Novel germline variant in the histone demethylase and transcription regulator KDM4C induces a multi-cancer phenotype

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ABSTRACT

Background Genes involved in epigenetic regulation are central for chromatin structure and gene expression. Specific mutations in these might promote carcinogenesis in several tissue types.

Methods We used exome, whole-genome and Sanger sequencing to detect rare variants shared by seven affected individuals in a striking early-onset multi-cancer family. The only variant that segregated with malignancy resided in a histone demethylase KDM4C. Consequently, we went on to study the epigenetic landscape of the mutation carriers with ATAC, Chip (chromatin immunoprecipitation) and RNA-sequencing from lymphoblastoid cell lines to identify possible pathogenic effects.

Results A novel variant in KDM4C, encoding a H3K9me3 histone demethylase and transcription regulator, was found to segregate with malignancy in the family. Based on Roadmap Epigenomics Project data, differentially accessible chromatin regions between the variant carriers and controls enrich to normally H3K9me3-marked chromatin. We could not detect a difference in global H3K9 trimethylation levels. However, carriers of the variant seemed to have more trimethylated H3K9 at transcription start sites. Pathway analyses of Chip-seq and differential gene expression data suggested that genes regulated through KDM4C interaction partner EZH2 and its interaction partner PLZF are aberrantly expressed in mutation carriers.

Conclusions The apparent dysregulation of H3K9 trimethylation and KDM4C-associated genes in lymphoblastoid cells supports the hypothesis that the KDM4C variant is causative of the multi-cancer susceptibility in the family. As the variant is ultrarare, located in the conserved catalytic JmjC domain and predicted pathogenic by the majority of available in silico tools, further studies on the role of KDM4C in cancer predisposition are warranted.

INTRODUC TION

Cancers arise from the accumulation of both genetic and epigenetic alterations. Numerous inherited genetic changes have been shown to predispose to certain or multiple cancer types through, for instance, defective DNA repair or cell-cycle checkpoint mechanisms. Examples of this are damaging point mutations in the tumour suppressor genes TP53, BRCA1 and BRCA2 that cause the well-known cancer syndromes Li-Fraumeni and hereditary breast and ovarian cancer. Cancer predisposing variants in epigenetic modifiers, such as TET2 and LSD1/KDMA1, have also been reported. Mutations in this type of genes can cause epigenetic dysregulation through, for example, aberrant DNA or histone methylation, which can subsequently alter the gene expression profiles of cells and thus promote carcinogenesis in several tissue types.

To this end, we studied a striking early-onset multi-cancer family with six confirmed cases of papillary thyroid carcinoma (PTC), as well as cases of chondrosarcoma and myeloid leukaemia. Some of the PTC affected individuals had also been diagnosed with other cancers, such as melanoma, breast cancer and adenocarcinoma of the cervix. According to patient records of affected relatives, there had been an additional case of thyroid cancer and two cases of leukaemia of unknown type among deceased first-degree relatives.

We found a previously undescribed missense change (NP_055876.2:p.(His217Arg)) in the catalytic Jumonji C (JmjC) domain of histone demethylase KDM4C (hereafter referred to as KDM4C:p.H217R) to segregate with malignancy in the family. KDM4C has numerous roles in genetic and epigenetic regulation. The JmjC domain of KDM4C specifically demethylates trimethylated lysine-9 and lysine-36 residues of histone H3 (H3K9me3 and H3K36me3), thus affecting chromatin conformation and gene expression. In addition, amino acids 1–333, which include the JmjC domain, have been shown to regulate transcriptional repression by interacting with enhancer of zeste homolog 2 (EZH2), a major regulator of gene expression, is frequently overexpressed and underexpressed in a wide variety of cancerous tissue types, including blood, prostate and breast. KDM4C also interacts with lysine-specific histone demethylase 1A (LSD1) and has a role in regulating the androgen receptor (AR). To determine the function of the novel KDM4C variant, differences in chromatin accessibility, H3K9me3 distribution and gene expression in lymphoblastoid cells between KDM4C:p.H217R carriers and healthy controls were evaluated. Our findings suggest that KDM4C:p.H217R is causative of the multi-cancer phenotype of the described
family, and that the effect leads to changes in chromatin accessibility and histone epigenetics. Understanding the impact of demethylase activity is critical when targeting epigenetic modifiers in the development of future cancer therapeutics.

**METHODS**

Please see online supplemental file 1 (online supplemental methodology) for a complete listing and descriptions of used methods.

**Patients and samples**

A family with a striking history of cancer, PTC in particular, was forwarded to us by a clinical geneticist. In two generations, there were six cases of PTC, as well as cases of myeloid leukaemia, chondrosarcoma, ductal breast carcinoma, melanoma and adenocarcinoma of the cervix (figure 1). According to patient records, deceased family members had also been affected by at least thyroid cancer and leukaemia of unknown type (figure 1). Peripheral blood samples were collected from individuals III:1, III:2, III:3 and IV:1, whereas for patients III:4, IV:2 and IV:3, peripheral blood samples were collected from individuals III:1, III:2, III:3 and IV:1, whereas for patients III:4, IV:2 and IV:3, formalin-fixed paraffin-embedded (FFPE)-tissue samples were obtained. We also collected blood samples of 10 patients from four unrelated Finnish PTC families. We used the Finnish Cancer Registry (FCR) to collect a validation set consisting of 59 probable familial cases of PTC. We had earlier performed systematic municipality at birth and family name at birth-based clustering of all cancer cases in the registry, which comprises all cancer diagnoses made in Finland after 1953. For a thorough description of the method, please refer to Kaasinen et al. For a thorough description of the method, please refer to Kaasinen et al.11 For the validation set, we collected FFPE-tissue samples from high-scoring PTC clusters, which are likely to consist of true relatives.

**DNA and cell lines**

Genomic DNA for exome, whole-genome and Sanger sequencing was extracted from blood and FFPE-tissue samples with the phenol-chloroform method.

Peripheral blood lymphocytes from patients III:1, III:2, III:3 and IV:1 were infected with Epstein-Barr virus (EBV) to generate lymphoblastoid cell lines. However, we used only three cell lines in this study, since the cell line of patient III:2 failed to grow. As controls, we used in-house lymphoblastoid cell lines from four unrelated cancer-free individuals. All used cell lines had low and similar estimated passage numbers (online supplemental table 1 (online supplemental data 1)).

**Variant calling and analysis**

WES data were processed with GATK best practices variant calling pipeline (GRCh37). WGS raw data were processed (primary analyses, alignment and variant calling) by Complete Genomics (2011). Variant analyses, including quality filtering, visualisation, sample comparison, gene annotation (Ensembl genes v89) and control data filtering (gnomAD v2.1.1), were performed with BasePlacer.12 The following parameters were used in the variant analysis:

- gnomAD allele frequency: 0.
- Non-synonymous/indel/splice site variant shared by all three samples.
- Allelic fraction: > =20%.
- Variant and genotype quality: > =20.

The analysis resulted in four candidate variants in four genes (table 1).

**ATAC-seq**

ATAC-seq was performed for three KDM4C:p.H217R-carrier and four control lymphoblastoid cell lines as described in previous work.13 See online supplemental data 1, online supplemental table 2 and online supplemental figure 1 for a detailed description of the procedure.

**ChIP-seq**

Chromatin immunoprecipitation followed by sequencing (ChIP-seq) with an antibody against H3K9me3 was performed for three KDM4C:p.H217R-carrier and four control lymphoblastoid cell lines. See online supplemental data 1 and online supplemental figure 2 for a detailed description of the procedure. Briefly, 10 million cells were crosslinked with formaldehyde and sheared to fragment length of 200–500 bp by sonication.

### Table 1: Ultrarare variants shared by the affected exome or genome-sequenced individuals

<table>
<thead>
<tr>
<th>Genomic location</th>
<th>Effect in transcript 1</th>
<th>Protein effect</th>
<th>Gene/Protein name</th>
<th>Segregation</th>
<th>Protein effect prediction*</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC_000001.10:g.223983870C&gt;G</td>
<td>NM_005426.2:c.1984G&gt;C</td>
<td>NP_005417.1:p.(Val662Leu)</td>
<td>Tumour protein p53 binding protein 2 (TP53BP2)</td>
<td>No</td>
<td>Benign</td>
</tr>
<tr>
<td>NC_000005.9:g.170305249dup</td>
<td>NM_022897.4:c.165+2dup</td>
<td>NP_075048.1:p.?</td>
<td>RAN binding protein 17 (RANBP17)</td>
<td>No</td>
<td>Uncertain (splice site insertion)</td>
</tr>
<tr>
<td>NC_000009.11:g.6880032A&gt;G</td>
<td>NM_015061.4:c.650A&gt;G</td>
<td>NP_055876.2:p.(His217Arg)</td>
<td>Lysine (K)-specific demethylase 4C (KDM4C)</td>
<td>Yes</td>
<td>Pathogenic</td>
</tr>
<tr>
<td>NC_000012.11:g.124915216C&gt;T</td>
<td>NM_006312.5:c.1000G&gt;A</td>
<td>NP_006303.4:p.(Glu334Lys)</td>
<td>Nuclear receptor corepressor 2 (NCOA2)</td>
<td>No</td>
<td>Pathogenic</td>
</tr>
</tbody>
</table>

*Protein effect prediction is based on multiple prediction tools used in VarSome search engine. Pathogenic=the majority of tools give damaging/pathogenic/deleterious prediction.
Chromatin was immunoprecipitated with an antibody against H3K9me3 (Active Motif 39062, lot 09919003). Sequencing libraries were prepared and sequenced at Macrogen using the TruSeq DNA Sample prep Kit (Illumina, San Diego, California, USA), HiSeq 2500 system (Illumina, San Diego, California, USA) and 100 bp single-end sequencing. DiffBind V2.14.0 in R V3.6.3 was used to calculate the binding affinity of H3K9me3. Ggplot2 V3.2.1 in R V3.6.1 was used in visualisation. Mann-Whitney U test with alternative hypothesis ‘greater’ in R V3.6.1 was used to compare RNA-seq log2FCs of TSS peaks with less H3K9me3 and no change in H3K9me3 levels.

Ingenuity pathway analysis
In total, 136 significantly differentially expressed genes (DESeq2 adjusted p value≤0.05) were analysed using Ingenuity pathway analysis (IPA; Qiagen, Redwood City, California, USA) version 52912811 core analysis feature.

We performed the same analysis (with and without expression scores separately) for genes with the top log2FCs of H3K9me3 binding at their transcription start sites. Five hundred genes with the highest positive and 500 genes with the highest negative score were included.

RESULTS
A novel germline missense variant in KDM4C segregates in a multi-cancer family
Variant analysis of three affected siblings in the family revealed a novel variant (NM_015061.4:c.650A>G; Chr9(GRCh37):g.6880032A>G; NP_055876.2:p.(His217Arg)) in KDM4C. The heterozygous p.H217R variant is located in the JmjC domain (figure 2A) of the catalytic domain and p.H217R in KDM4C. (B) DynaMut prediction results for KDM4C:p.H217R.

Gene expression changes predict activation of PLZF in KDM4C:p.H217R carriers
We examined the effect of the discovered KDM4C:p.H217R variant on gene expression by RNA-seq. Using DESeq2, we identified 136 differentially expressed genes (adjusted p value≤0.05) (figure 3 and online supplemental table 3 (online supplemental data 2)), of which 76 were downregulated (log2FC<0) and 60 upregulated (log2FC>0) in KDM4C:p.H217R carriers. No change was detected in the expression level of KDM4C (log2FC=−0.12, adjusted p value=0.93) between KDM4C:p.H217R carriers and non-carriers.

We analysed the differentially expressed genes and their fold changes with IPA. The results indicated an overall decrease in the activity of the xenobiotic metabolism CAR and PXR signalling pathways (online supplemental figure 3 (online supplemental data 3)). Changes in gene expression predicted the activation (activation z-score 2.000, p value of overlap 0.00497) of transcription factor, promyelocytic leukaemia zinc finger protein (PLZF) (encoded by ZBTB16; online supplemental table 4 (online supplemental data 4)), which is an interaction partner of EZH2. PLZF was the only upstream regulator predicted to be activated with a significant overlap p value.
ATAC-seq reveals differential DNA accessibility at H3K9me3 occupied regions

We examined the effect of KDM4C:p.H217R on chromatin accessibility in lymphoblastoid cell lines of variant carriers (n=3) and non-carriers (n=4) with ATAC-seq. Altogether, 214,762 reproducible open chromatin regions were identified in the seven samples. First, we examined if open chromatin profiles of KDM4C:p.H217R carriers differ from the non-carrier control lymphoblastoid cell lines more than randomly chosen combinations of these samples differ from each other. We divided six samples (three KDM4C:p.H217R carriers and three non-carriers) randomly into two groups and compared the numbers of differentially accessible regions (DARs, FDR≤0.05) and the enrichment of DARs at histone modifications from the Roadmap Epigenomics Project. The largest number of DARs (2141) was identified when carriers of KDM4C:p.H217R were compared against non-carriers, for which the enrichment to active chromatin marks and histone 3 lysine 9 trimethylation (H3K9me3) was the most significant (figure 4A). The next largest numbers of DARs were 1560, 1025, 741 and 558 in random groups. The rest had less than 300 DARs.

Next, we analysed differential accessibility between the three KDM4C:p.H217R carriers and four healthy non-carriers (the ones described previously and an additional sample), and identified 2225 more accessible (log2FC>0 and FDR≤0.05) and 957 less accessible (log2FC<0 and FDR≤0.05) regions (online supplemental table 5 (online supplemental data 5)). When compared with all regions of open chromatin, the more accessible regions in KDM4C:p.H217R carriers displayed enrichment at the H3K9me3 histone mark derived from Roadmap Epigenomics Project data on blood cells (figure 4B). The finding is compatible with the specific H3K9me3 demethylase activity of KDM4C.

The less accessible regions in KDM4C:p.H217R carriers also displayed enrichment at the H3K9me3 mark, pointing to a general dysregulation of H3K9 trimethylation (figure 4C). In addition, the less accessible regions showed an enrichment at the active chromatin marks H3K4me1 and H3K27ac, as well as at open chromatin regions defined by DNase hotspots. This suggests that these normally active sites are repressed in KDM4C:p.H217R carriers.

Next, we examined if the changes in chromatin accessibility observed in KDM4C:p.H217R carriers were connected to changes in gene expression. We annotated the closest gene to the more and less accessible regions, and compared the gene expression log2FCs of the genes in these groups. More accessible regions in proximity enhanced nearby gene expression (figure 4D). The same phenomenon was observed at less accessible sites that showed decreased expression in carriers versus controls. This confirms the quality of the performed ATAC-seq experiments and provides evidence for the functional significance of the DARs discovered in KDM4C:p.H217R carriers.

Changes in H3K9me3 levels at transcription start sites point to aberrant interaction with EZH2

Next, we analysed the distribution of H3K9me3 in KDM4C:p.H217R carrier and non-carrier lymphoblastoid cells with ChIP-seq. We identified 174,611 H3K9me3 binding sites present in at least two samples. Genome-wide significant changes (FDR≤0.05) in H3K9me3 levels were not detected between KDM4C:p.H217R carriers and non-carriers. We examined the H3K9me3 levels at the H3K9me3 peaks overlapping with more and less accessible regions defined by ATAC-seq, as the previous analyses had revealed an enrichment of DARs at H3K9me3 occupied loci. At the H3K9me3 peaks overlapping the more accessible sites (n=118), H3K9me3 levels were higher in cases (figure 5A). At the less accessible sites (n=37), there was no such difference in H3K9me3 levels between KDM4C:p.H217R carriers and non-carriers. Next, we analysed H3K9me3 levels
Due to the low number of obtained data points at more and less accessible sites (118 and 37, respectively), we performed H3K9me3 distribution analyses for all 214762 reproducible open chromatin regions, regardless of overlapping ChIP-seq peaks. We were interested in H3K9me3 levels at more accessible regions in particular, as in the previous analysis described above (figure 5A) we measured—counterintuitively—higher levels of H3K9me3 at the 118 sites included in the analysis. Most more accessible regions were located in intergenic and intronic regions (figure 5B). In this analysis, including all open chromatin regions, we detected reduced H3K9me3 levels in KDM4C:p.H217R carriers at intergenic and intronic regions, as well as more accessible TSs (figure 5C–E). At less accessible TSSs, KDM4C:p.H217R carriers had more H3K9me3 than controls (figure 5E). These data are consistent with the ATAC-seq findings as well as the gain-of-function prediction of the mutation.

As H3K9me3 was differentially distributed at TSSs between KDM4C:p.H217R carriers and non-carriers, we examined if these differences contribute to changes in gene expression. We divided H3K9me3 peaks (n=174611) into groups based on log2FC in KDM4C:p.H217R carriers: less H3K9me3 (log2FC<−1), more H3K9me3 (log2FC>1) and no change in H3K9me3 level (−1<log2FC<1). These peaks were further divided into TSS (±1000 bp) and non-TSS regions, and expression log2FC of the nearest gene of each peak was examined. We detected slightly higher gene expression log2FCs, although not statistically significant (Mann-Whitney U test, W=28884, p value=0.06752), in genes with less H3K9me3 at their TSS compared with genes with no change in H3K9me3 at TSS (figure 5F). This is compatible with the role of H3K9me3 in gene repression.18

We performed IPA for genes with H3K9me3 ChIP-seq peaks at TSS showing the highest positive and negative log2FC. The analysis without gene expression log2FC information identified the transcription factor EZH2 as one of the most significant upstream regulators, with an overlap p value of 0.000624 based on 23 target molecules in the dataset (online supplemental table 6 (online supplemental data 6)). We also performed the analysis for the same gene set with expression log2FC scores. PLZF was predicted to be activated (z-score=2.646) based on changes in gene expression, although p value of overlap was not significant (0.0768) (online supplemental table 7 (online supplemental data 7)). This provides more evidence of the activation of PLZF in KDM4C:p.H217R carriers.

DISCUSSION
Here, we describe a novel germline variant in the highly conserved catalytic JmjC domain of the histone demethylase KDM4C. The missense variant was discovered by exome and whole-genome sequencing of selected multi-cancer family members and was confirmed to segregate with malignancy in the family. We did not detect the variant in our validation set consisting of 63 candidate Finnish PTC families or any major publicly available datasets. The consequent amino acid change (NP_055876.2:p.(His217Arg)) is predicted pathogenic by the majority of commonly used in silico variant prediction tools.

The KDM4 subfamily histone demethylases are epigenetic regulators that control chromatin structure and thus gene expression by demethylating histones H3K9, H3K36 and H1.4K26. The subfamily consists of five proteins (KDM4A-E), all of which harbour the catalytic Jumonji C domain (JmjC). The selectivity of the demethylases is determined by multiple interactions within the catalytic domain. KDM4C specifically catalyses at TSSs (±1000 bp) and outside TSS regions. TSSs displayed increased H3K9me3 levels in KDM4C:p.H217R carriers with no change in chromatin accessibility, and regions outside TSS displayed increased H3K9me3 levels in KDM4C:p.H217R carriers when accessibility was increased (figure 5A).
the demethylation of trimethylated lysine-9 and lysine-36 residues of histone H3. In addition, it has been shown to be involved in transcriptional regulation through interaction with EZH2.\(^7\) Both of these functions are carried out by the JmjC domain, in which KDM4C:p.H217R is located. Recently, rare variants in KDM4C were associated with schizophrenia and autism spectrum disorder,\(^9\) and the encoded protein was shown to control tumorigenesis by epigenetically regulating p53 and c-Myc.\(^{20}\)

To confirm that the variant indeed has biological consequences, we performed ATAC, ChIP and RNA-sequencing of EBV-transformed lymphoblastoid cell lines derived from three patients carrying the KDM4C:p.H217R mutation and four healthy controls. These results have limitations due to the small number of samples and characteristics of EBV-transformed cell lines as transformation is known to cause dysregulation of gene expression and cancer-related pathways.\(^{27}\) It should also be noted that all KDM4C:p.H217R carrier cell lines shared an additional possibly pathogenic variant in the Nuclear receptor corepressor 2 (NCOR2). NCOR2 has a role in AR signalling and acts as a transcriptional corepressor by promoting chromatin condensation.\(^{22}\)

RNA-seq analysis revealed 136 differentially expressed genes. The gene with the highest fold change with significant p value was H3-2, a member of the H3 family of histones (figure 3). Interestingly, according to the STRING protein–protein interaction network,\(^{21}\) Histone cluster 2 H3 pseudogene 2 (H3-2;HIST2H3P2) and KDM4C are interaction partners with an interaction and experiment scores of 0.718 and 0.336, respectively, making H3-2 one of the highest scoring interaction partners of KDM4C in the database. The possible pathogenic significance of H3-2, if any, needs further work.

The most significantly differentially expressed gene, UGT2B17, has previously been associated with increased risk of prostate cancer.\(^{24}\) Another gene coding a similar enzyme, UGT2B15, also had significantly lower expression in the KDM4C:p.H217R carriers as compared with controls (figure 3). UGT2B15 and UGT2B17 are regulated by the AR and are not expressed in AR negative prostate cancer cell lines.\(^{25}\) We did not detect significant differences in AR expression between the mutation carriers and non-carriers, however, KDM4C has been shown to interact and co-localise with AR, and more importantly, to regulate its function.\(^{10,26}\) The NCOR2 variant could also have contributed to this result, as the protein is known to regulate AR signalling.

Upstream regulator analysis revealed that the expression changes of CD180, ICOS, KLF2 and TNFSF11 are consistent with increased activity of the EZH2-associated protein PLZF. PLZF and EZH2 co-associate at the chromatin level, and EZH2 activity was recently shown to regulate PLZF transcriptional output.\(^{17}\) PLZF is an epigenetic regulator that balances self-renewal and differentiation of haematopoietic cells through binding of chromatin-modifying factors, and gene rearrangements at this locus have been associated with acute promyelocytic leukaemia, a subtype of acute myeloid leukaemia and the very disease the gene was named after.\(^{27}\) Since one member of the studied family suffered from myeloid leukaemia, and two others of leukaemia of unknown type, and as the measurements were performed with blood samples, this result is particularly interesting.

ATAC-seq revealed 2225 more and 957 less accessible sites between KDM4C:p.H217R carriers and controls. These DARs enrich at normally H3K9me3-marked chromatin, pointing to epigenetic plasticity at these sites in KDM4C:p.H217R carrier cells. When we examined levels of H3K9me3 at open chromatin regions, we found that intergenic and intronic regions have reduced H3K9me3 in KDM4C:p.H217R carriers. As KDM4C specifically demethylates H3K9me3 and the variant is predicted to be gain-of-function (figure 2B), the changes in chromatin accessibility and H3K9me3 levels at these loci support the functional significance of KDM4C:p.H217R.

We examined the distribution of H3K9me3 in KDM4C:p.H217R carrier cells with ChIP-seq. We did not detect a global reduction or increase in H3K9me3 levels in KDM4C:p.H217R carriers compared with controls. However, we detected increased H3K9me3 levels between KDM4C:p.H217R carriers and non-carriers at transcription start sites with no change in chromatin accessibility. This result is of particular interest because transcription start sites are commonly occupied by KDM4C.\(^{29}\) We examined how the changes in H3K9me3 levels at TSS contribute to gene expression changes in KDM4C:p.H217R carriers, and found that reduced H3K9me3 at TSSs weakly associates with increased gene expression. Interestingly, genes with increased H3K9me3 levels at their TSS did not have globally decreased expression compared with genes with no change in H3K9me3 levels. Thus, increased H3K9me3 at TSSs does not seem to globally repress gene expression in KDM4C:p.H217R carriers.

KDM4C associates with EZH2 and their binding sites overlap. Full EZH2-associated gene repression requires the co-occupation of KDM4C and EZH2 at gene promoters.\(^{7}\) When we analysed the genes with the highest positive and negative log2FCs of H3K9me3 ChIP-seq peaks at their transcription start sites (ie, sites and genes that are likely to be occupied by dysfunctional KDM4C and dysregulated through aberrant H3K9 methylation), EZH2 was one of the most significant upstream regulators according to IPA. Thus, KDM4C:p.H217R may also affect the interaction between KDM4C and EZH2. We further examined expression changes of genes with differential H3K9me3 levels at their TSS with IPA, and identified predicted activation of upstream regulator PLZF. Our findings raise the possibility that TSSs with dysregulated H3K9me3 levels in KDM4C:p.H217R carriers are regulated by EZH2 and their expression changes, as predicted through IPA, point to activation of its interaction partner PLZF.

Our data suggest that KDM4C:p.H217R drives tumourigenesis in the studied family by perturbing the demethylase and transcriptional regulator functions of KDM4C carried out by the JmjC domain. Multiple layers of data support this conclusion, and genetic validation of the finding in other multi-cancer families is an important future goal. KDM4C:p.H217R causes chromatin accessibility changes at H3K9me3-marked loci as detected with ATAC-seq and increased H3K9me3 levels at TSSs. EZH2 was identified as an upstream regulator of genes with dysregulated H3K9me3 levels at TSS, and increased PLZF activity was detected by both differentially expressed genes and genes with changes in H3K9me3 levels at their TSS. ATAC, ChIP and RNA-seq were performed using EBV-transformed lymphoblastoid cells derived from normal blood rather than tumour tissue. Even so, the detected difference in chromatin accessibility between KDM4C:p.H217R carrier and control cells is striking. The fact that these changes in chromatin conformation are already present in normal lymphoblastoid cells from mutation carriers strongly supports a role for KDM4C:p.H217R in tumour susceptibility. KDM4C has been detected in all tissue types and has low tissue specificity. It is thus likely to play a central role in most tissues, which would explain the multi-cancer phenotype observed in the family.

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MH provided the samples. LAA supervised the study. RK, ID and MR wrote the manuscript. AR performed pathway analyses. RK performed structural dynamics predictions.

Competing interests
None declared.

Patient consent for publication
Obtained.

Ethics approval
This study was approved by the National Supervisory Authority for Welfare and Health (Valiera; 1423/06.01.03.01/2012), National Institute for Health and Welfare (THL, 151/5.05.00/2017), and the ethics committee of the Hospital District of Helsinki and Uusimaa (HUS; 408/15/03/08). All living patients gave written informed consent.

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Data availability statement
Data are available on reasonable request. All data relevant to the study are included in the article or uploaded as supplementary information. Data that potentially allow the identification of individuals must be protected and thus, sequencing data produced in this study cannot be deposited to public databases. Roadmap epigenomics CHIP-seq and DNase hotspot data provided in LOLA Core and Extended databases was downloaded from http://cloud.databio.org/regionid/.

Supplemental material
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Cancer genetics

