A translocation t(6;14) in two cases of leiomyosarcoma: Molecular cytogenetic and array-based comparative genomic hybridization characterization

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ORIGINAL ARTICLE

A translocation t(6;14) in two cases of leiomyosarcoma: Molecular cytogenetic and array-based comparative genomic hybridization characterization

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Leiomyosarcomas are malignant mesenchymal tumors that recapitulate smooth muscle cell differentiation. Tumors are characterized by a genetic heterogeneity with complex karyotypes without a tumor-specific genetic aberration. Their pathobiology is still poorly understood and no specific targeted treatment is currently available for these aggressive tumors. For six leiomyosarcomas, cells were cultured and analyzed by combined binary ratio labeling fluorescence in situ hybridization (COBRA-FISH) karyotyping. A t(6;14) was identified in two cases. FISH breakpoint mapping of case L1339 reveals a breakpoint at chromosome 6p21.31 close to *HMGA1*, and a small deletion was observed on the distal side of the gene. A small homozygous deletion was also found in the breakpoint region of chromosome 14q24.1 involving *ACTN1*. The second case revealed a der(6)t(6;14)(p21.1;q21.3), with a duplication adjacent to the breakpoint at chromosome 6. Confirmatory FISH revealed a second leiomyosarcoma with an aberration at 14q24.1. Alterations at this locus were found in 5% (2 of 39) of the leiomyosarcomas in this study. The other identified breakpoints appeared to be non-recurrent, because they were not detected in other leiomyosarcomas, uterine leiomyomas, undifferentiated spindle cell sarcomas, or undifferentiated pleomorphic sarcomas.

Keywords Leiomyosarcoma, soft tissue sarcoma, translocation, FISH, array-CGH, HMGA1

Leiomyosarcomas are malignant tumors originating from smooth muscle cells and are responsible for 10-15% of adult soft tissue sarcomas. Tumors show a varying degree of smooth muscle differentiation, which is inversely proportional to tumor grade. Histologically low grade tumors are composed of sharply demarcated bundles of spindle cells intersecting at right angles, whereas high grade lesions might contain poorly differentiated regions with nuclear pleomorphism and atypical mitoses. Areas of myxoid change, epithelioid morphology, fibrosis, hemorrhage, or necrosis can be present. Smooth muscle differentiation can be detected with desmin and h-caldesmon immunohistochemistry. The retroperitoneum is the most common location, but the large blood vessels, with a predilection for the vena cava inferior, the uterus, and other soft tissue sites, such as the lower extremities, are also frequently involved (1). Lesions of the retroperitoneum and blood vessels are encountered more frequently in women; no gender predilection is present for other soft tissue locations. Leiomyosarcomas are responsible for a substantial morbidity and mortality because they are characterized by aggressive behavior, with a 5-year overall survival (OS) of 64% (2,3). A high tumor grade, deep tumor location, and large tumor size (>5 cm) were independent adverse prognostic factors for metastatic disease and OS (2–4). Wide surgical excision remains the mainstay of treatment, often in combination with radiation or conventional chemotherapy. At the moment, no specific targeted treatment against leiomyosarcomas is available because the pathophysiology still remains poorly understood (5).

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Genetically, leiomyosarcomas are characterized by complex karyotypes with numerous reported non-recurrent and non-specific aberrations that result from a high degree of genetic instability (1,6,7). Although gains and losses of many different chromosomes have been reported and the inter-tumor heterogeneity is extensive, some similarities are also described. Both cytogenetic and array-based comparative genomic hybridization (array-CGH) analyses have revealed recurrent involvement of losses of 1p, 2p, 10q, 11q, 13q, 16q, and 17p, and gains of 17q and 17p (2,8).

The main objective of this study is to investigate the genetic alterations in leiomyosarcomas and to search for a common molecular genetic aberration in order to improve the understanding of this malignant tumor and to identify prognostic factors or candidate targets for future therapeutic regimens. We identified two cases with a t(6;14) by using state-of-the-art molecular karyotyping tools, and fine mapped breakpoint regions were tested on a tissue microarray (TMA) that consisted of a large panel of leiomyosarcomas, uterine leiomyomas, undifferentiated spindle cell sarcomas, and undifferentiated pleomorphic sarcomas with interphase fluorescence in situ hybridization (FISH).

Materials and methods

Cell culture and combined binary ratio labeling FISH (COBRA-FISH)

Tumor specimens were collected directly after surgery and manually dissected in small fragments. After the addition of IMDM, supplemented with 10% FBS and 1% penicillin/streptomycin (Gibco; Life Technologies, Bleiswijk, The Netherlands), the specimens were placed in a humidified 5% CO_2 incubator at 37°C. Cells were cultured for several passages and harvested after 25 min of incubation with Calyculin A (Sigma-Aldrich, Zwijndrecht, The Netherlands). Subsequently, cells were placed in a hypotonic 0.075 M KCl solution followed by three fixation steps of methanol/glacial acetic acid (4:1 ratio). Slides with metaphase spreads were made in a conditioned chamber (25°C, 50% humidity; Thermotron, Holland, MI).

COBRA-FISH karyotyping was performed on slides with metaphase spreads of six leiomyosarcomas; no conventional G-banding studies were performed. A detailed protocol on the pre- and post-hybridization treatments was published previously (9). A DMRA fluorescence microscope (Leica Microsystems, Rijswijk, The Netherlands) was used to capture images, which were analyzed with the ColorProc software tool that was developed in-house (Leiden University Medical Center (LUMC), Leiden, The Netherlands). Karyotypes were described according to the International System for Human Cytogenetic Nomenclature (ISCN 2013) (10). In three leiomyosarcomas, no detectable cytogenetic abnormalities were found in the analyzed cells. Tumor cells and fibroblasts show a similar, spindle cell morphology in vitro, thereby making it difficult to discriminate them morphologically. The leiomyosarcomas with a seemingly normal karyotype might have contained a mix in which fibroblasts have overgrown the tumor cells. Therefore, these three cases were excluded from further analysis.

FISH breakpoint mapping

Two-color FISH was performed to investigate the exact breakpoints of chromosomes 6p and 14q of two selected leiomyosarcoma cases. To detect possible rearrangements of the region of *HMGA1* on chromosome 6p21 bacterial artificial chromosome (BAC) clones, RP3-349A12, proximal to the breakpoint, and RP11-936A3, distal to the breakpoint, were selected. BAC clones used in the fine mapping of the deletion breakpoints on chromosome 6 were RP11-175A, RP5-1077I5, RP3-468B3, and RP11-974K1. On region 14q24, around the *ACTN1* gene, RP11-204K16 was selected proximally and BAC clone RP11-486O13 was located distally from the breakpoint. Other BAC clones used in the fine mapping of the breakpoint on chromosome 14 were RP11-226F19 and RP11-565I3. All BAC clones were obtained from Wellcome Trust Sanger Institute (Cambridge, UK). Probes were directly labeled with fluorescein isothiocyanate (FITC) or Cy3 using a nick translation labeling reaction. Probes were hybridized overnight on metaphase slides using a protocol otherwise identical to the COBRA-FISH protocol as described previously.

Array-CGH analysis

Genomic DNA was isolated from frozen tumor sections of the two selected cases with a Nucleospin DNA extraction protocol (Macherey-Nagel, Düren, Germany). Histologic evaluation confirmed that the tumor content exceeded 80-90%. DNA labeling and purification were done according to the BioPrime Total Genomic Labeling System (Invitrogen, Bleiswijk, The Netherlands); labeling efficiency was calculated with a Nanodrop ND-1000 spectrophotometer (Thermo Scientific, Wilmington, DE) measuring A_{260} (DNA), A_{550} (Cy3), and A_{649} (Cy5). Array-CGH was performed with an oligonucleotide-based human genome CGH microarray 4×44 k (Agilent Technologies, Santa Clara, CA) at 65°C for 40 h. Slides were washed according to the manufacturer's protocols and scanned using an Agilent microarray scanner with a 5-μm scan resolution. Images were imported to Feature Extraction Software and Genomic Workbench (Agilent) with a human reference genome and standard settings for analysis. Commercially available healthy male or female DNA (Promega, Madison, WI) was used as reference DNA. Test and reference samples were hybridized as a gender mismatch to illustrate the dynamic range of hybridization at the X and Y chromosomes.

Tissue microarray

A TMA with a broad selection of soft tissue tumors, which were diagnosed at the Department of Pathology of the LUMC, was used for confirmatory FISH analysis (11). In this study, the evaluable cases included 37 leiomyosarcomas, 17 undifferentiated pleomorphic sarcomas, 4 undifferentiated spindle cell sarcomas, and 4 uterine leiomyomas. The histologic diagnosis of all samples was confirmed upon review of the H&E-stained slides by a specialized bone and soft tissue tumor pathologist (J.V.M.G.B. and P.C.W.H.). At least one of the smooth muscle markers—h-caldesmon or desmin—was positive in the leiomyosarcomas. The included leiomyosarcomas were negative for HMB45, which is a marker positive in perivascular epithelioid cell tumors (PEComas). Soft tissue

Table 1 Clinicopathological and COBRA-FISH karyotyping results of three leiomyosarcoma cases

Case	Age (y)/ Sex	Tumor grade	Tumor size (cm)	Location	Histological features	Karyotype
L1091	70/M	3	8 × 7 × 7	Gastrocnemius muscle	Myxoid	46,XY,t(6;7)(p;p)[3]/46,XY[15]
L1339	39/F	N/A[a]	9 × 7	Uterus	Regular/ Spindle cell	45,XX,der(1;13)t(1;13)(q10;q10), t(2;10)(q;q),t(6;14)(p21.31;q24.1-24.2),der(13)t(6;13)(q?;q10),-14[6]
L1814	56/F	3	10.5 × 5 × 4.3	Hamstring muscle	Epithelioid	81,XXXX,del(X)(q),der(1;10)(q10;q10),der(1)t(1;9)(p10;p?),der(3;6)(q10;p10),+der(3)t(3;17)(q10;p10),-4,der(5)t(5;8)(q10;p10)x3, t(5;16)(q;p),+der(5)t(5;16)(q;p),-6,der(6)t(6;14)(p21.1;q21.3)hsr(6)(p?), der(7)t(6;7)(q?;q?) ,i(8)(q10)x2,der(8) t(8;22)(q10;q10), der(8),der(9)t(8;9)(q;p)x2,-10,-10,-11, der(11) t(1;11)(p;p),-13, + der(14)t(8;14)(q10;q10),-15,der(15)t(15;18)(p10;p?),-16,-18,-18,-19,-20,-22, der(22)t(8;9;22)(q;p;q)[3]

Abbreviation: N/A, not applicable.

[a] Uterine leiomyosarcomas are not FNCLCC-graded according to the WHO.

sarcomas were graded according to the FNCLCC (Fédération Nationale des Centres de Lutte Contre le Cancer) grading system as accepted by the WHO classification (1). Exclusion criteria were pretreatment with neoadjuvant chemotherapy or radiotherapy and radiation-induced sarcomas. All samples were handled in a coded fashion, and all procedures were performed according to the ethical guidelines, "Code for Proper Secondary Use of Human Tissue in the Netherlands" (Dutch Federation of Medical Scientific Societies).

Confirmatory TMA FISH and scoring

Four different sets of BAC clones were used to screen the samples on the TMA for a recurrent breakpoint as demonstrated in the two index cases (Supplementary Table S1). For the interphase FISH on the TMA sections, probes were labeled with biotin-dUTP or digoxigenin-dUTP using a nick translation labeling reaction. Biotin- and digoxigenin-labeled probes were visualized by indirect detection with Cy3-labeled streptavidin (1:500; Sigma), FITC-labeled mouse antidigoxigenin antibody (1:250; Sigma), and FITC-labeled rabbit anti-mouse antibody (1:1000; Sigma). A detailed protocol of two-color FISH on formalin-fixed, paraffin-embedded (FFPE) tissue sections was published previously (12). For digital archiving and annotation, all slides used for various staining procedures were scanned with the Pannoramic MIDI scanner (3DHistech, Budapest, Hungary) using brightfield or fluorescent settings for H&E sections or interphase FISH staining, respectively. Scanned images were visualized using the Pannoramic Viewer (v15.0; 3DHistech), and scoring was performed visually. For the TMA slides, at least 50 nuclei were evaluated per core with retained tissue and good signals.

Results

Clinicopathological data and COBRA-FISH karyotyping

In this study, cultured tumor cells from three leiomyosarcoma patients were suitable for cytogenetic analysis. Two patients were diagnosed with a high grade (grade 3, according to the FNCLCC grading system) leiomyosarcoma of soft tissue located in the muscles of the lower limb. One patient presented with a uterine leiomyosarcoma, which was staged according to the International Federation of Gynaecology and Obstetrics (FIGO) criteria (13,14). All tumors expressed desmin using immunohistochemistry (Table 1).

The uterine leiomyosarcoma L1339 harbored a diploid karyotype with translocations involving several chromosomes: 45,XX,der(1;13)t(1;13)(q10;q10),t(2;10),t(6;14)(p21.31;q24.1-24.2),der(13)t(6;13)(q?;q10),-14[6]. Soft tissue leiomyosarcoma L1814 displayed a complex, hypotetraploid karyotype with multiple chromosomal rearrangements and whole chromosome gains and losses: 81,XXXX,del(X)(q),der(1;10)(q10;q10),der(1)t(1;9)(p10;p?),der(3;6)(q10;p10),+der(3)t(3;17)(q10;p10),-4,der(5)t(5;8)(q10;p10)x3,t(5;16)(q;p),+der(5)t(5;16)(q;p),-6,der(6)t(6;14)(p21.1;q21.3)hsr(6)(p?),der(7)t(6;7)(q?;q?),i(8)(q10)x2,der(8)t(8;22)(q10;q10),der(8),der(9)t(8;9)(q;p)x2,-10,-10,-11,der(11)t(1;11)(p;p),-13, + der(14)t(8;14)(q10;q10),-15,der(15)t(15;18)(p10;p?),-16,-18,-18,-19,-20,-22,der(22)t(8;9;22)(q;p;q)[3] (Figure 1).

FISH breakpoint mapping and array-CGH profile

A seemingly balanced translocation was observed in case L1339. The breakpoint regions on chromosomal arms 6p and 14q were compatible with translocation breakpoint regions described in uterine leiomyoma involving the *HMGA1* and *RAD51L1* genes on chromosome 6 and chromosome 14, respectively (15). FISH mapping of the translocation regions was performed with the probe sets depicted in Figure 2. Clones RP3-349A12 and RP11-936A3—proximal to and partly overlapping with the *HMGA1*, locus respectively—demonstrated a split-apart in which the RP3-349A12 signal was retained on chromosome 6, whereas the signal of RP11-936A3 was translocated to the derivative chromosome 14. Fine mapping of this region revealed a deletion of clones RP11-175A4 and RP3-468B3, and the retention of RP5-1077I5 and RP11-974K1 bracketing this region on chromosome 6p. Breakpoint mapping on chromosome 14 using BAC clones located proximal

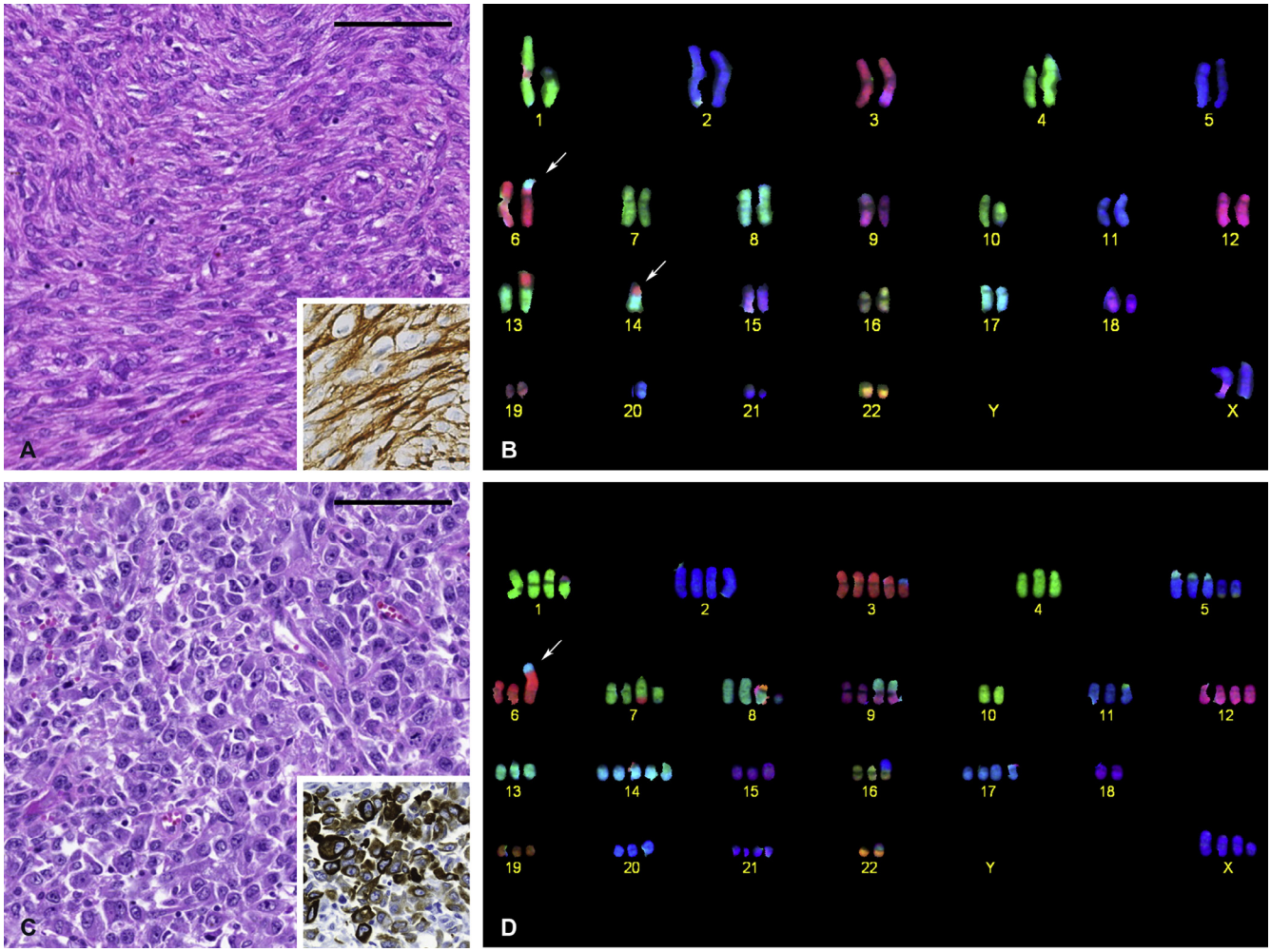

Figure 1 Histology and molecular cytogenetic results of two leiomyosarcoma cases. (**A**) H&E stained section of uterine leiomyosarcoma L1339 showing intersecting bundles of spindle cells. Inset shows immunoreactivity for h-caldesmon; scale bar represents 100 μm. (**B**) COBRA-FISH karyotype of L1339. The balanced t(6;14)(p21.31;q24.1–24.2) is indicated with white arrows. (**C**) H&E stained section of grade 3 leiomyosarcoma L1814 with nuclear pleomorphism and multiple mitotic figures. Tumor cells exhibit epithelioid morphology with eosinophilic cytoplasm. Inset shows a focal strong, positive desmin staining. (**D**) Hypotetraploid karyotype of L1814 with several translocations, including the der(6)t(6;14)(p21.1;q21.3) indicated by an arrow.

(RP11-204K16) and distal (RP11-486O13) to *ACTN1* on chromosome 14q24 showed a split signal, and the distal clone was located on the derivative chromosome 6. The mapping also revealed a homozygous deletion of clones RP11-226F19 and RP11-565I3 (Figure 2B) that covered the *ACTN1* gene. Secondary rearrangements at or around translocation breakpoint regions have been observed more often; therefore, we further characterized these regions by using a high resolution array-CGH approach. The array-CGH profile of L1339 detected a 603-kb deletion on 6p21.31–p21.32, which was located 333 kb distal to *HMGA1* without the involvement of the *HMGA1* locus itself (Figure 2A). *TAPBP* was overlapping with the last distal deleted probe and might have been involved in the deletion breakpoint. No copy number alteration was identified at the translocation breakpoint proximal to *HMGA1*. On chromosome 14q24.1, a 449-kb deletion was observed, which involved the *ACTN1* and *WDR22* genes (Supplementary Table S2). A second, 77-kb deletion was detected inside the distal part of *RAD51L1*, close to the locus of the BAC clone RP11-204K16, which was retained on chromosome 14 in the translocation. These deletions on chromosome 14 resulted in a homozygous loss of the involved chromosomal regions because monosomy 14 was observed in all tumor cells. A 7.3-Mb region at 14q21.1–q21.3 was retained based on the array-CGH and likely was inserted into one of the derivative chromosomes containing chromosome 14 because no other regions were stained by the whole chromosome paint (WCP) probes in a confirmatory FISH test using WCP 6 and WCP 14 (data not shown). Taking this together with the FISH mapping results, a balanced translocation with complex rearrangements at translocation breakpoint regions involving the *HMGA1* and *RAD51L* loci can be concluded (Figure 2).

The hypotetraploid karyotype of L1814 resulted in a complex array-CGH profile in which the copy number varied from two to five or more of certain genomic regions. A derivative chromosome 6, which involved translocations between chromosome 6 and chromosome 14, was detected. Array-CGH profiling showed that the der(6)t(6;14) translocation was complicated with

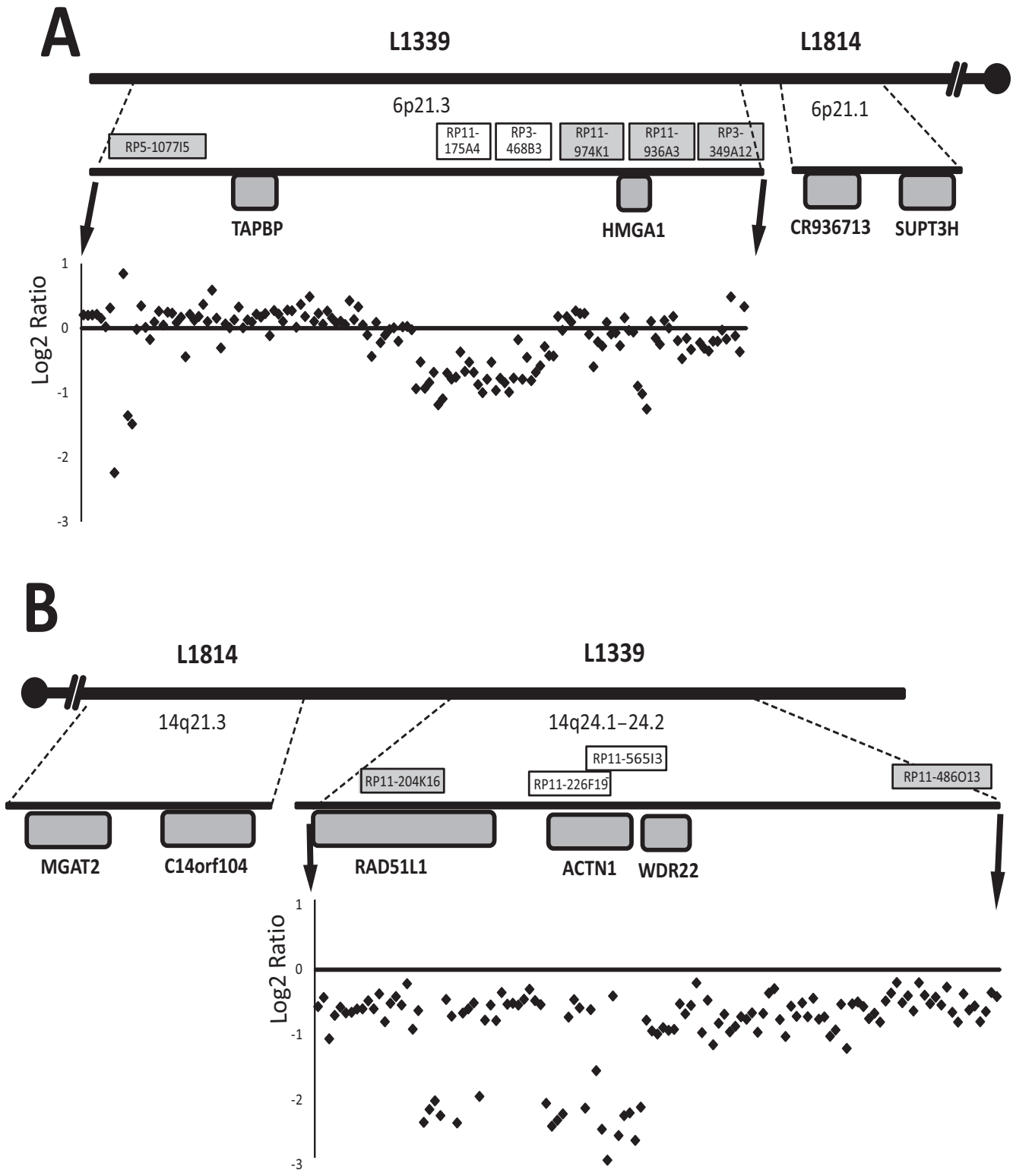

Figure 2 Schematic representation of breakpoints of leiomyosarcomas L1339 and L1814. (**A**) Schematic picture of 6p21 region with location of genes and BAC clones used for fine mapping of the translocation and deletion breakpoints of L1339, and the relation of this breakpoint compared with the breakpoint of L1814. (**B**) Schematic diagram of region 14q21–q24, including the genes and BAC clones involved in the translocation and deletion breakpoints. (**A,B**) BAC clones in white boxes represent clones deleted in L1339 and are not to scale. Corresponding array-CGH profiles are indicated by arrowheads.

an amplification of 3.8 Mb in size at locus 6p21.1. The probes spanning the proximal breakpoint of the amplicon were 40 kb apart, and *SUPT3H* was located in this region. The distance between the two probes spanning the distal amplicon breakpoint was 52 kb and overlapped with *CR936713*. The amplification was located 6.7 Mb proximal to the *HMGA1* locus. On chromosome 14, a gain of 5.3 Mb in size was found at 14q24.2–q24.3, which was located 3.7 Mb distal to *ACTN1*. The proximal and distal breakpoints of this gained region spanned the *DPF3* and *ADCK1* loci, respectively. Based on the array-CGH data, the translocation breakpoint was located at 14q21.3, because a slight change in copy number variation was observed at that location. The proximal probe of the translocation breakpoint corresponded to the *MGAT2* locus, and the distal probe overlapped with *C14orf104*. More detailed FISH-based fine mapping of the der(14)t(6;14)(p21.1;q21.3) could not be performed due to a lack of cultured tumor cells.

The unbalanced cytogenetic aberrations identified with COBRA-FISH were also confirmed by the array-CGH profiles of both leiomyosarcoma cases. Furthermore, the higher resolution of array-CGH revealed several other small deletions and gains in both cases.

Validation of breakpoints in other soft tissue tumors

A TMA with several soft tissue tumors was used to investigate the recurrence of the aberrations by using interphase FISH of four BAC clone sets that corresponded to the regions of *HMGA1* at 6p21.31, *TAPBP* at 6p21.32, the amplicon at 6p21.1, and *ACTN1* at 14q24 (Supplementary Table S1). The two index cases were also present on the TMA, and a split-apart at the *HMGA1* and *ACTN1* locus, as well as a deletion around *TAPBP*, was confirmed in L1339. L1814 harbored numerous copies of BAC clone RP11-501I18 at 6p21.1, which was 2 Mb distal from *SUPT3H* and consistent with an amplification of that particular region. The tumor cells only contained two to three copies of centromere 6, which was included as a control. The majority of the cells of one leiomyosarcoma (L1566) revealed twice the co-localization of the signals of the BAC clone set that bracketed *ACTN1*. Two additional signals of clone RP11-486O13 distal to *ACTN1* were present, which indicated an unbalanced translocation of this region. In this series, alterations involving a split-apart of the signals in the 1.6 Mb region at 14q24.1–q24.2 were found with FISH in 5% (2 of 39) of all investigated leiomyosarcomas. Copy number alterations with an equal number of the red and green signals were observed in several tumors. None of the investigated loci showed any structural alteration in any of the additional evaluable cases, including 37 leiomyosarcomas, 17 undifferentiated pleomorphic sarcomas, 4 undifferentiated spindle cell sarcomas, and 4 uterine leiomyomas.

Discussion

Leiomyosarcomas belong to a group of sarcomas with a complex genetic profile that does not have a currently identified specific, known genetic aberration. The complex karyotypes of most leiomyosarcomas might merely represent tumor progression associated changes; however, a causative role of a hidden, recurrent chromosomal aberration cannot be excluded in the development of these malignancies. In this study, COBRA-FISH karyotyping of three tumors revealed a translocation t(6;14) in two unrelated cases.

In case L1339, *HMGA1* might be involved in the breakpoint. HMGA proteins are evolutionary conserved members of the heterogeneous high-mobility group family of non-histone DNA-binding proteins. They bind in the minor groove to AT-rich DNA sequences and regulate gene transcription by affecting the promotor activity and influencing the accessibility of transcription factors to target genes. They are involved in the differentiation and proliferation of mesenchymal tissues during embryonic development (16). Some lipomas, angiomyxomas, and uterine leiomyomas harbor a translocation involving *HMGA2*, at 12q15, which leads to a chimeric fusion product with different partners (15,17–19). Translocations involving *HMGA1* are identified in a subset of lipomas and uterine leiomyomas, including benign uterine metastasizing leiomyoma, which results in an upregulated expression of the chimeric protein (16,20–22). Elevated expression has been encountered in synovial sarcoma and malignant peripheral nerve sheath tumor, and is correlated with increased tumor grade and poor prognosis (23,24). The molecular mechanism is considerably complex, because overexpression of wild-type HMGA leads to deregulation of the cell cycle machinery and apoptosis in normal cells (25), whereas overexpression in immortalized cells stimulates tumor development (26). The leiomyosarcomas in this study showed no intragenic *HMGA1* involvement, but a trans-regulatory effect due to the complex rearrangements cannot be excluded. Previously published studies of benign mesenchymal tumors with *HMGA1* translocations mostly revealed a break at the 3′-end, instead of an intragenic break; the breakpoint in L1339 is located less than 428 kb from the 3′-end. It has been postulated that transcriptional upregulation due to the genomic rearrangement can induce tumor formation (20). Similarly complex rearrangements, which involve regulatory sequences upstream of the coding sequence, have been described recently in chondromyxoid fibromas (27).

FISH mapping showed that the breakpoint at 14q24.1 in case L1339 was located at the *ACTN1* (α-actinin-1) locus, which, similar to other cytoskeletal proteins, is a member of the spectrin superfamily. This isoform is mainly expressed in non-muscular cells, and it regulates the role of focal adhesions and stress fibers as well as the association with cell motility (28). High resolution array-CGH showed a homozygous deletion of the *ACTN1* gene, which might be relevant for tumorigenesis. *RAD51L1*, which is located <200 kb from the 14q24 breakpoint, has been identified as a fusion partner of *HMGA2* in leiomyomas (15,29). It is part of the homologous recombination repair machinery of double-strand DNA breaks. Although FISH mapping showed that the probe overlapping with *RAD51L1* was still retained to chromosome 14, array-CGH revealed a small intragenic deletion that indicated a more complex rearrangement at the translocation breakpoint region with involvement of *RAD51L1*. In this way, both fusion and a truncated protein expression might be possible, similar to mono-allelic knockout of the uterus-specific RAD51L1-11c splice variant as described in leiomyomas (30). A uterine leiomyoma from a pseudo-Meigs' syndrome patient harbored a fast-growing subclone with a deletion of the second *RAD51L1* allele next to the *RAD51L1-HMGA2* fusion (31). Due to the monosomy 14, L1339 also had no normal copies of the

gene left; the influence on tumor progression remains uncertain. Recently, *RAD51L1* gene fusions were found in three uterine PEComas, and it was interesting that these different mesenchymal tumors shared involvement of the same gene (32). Further research needs to be done to elucidate whether a common pathogenetic mechanism exists in the early development of these tumors. However, in our cases, PEComa was excluded with immune-histochemical markers.

In L1814, a duplication at 6p21.1 complicated the translocation breakpoint, forming the der(6)t(6;14)(p21.1;q21.3). These breakpoints differed from those in L1339. Confirmatory FISH on a TMA revealed a second leiomyosarcoma with an aberration at 14q24.1, but without involvement of the investigated regions on chromosome 6. In this study, alterations at genomic region 14q24.1 were identified in 5% of the leiomyosarcomas. None of the other alterations appeared to be recurrent in the investigated soft tissue tumors. Nevertheless, an influence of cryptic rearrangements around *HMGA1*, *ACTN1*, or *RAD51L1* cannot be excluded completely, because they are expressed in smooth muscle cells and play a role in the development of these tumors.

Both cases harbored several other structural chromosomal aberrations, but because no other recurrent translocation was identified, these were not investigated further. In one case (L1091), we detected a balanced t(6;7), which indicated that the breakpoint region on chromosome 6 might be compatible with the *HMGA* locus. The breakpoint on chromosome 7p is different from the regions described in earlier studies (21). However, we had no access to more tumor cells; therefore, FISH mapping experiments could not be performed on this case. The quite simple karyotype is remarkable for a high grade leiomyosarcoma, but in the Mitelman Database of Cancer, 9 of the 129 reported cases showed a similarly simple translocation, which indicated a genetic subtype of leiomyosarcoma (33). None of the reported cases had translocation breakpoints similar to the one observed by us. The case was included on the TMA, but, unfortunately, few cells were left with good signals, so this case was not eligible for scoring.

With the currently available techniques, it is challenging to identify common aberrations in these genetically heterogeneous and unstable tumors. Improvements in the field of next generation sequencing have led to an increased possibility of detecting aberrations. Whole genome sequencing of osteosarcomas, a genomically complex and unstable bone sarcoma, has recently shown that tumors undergo chromothripsis, which leads to numerous genomic rearrangements due to reshuffling of small chromosome segments that probably takes place during a crisis-phase (34). Chromothripsis is also found in 42% of uterine leiomyomas, and it has been postulated that similar events occur during the development of leiomyosarcomas (35). Modern sequencing techniques might be helpful to identify pathogenetic mechanisms responsible for the development of these tumors. Amplification of myocardin (*MYOCD*) at 17p is frequently encountered in leiomyosarcomas (36). Some genetic alterations are found in only a subset of tumors, which indicates that they might be the secondary instead of the causative tumor-initiating event. Recently, mutations in dystrophin (*DMD*) have been identified in high grade mesenchymal tumors with certain levels of muscle differentiation, including leiomyosarcomas, rhabdomyosarcomas, and gastrointestinal stromal tumors (37). In that study, a high percentage of the tumors had aberrations in *DMD*, suggesting that these different tumors might develop via a similar way. It will be interesting to study the role of *DMD*, because deregulation of this gene might play a role in the early tumorigenesis of myogenic sarcomas.

This study reported the identification of a t(6;14) in two leiomyosarcoma cases. The translocation breakpoints differed; therefore, a common driver alteration for leiomyosarcomas was not found. This was consistent with the genetic heterogeneity of these tumors. However, we identified genes that might be involved in the pathogenesis of these particular leiomyosarcoma cases. In the future, next generation sequencing will be a helpful tool in the search for a common driver alteration of these malignant tumors.

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Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.cancergen.2015.07.005.

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