen, as the blue peak (G) for Hg *B* and the green (A) for Hg *N* on Fig. 2. These decisions however must be handled with caution, therefore the presence of the *B* Hg defining 9 bp deletion also had been confirmed in (Neparáczki et al., 2016), with singleplex PCR and agarose gelelectrophoresis. In other cases phylogenetic relations are taken into account (Cooper and Poinar, 2000), for example if the *preHV* allele is derived the *HV* allele must also be derived, this is why we have considered the lower peak (A) for *HV* in Fig. 2 (Neparáczki et al., 2016). The summary of repeated SNaPshot reactions considered together with multiple HVR sequence reads warrants trustable Hg classification.

The studied conqueror samples were excavated between the 1930-90s, and had been handled by a large number of researchers, many with untraceable identity. It follows that these samples were inevitably contaminated during sample collection and storage. (Tömöry et al., 2007) collected samples from a large number of cemeteries, and published the ones with best DNA preservation. In spite of careful sampling their available method was error prone. (Neparáczki et al., 2016) aimed at characterizing an entire cemetery which limited the ability of sample selection, so in spite of the more reliable method their haplotype determination proved error prone. The lesson from this study is that PCR based haplotypes need to be handled cautiously, which has been well known in the aDNA field (Handt et al., 1994), (Richards et al., 1995), (Gilbert et al., 2005), (Sampietro et al., 2006). It also follows that incorrect haplotypes particularly distort sequence based statistical analysis, like *Fst* statistics or shared haplotype analysis applied in (Tömöry et al., 2007) and (Csösz et al., 2016). The

accumulation of authentic NGS ancient DNA sequence data in databases will greatly facilitate reliable population genetic studies.

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Table 1. Comparison of Haplogroups identified with different PCR based methods and NGS. Hg-s determined incorrectly with PCR methods are labelled with enlarged bold italic and lined through, while correct Hg-s with incorrect haplotypes are labelled with enlarged bold italic. Haplogroups and haplotypes were determined with the HaploGrep 2 version 2.1.0 (Weissensteiner et al., 2016) based on Phylotree 17 (van Oven, 2015) from the available SNP-s. For the (Tömöry et al., 2007) samples HaploGrep assignment, based on their identified SNP positions is given in parenthesis. *data from Ph.D thesis of Tömöry 2008.

	cemetery/grave no. / sample name	HVR-I mutations found (position -16000)	HVR-II and coding region mutations studied / method	HVR-II and coding region mutations found	Hg described in the study (Hg with Haplogrep)	Haplotype identified by NGS in the present study	unnoticed SNP-s, or <i>erroneously-identified-SNP-s</i> in the region studied
Tömöry et al. 2007 samples	Magyarhomoróg/120/ anc2	CRS	73 7028 14766 / RFLP	-	H (H2a2a1)	H84	none
	Orosháza-Görbics tanya/2/ anc3	147A 172C 183C 189C 223T 320T 355T	10238 / RFLP	10238C	N1a (L3e2b)	N1a1a1a1a	none
	Szabadkígyós-Pálliget/7/ anc4	223T 356C	10400 12308 12705 / sequencing	12308G	<i>U4 (U4a2b)</i>	N1a1a1a1	16147A 16172C 16248T 16320T 16355T <i>16356C</i> 10398G <i>12308G</i> 12705T
	Szegvár-Oromdűlő/412/ anc5	CRS	73 7028 14766 / RFLP	14766T	<i>H (R0)</i>	K1c1d	16224C 16311C 73G 7028T
	Szegvár-Oromdűlő/593/ anc6	114A 192T 256T 270T 294T	12308 / sequencing	12308G	U5a1 (U5a2a)	U5a2a1b	none
	Sárrétudvar-Hízóföld/5/ anc10	129A 148T 223T	10238 / RFLP 12705 / sequencing	10238C 12705T	<i>I (N1)</i>	I5a1a	16391A
	Sárrétudvar-Hízóföld/118/ anc12	126C 182C 183C 189C 294T 296T 298C	9 bp del / electrophoresis	9 bp del*	T (T2f1a)	T2f1a1	none
	Sárrétudvar-Hízóföld/213/ anc13	311C	73 14766 / RFLP 11719 12308 12705 / sequencing	73G 11719A 14766T	<i>R (R1)</i>	J1c3g	16069T 16126C <i>16311C</i>
	Harta-Freifelt/10/ anc25	294T 304C	73 7028 14766 / RFLP 10310 / sequencing	-	H (H5a4)	H5e1a	none
Neparáczki et al. 2016 samples	Karos-III/1	183C 189C 217C		263G 7028T 9bp del 11719A 14766T	<i>B4</i>	B4d1	207A
	Karos-III/3	362C		239C 263G	H6	H6a1b	none
	Karos-III/4	069T 092C 126C 261T		228A 263G 295T 7028T 11719A 12612G 14766T	J1c7	J1c7a	none
	Karos-III/5	183C 189C 217C		263G 7028T 9bp del 11719A 14766T	B4	B4d1	none
	Karos-III/6	189C		263G 7028T 9bp del 11719A 14766T	<i>B4'5</i>	B4d1	16183C, 16217C
	Karos-III/8	051G 189C 362C		263G 7028T 11467G 11719A 14766T	<i>U2e</i>	U2e1b	217C, 16129C, 16256T,
	Karos-III/10	304C		263G	<i>H5</i>	H5e1	16189C 16294T
	Karos-III/11	189C 223T 278T		195C 257G 263G 6371T 7028T 11719A 12705T 14766T	<i>X2f</i>	X2f	16093C
	Karos-III/12	183C 189C 223T 290T 319A		235G 263G 4248C 7028T 11719A 12705T 14766T	A	A12	none
	Karos-III/14	126C 163G 186T 189C 294T		195G 263G 7028T 11719A 13368A 14766T	T1a	T1a1b	none
	Karos-III/15	069T 126C 362C		263G 295T 7028T 11719A 12612G 14766T	<i>J</i>	J2a1	16263 del
	Karos-III/16	256T 270T		263G 7028T 11467G 11719A 14766T	<i>U5a</i>	U5a1a2a	16399G
	Karos-III/17	362C		239C 263G	H6	H6a1a	none
	Karos-III/18	126C 163G 186T 189C 294T		214G 263G 7028T 11719A 13368A 14766T	T1a10a	T1a10a	none
Karos-III/19	126C 163G 186T 189C 294T		214G 263G 7028T 11719A 13368A 14766T	T1a10a	T1a10a	none	

Table 2. Details of NGS data for each samples. Data shown are all from UDG treated libraries.

cemetery/grave no. /sample name	sample source	total no. of reads	no. of reads mapped on rCRS	no. of unique mapped reads	average fragment length	(%) of nucleotides above 10x coverage	estimated contamination (%)	(%) G to A misincorp. at 3' end (MapDamage)	(%) C to T misincorp. at 5' end (MapDamage)
Magyarhomoróg/120/anc2	tooth	26152	12519	1656	55,97	89,62	0,00	6,11	7,81
Orosháza-Görbics tanya/2/ anc3	femur	85178	50555	3444	79,37	99,89	0,43	8,13	8,89
Szabadkígyós-Pálliget/7/anc4	tooth	53176	27002	2854	63,85	97,46	0,45	8,19	9,22
Szegvár-Oromtölő/412/anc5	tooth	47760	23426	6150	60,07	99,95	0,75	5,49	6,40
Szegvár-Oromtölő/593/anc6	tooth	66798	35260	3841	58,09	98,64	2,08	6,47	8,70
Sárrétudvari-Hízó föld/5/anc10	tooth	17632	6664	2205	69,94	95,11	0,00	7,40	10,29
Sárrétudvari-Hízó föld/118/anc12	tooth	36214	14708	3394	63,96	98,81	0,36	8,75	11,53
Sárrétudvari-Hízó föld/213/anc13	tooth	42326	20383	4997	62,44	95,01	0,83	9,01	10,22
Harta-Freifelt/10/anc25	tooth	135472	66169	4803	80,75	99,93	1,75	6,00	7,10
Karos-III/1	femur	30830	5968	2414	81,44	98,07	0,00	13,09	11,48
Karos-III/3	femur	58982	12858	3839	76,84	98,91	1,68	12,51	10,66
Karos-III/4	femur	82194	22930	4862	68,71	99,98	0,33	12,93	11,98
Karos-III/5	metatarsus	394292	23740	10299	85,35	99,96	3,44	8,45	6,84
Karos-III/6	femur	41054	3863	955	70,68	87,24	0,00	6,71	6,75
Karos-III/8	femur	75724	26747	5938	64,26	99,67	1,79	11,37	11,08
Karos-III/10	femur	67416	6371	1768	68,22	89,61	0,00	9,89	9,04
Karos-III/11	femur	346124	4496	1569	79,62	93,91	1,32	12,78	11,42
Karos-III/12	femur	52738	5843	2406	70,76	95,80	3,96	12,40	11,19
Karos-III/14	femur	61346	16134	4532	69,29	99,69	1,82	14,53	14,13
Karos-III/15	femur	422796	80431	13248	81,03	99,98	0,29	11,02	9,95
Karos-III/16	femur	90950	23233	2851	75,65	99,14	1,34	11,34	11,12
Karos-III/17	femur	43330	2626	1191	79,64	87,55	0,00	10,31	9,91
Karos-III/18	femur	9184	3208	1596	68,48	90,49	0,00	15,42	12,11
Karos-III/19	tooth	59102	30135	3244	69,07	98,78	0,00	6,39	6,55

Figure 1. Chromatogram of two HVR-I sequence fragments of the Karos-III/16 sample from (Neparáčzki et al., 2016). Arrows label double peaks, correct reads according to NGS data are listed above the arrows.

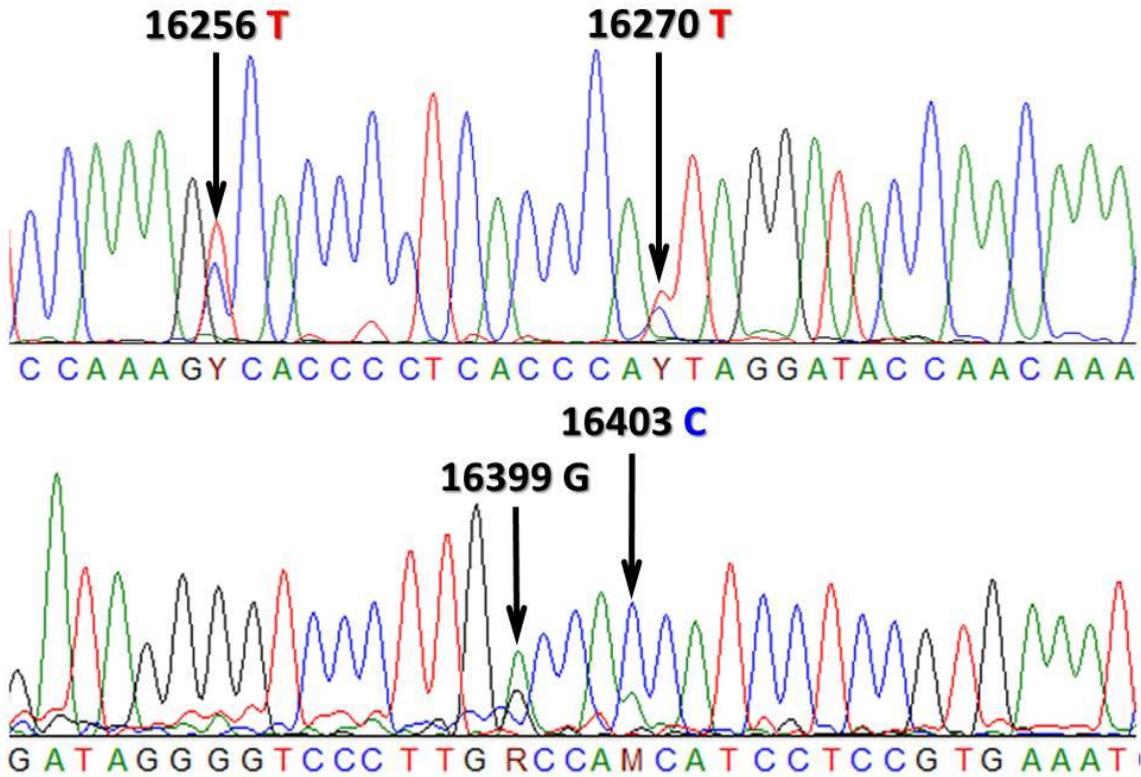
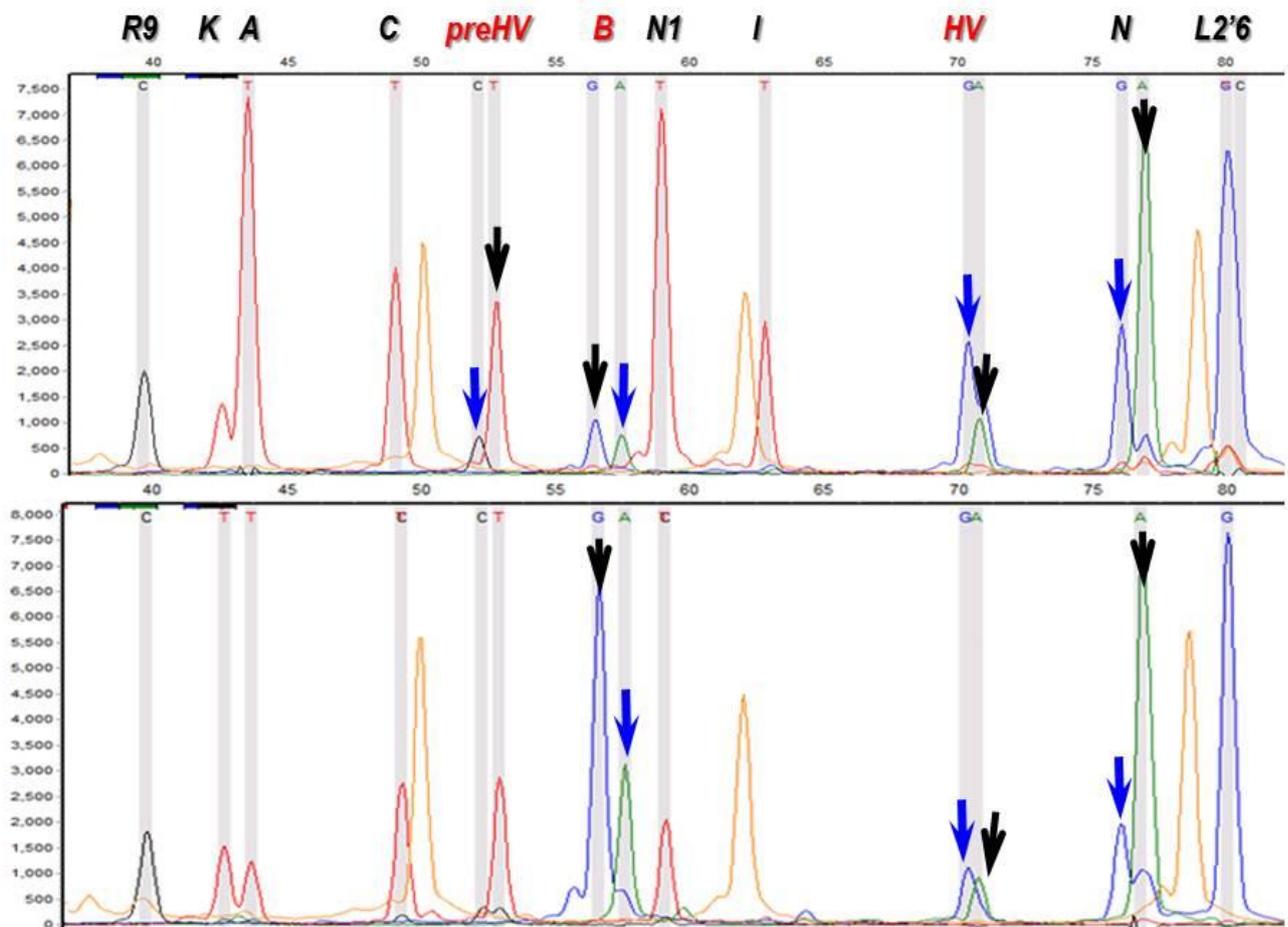
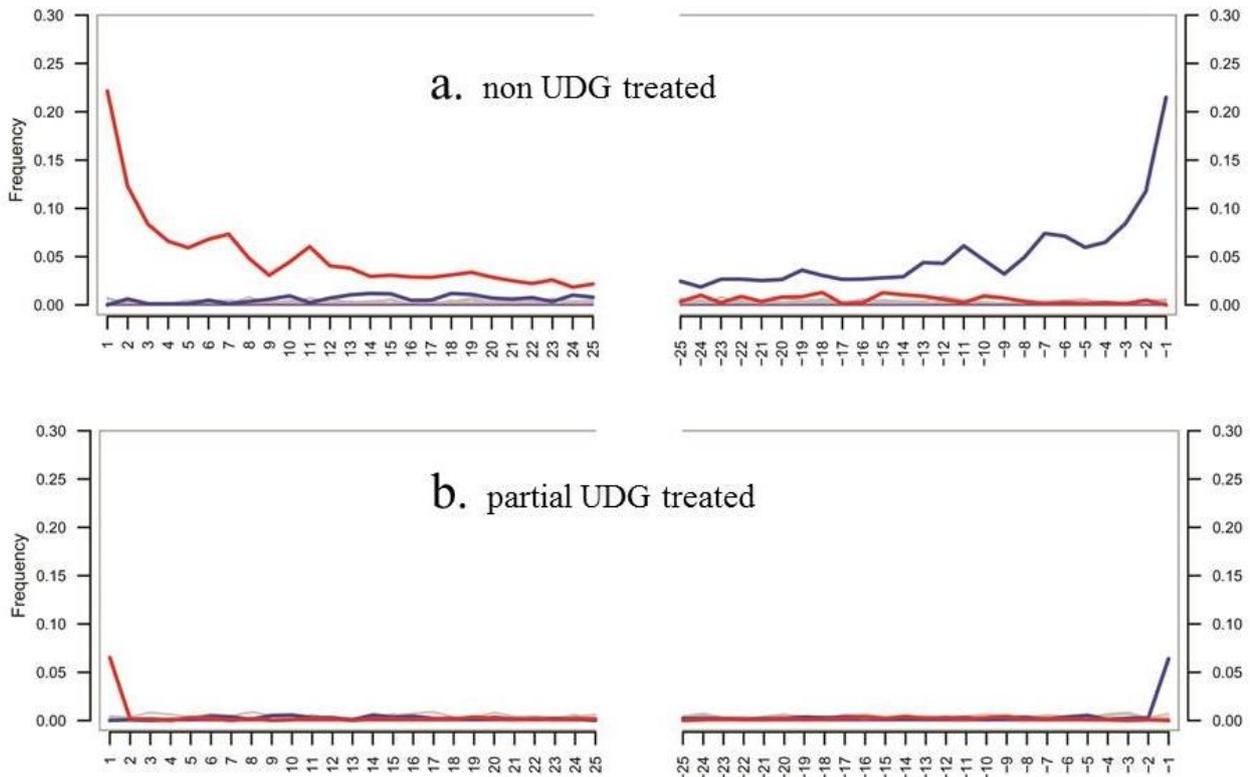


Figure 2. Electropherograms of two SNaPshot SBE-II reactions from two extracts of the same Karos-III/6 sample (Neparáčzki et al., 2016). Characters at the top indicate Hg-s defined by the corresponding peaks. Black characters indicate peaks defining the ancestral allele, read characters indicate peaks defining the derived allele. Arrows point at double peaks. As each dye has a different influence on DNA mobility, positions of identical fragments with different dyes are not the same. Black arrows point at peaks taken into account, while blue arrows indicate neglected peaks, considered to have been derived from contamination. Orange peaks are size standards (GeneScan-120 LIZ, Applied Biosystems).



Supplementary Figure 1.

Damage patterns of libraries generated by MapDamage 2.0 20. a. non UDG treated library showing C to T (and complementary G to A) misincorporations at the 5' and 3' termini of the last 25 nucleotides. b. Damage pattern of partial UDG treated library derived from the same extract. As expected the nontreated library contains much higher rate of transitions, most of which was removed by partial UDG treatment. Only data from one extract are shown, as all libraries displayed similar pattern.



Supplementary Table 1.

Mitochondrial sequence haplotypes of the 24 ancient samples. SNPs are provided against rCRS. Following the recommendations in ³⁶, we excluded common indels (hotspots) at nucleotide positions: 309.1C(C), 315.1C, 523-524del (or 522-523del), 3106del, 16182C, 16183C, 16193.1C(C), 16519C.

References

- Andrews, R.M., Kubacka, I., Chinnery, P.F., Lightowlers, R.N., Turnbull, D.M., Howell, N., 1999. Reanalysis and revision of the Cambridge reference sequence for human mitochondrial DNA. *Nat. Genet.* 23, 147. doi:10.1038/13779
- Behar, D.M., Rosset, S., Blue-Smith, J., Balanovsky, O., Tzur, S., Comas, D., Mitchell, R.J., Quintana-Murci, L., Tyler-Smith, C., Wells, R.S., 2007. The genographic project public participation mitochondrial DNA database. *PLoS Genet.* 3, 1083–1095. doi:10.1371/journal.pgen.0030104
- Bouakaze, C., Keyser, C., Amory, S., Crubézy, E., Ludes, B., 2007. First successful assay of Y-SNP typing by SNaPshot minisequencing on ancient DNA. *Int. J. Legal Med.* 121, 493–499. doi:10.1007/s00414-007-0177-3
- Brown, W.M., 1980. Polymorphism in mitochondrial DNA of humans as revealed by restriction endonuclease analysis. *Proc. Natl. Acad. Sci. U. S. A.* 77, 3605–3609. doi:10.1073/pnas.77.6.3605
- Cooper, A., Poinar, H.N., 2000. Ancient DNA: do it right or not at all. *Science*. doi:10.1126/science.289.5482.1139b
- Csősz, A., Szécsényi-Nagy, A., Csákyová, V., Langó, P., Bódis, V., Köhler, K., Tömöry, G., Nagy, M., Mende, B.G., 2016. Maternal Genetic Ancestry and Legacy of 10th Century AD Hungarians. *Sci. Rep.* 6, 33446. doi:DOI: 10.1038/srep33446
- Damgaard, P.B., Margaryan, A., Schroeder, H., Orlando, L., Willerslev, E., Allentoft, M.E., 2015. Improving access to endogenous DNA in ancient bones and teeth. *Sci. Rep.* 5, 11184. doi:10.1038/srep11184
- Fu, Q., Mittnik, A., Johnson, P.L.F., Bos, K., Lari, M., Bollongino, R., Sun, C., Giemsch, L., Schmitz, R., Burger, J., Ronchitelli, A.M., Martini, F., Cremonesi, R.G., Svoboda, J., Bauer, P., Caramelli, D., Castellano, S., Reich, D., Pääbo, S., Krause, J., 2013. A revised timescale for human evolution based on ancient mitochondrial genomes. *Curr. Biol.* 23, 553–559. doi:10.1016/j.cub.2013.02.044
- Gilbert, M.T.P., Rudbeck, L., Willerslev, E., Hansen, A.J., Smith, C., Penkman, K.E.H., Prangenberg, K., Nielsen-Marsh, C.M., Jans, M.E., Arthur, P., Lynneruo, N., Turner-Walker, G., Biddle, M., Kjølbye, B., Collins, M.J., 2005. Biochemical and physical correlates of DNA contamination in archaeological human bones and teeth excavated at Matera, Italy. *J. Archaeol. Sci.* 32, 785–793. doi:10.1016/j.jas.2004.12.008
- Haak, W., Balanovsky, O., Sanchez, J.J., Koshel, S., Zaporozhchenko, V., Adler, C.J., der Sarkissian, C.S.I., Brandt, G., Schwarz, C., Nicklisch, N., Dresely, V., Fritsch, B., Balanovska, E., Villems, R., Meller, H., Alt, K.W., Cooper, A., 2010. Ancient DNA from European early Neolithic farmers reveals their near eastern affinities. *PLoS Biol.* 8. doi:10.1371/journal.pbio.1000536
- Handt, O., Höss, M., Krings, M., Pääbo, S., 1994. Ancient DNA: Methodological challenges. *Experientia*. doi:10.1007/BF01921720
- Heupink, T.H., Subramanian, S., Wright, J.L., Endicott, P., Westaway, M.C., Huynen, L., Parson, W., Millar, C.D., Willerslev, E., Lambert, D.M., 2016. Ancient mtDNA sequences from the First Australians revisited. *Proc. Natl. Acad. Sci.* 201521066. doi:10.1073/pnas.1521066113
- Hofreiter, M., Serre, D., Poinar, H.N., Kuch, M., Pääbo, S., 2001. Ancient DNA. *Nat. Rev. Genet.* 2, 353–9. doi:10.1038/35072071
- Jónsson, H., Ginolhac, A., Schubert, M., Johnson, P.L.F., Orlando, L., 2013. MapDamage2.0: Fast approximate Bayesian estimates of ancient DNA damage parameters, in: *Bioinformatics*. pp. 1682–1684. doi:10.1093/bioinformatics/btt193
- Kircher, M., Sawyer, S., Meyer, M., 2012. Double indexing overcomes inaccuracies in multiplex sequencing on the Illumina platform. *Nucleic Acids Res.* 40. doi:10.1093/nar/gkr771
- Knapp, M., Clarke, A.C., Horsburgh, K.A., Matisoo-Smith, E.A., 2012. Setting the stage—building and working in an ancient DNA laboratory. *Ann. Anat.* 194, 3–6.
- Li, H., Durbin, R., 2009. Fast and accurate short read alignment with Burrows-Wheeler transform. *Bioinformatics* 25, 1754–60. doi:10.1093/bioinformatics/btp324

- Li, H., Handsaker, B., Wysoker, A., Fennell, T., Ruan, J., Homer, N., Marth, G., Abecasis, G., Durbin, R., 2009. The Sequence Alignment/Map format and SAMtools. *Bioinformatics* 25, 2078–9. doi:10.1093/bioinformatics/btp352
- Malmström, H., Storå, J., Dalén, L., Holmlund, G., Götherström, A., 2005. Extensive human DNA contamination in extracts from ancient dog bones and teeth. *Mol. Biol. Evol.* 22, 2040–2047. doi:10.1093/molbev/msi195
- Maricic, T., Whitten, M., Pääbo, S., 2010. Multiplexed DNA Sequence Capture of Mitochondrial Genomes Using PCR Products. *PLoS One* 5, e14004. doi:10.1371/journal.pone.0014004
- Meyer, M., Kircher, M., 2010. Illumina sequencing library preparation for highly multiplexed target capture and sequencing. *Cold Spring Harb. Protoc.* 5. doi:10.1101/pdb.prot5448
- Neparáczi, E., Juhász, Z., Pamjav, H., Fehér, T., Csány, B., Zink, A., Maixner, F., Pálfi, G., Molnár, E., Pap, I., Kustár, Á., Révész, L., Raskó, I., Török, T., 2016. Genetic structure of the early Hungarian conquerors inferred from mtDNA haplotypes and Y-chromosome haplogroups in a small cemetery. *Mol. Genet. Genomics*.
- Pickrell, J.K., Reich, D., 2014. Toward a new history and geography of human genes informed by ancient DNA. *Trends Genet.* doi:10.1016/j.tig.2014.07.007
- Pilli, E., Modi, A., Serpico, C., Achilli, A., Lancioni, H., Lippi, B., Bertoldi, F., Gelichi, S., Lari, M., Caramelli, D., 2013. Monitoring DNA Contamination in Handled vs. Directly Excavated Ancient Human Skeletal Remains. *PLoS One* 8. doi:10.1371/journal.pone.0052524
- Richards, M.B., Sykes, B.C., Hedges, R.E.M., 1995. Authenticating DNA Extracted From Ancient Skeletal Remains. *J. Archaeol. Sci.* 22, 291–299. doi:10.1006/jasc.1995.0031
- Rizzi, E., Lari, M., Gigli, E., De Bellis, G., Caramelli, D., 2012. Ancient DNA studies: new perspectives on old samples. *Genet. Sel. Evol.* 44, 21. doi:10.1186/1297-9686-44-21
- Rohland, N., Harney, E., Mallick, S., Nordenfelt, S., Reich, D., 2015a. Partial uracil-DNA-glycosylase treatment for screening of ancient DNA. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 370, 20130624. doi:10.1098/rstb.2013.0624
- Rohland, N., Harney, E., Mallick, S., Nordenfelt, S., Reich, D., 2015b. Partial uracil – DNA – glycosylase treatment for screening of ancient DNA. *Phil. Trans. R. Soc. B* 370, 20130624. doi:10.1098/rstb.2013.0624
- Rohland, N., Hofreiter, M., 2007. Ancient DNA extraction from bones and teeth. *Nat. Protoc.* 2, 1756–1762. doi:10.1038/nprot.2007.247
- Salas, A., Quintáns, B., Álvarez-iglesias, V., 2005. SNaPshot Typing of Mitochondrial DNA Coding Region Variants, in: *Forensic DNA Typing Protocols*. pp. 197–208.
- Sampietro, M.L., Gilbert, M.T.P., Lao, O., Caramelli, D., Lari, M., Bertranpetit, J., Lalueza-Fox, C., 2006. Tracking down human contamination in ancient human teeth. *Mol. Biol. Evol.* 23, 1801–1807. doi:10.1093/molbev/msl047
- Sawyer, S., Krause, J., Guschanski, K., Savolainen, V., Pääbo, S., 2012. Temporal patterns of nucleotide misincorporations and DNA fragmentation in ancient DNA. *PLoS One* 7. doi:10.1371/journal.pone.0034131
- Tömöry, G., Csányi, B., Bogácsi-Szabó, E., Kalmár, T., Czibula, Á., Csősz, A., Priskin, K., Mende, B., Langó, P., Downes, C.S., Raskó, I., 2007. Comparison of maternal lineage and biogeographic analyses of ancient and modern Hungarian populations. *Am. J. Phys. Anthropol.* 134, 354–368. doi:10.1002/ajpa.20677
- van Oven, M., 2015. PhyloTree Build 17: Growing the human mitochondrial DNA tree. *Forensic Sci. Int. Genet. Suppl. Ser.* 5, 9–11. doi:10.1016/j.fsigs.2015.09.155
- van Oven, M., 2010. Revision of the mtDNA tree and corresponding haplogroup nomenclature. *Proc. Natl. Acad. Sci. U. S. A.* 107, E38–NaN-e41. doi:10.1073/pnas.0915120107
- Weissensteiner, H., Pacher, D., Kloss-Brandstätter, A., Forer, L., Specht, G., Bandelt, H.-J., Kronenberg, F., Salas, A., Schönherr, S., 2016. HaploGrep 2: mitochondrial haplogroup classification in the era of high-throughput sequencing. *Nucleic Acids Res.* 44, W58–63. doi:10.1093/nar/gkw233