Revertant mosaicism in a human skin fragility disorder results from slipped mispairing and mitotic recombination

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Spontaneous gene repair, also called revertant mosaicism, has been documented in several genetic disorders involving organs that undergo self-regeneration, including the skin. Genetic reversion may occur through different mechanisms, and in a single individual, the mutation can be repaired in various ways. Here we describe a disseminated pattern of revertant mosaicism observed in 6 patients with Kindler syndrome (KS), a genodermatosis caused by loss of kindlin-1 (encoded by FERMT1) and clinically characterized by patchy skin pigmentation and atrophy. All patients presented duplication mutations (c.456dupA and c.676dupC) in FERMT1, and slipped mispairing in direct nucleotide repeats was identified as the reversion mechanism in all investigated revertant skin spots. The sequence around the mutations demonstrated high propensity to mutations, favoring both microinsertions and microdeletions. Additionally, in some revertant patches, mitotic recombination generated areas with homozygous normal keratinocytes. Restoration of kindlin-1 expression led to clinically and structurally normal skin. Since loss of kindlin-1 severely impairs keratinocyte proliferation, we predict that revertant cells have a selective advantage that allows their clonal expansion and, consequently, the improvement of the skin condition.

Introduction
Spontaneous gene repair, also called revertant mosaicism, has been observed in genetic disorders primarily involving organs that undergo self-regeneration, such as bone marrow, liver, and skin (1). Depending on the frequency of the reversion and the clonal expansion of the reverted cells, the phenotype may improve in a sense of natural healing (2). Genetic reversion can occur through recombination, back, or second-site mutations, and in a single individual, the disease-causing mutation can be mended in various ways (3). The accessibility of the skin facilitates the recognition of revertant mosaicism, which has previously been described in epidermolysis bullosa (4, 5) and ichthyosis (6).

Kindler syndrome (KS; OMIM 173650) is an autosomal-recessive skin fragility disorder that results from loss-of-function mutations in FERMT1, which encodes kindlin-1, a key regulator of integrin activation. KS is characterized by congenital skin blistering and photosensitivity, evolving to poikiloderma with pronounced skin atrophy (7). Poikiloderma refers to a combination of hypo- and hyperpigmentation, atrophy, and telangiectasias and is morphologically characterized by thin epidermis without rete ridges, focal vacuolization of basal keratinocytes, and pigment incontinence. Typically, KS skin shows multiple planes of cleavage at the dermal-epidermal junction (DEJ) and reduplication and interruption of the epidermal basement membrane. Consistent with the epidermal atrophy, basal keratinocytes exhibit minimal proliferation (8, 9).

Here, we describe 6 patients with KS caused by inherited FERMT1 duplicating insertions and a disseminated pattern of revertant skin patches. The reversion mechanism in each investigated skin patch was back mutation by slipped mispairing in direct nucleotide repeats. In addition, mitotic recombination was documented in some reverted areas.

Results and Discussion
Patient 1 (P1), who exhibited the hallmark feature of KS (poikiloderma with pronounced skin atrophy), was the index case, with innumerable normal-appearing skin patches. Subsequently, we observed a similar pattern in P2. Notably, both patients had FERMT1 duplication insertion mutations, which led to frame shifts, premature termination codons, and loss of full-length kindlin-1, as demonstrated by immunoblotting of keratinocyte lysates (10). A systematic review of 24 additional KS patients revealed that all individuals harboring duplicating insertions (P3–P6; Table 1) exhibited the same skin pattern (Supplemental Figures 1 and 2; supplemental material available online with this article; doi:10.1172/JCI61976DS1). P1 and P2 were available for systematic investigation.

P1, a 29-year-old male born to consanguineous parents, was homozygous for c.456dupA (11). During a 3-year follow-up, we noted normal-appearing patches with preserved texture, measuring between several mm² and 15 cm², disseminated over the entire integument, that contrasted the atrophic, dry, hyperpigmented, and often erythematous skin (Figure 1, A–C). Immunofluorescence staining of a skin sample obtained from an atrophic area (P1-1) revealed absence of kindlin-1 at the DEJ (Figure 2B). In contrast, 3 normal-appearing patches (P1-2, P1-3, and P1-4) showed positive kindlin-1 signals over the entire length of the biopsy, similar to normal skin (Supplemental Table 1).

P2, a 24-year-old female homozygous for c.676dupC, exhibited multiple normal-appearing patches, measuring 0.5–2 cm², that were clearly distinguishable from the atrophic integument.

Conflict of interest: The authors have declared that no conflict of interest exists.
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Table 1
Clinical and genetic features

<table>
<thead>
<tr>
<th>Pt</th>
<th>Sex</th>
<th>Age (yr)a</th>
<th>Origin</th>
<th>Clinical features</th>
<th>Revertant patch characteristics</th>
<th>FERMT1 mutations</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Male</td>
<td>29</td>
<td>Germany</td>
<td>Poikiloderma with marked atrophy, erythema, hypertrophic gingivitis, cheilitis angularis, urethral strictures, ectropion</td>
<td>Innumerable to several mm² to 15 cm² Hands, entire integument</td>
<td>c.456dupA homozygous, p.Asp153ArgfsX4</td>
</tr>
<tr>
<td>P2</td>
<td>Female</td>
<td>24</td>
<td>Kosovo</td>
<td>Poikiloderma with marked atrophy, hypertrophic gingivitis, esophageal stenosis, ectropion</td>
<td>&lt;10 to 0.5 cm² Hands, lower legs</td>
<td>c.676dupC homozygous, p.Gln226ProfsX17</td>
</tr>
<tr>
<td>P3</td>
<td>Female</td>
<td>17</td>
<td>Turkey</td>
<td>Poikiloderma with marked atrophy, photosensitivity, gingivitis</td>
<td>&lt;10 to 0.5 cm² Hands</td>
<td>c.676dupC homozygous, p.Gln226ProfsX17</td>
</tr>
<tr>
<td>P4</td>
<td>Female</td>
<td>21</td>
<td>Kosovo</td>
<td>Poikiloderma with marked atrophy, webbing of fingers, microstoma, esophageal stenosis, genital involvement</td>
<td>&lt;10 to 0.5 cm² Hands, neck, legs</td>
<td>c.676dupC homozygous, p.Gln226ProfsX17</td>
</tr>
<tr>
<td>P5</td>
<td>Female</td>
<td>11</td>
<td>Kosovo</td>
<td>Discrete poikiloderma and atrophy, colitis</td>
<td>&gt;10 to 0.5 cm² Hands, lower legs</td>
<td>c.676dupC homozygous, p.Gln226ProfsX17</td>
</tr>
<tr>
<td>P6</td>
<td>Male</td>
<td>9</td>
<td>Serbia/Greece</td>
<td>Discrete poikiloderma and atrophy, urethral strictures</td>
<td>Innumerable to several mm² to 1 cm² Hands, arms, legs</td>
<td>c.[676dupC][1677G&gt;A], p.[Gln226ProfsX17][Trp559X]</td>
</tr>
</tbody>
</table>

aAge at last examination. bConsanguineous parents, not available for analysis. cNonconsanguineous parents, all heterozygous carriers of the mutations.
dIdentical FERMT1 SNPs. eTo our knowledge, c.1677G>A was not previously reported.

In the dermis below the reverted areas, the mutations were present in a homozygous state. Thus, the reversion had occurred only in keratinocytes, which are the sole kindlin-1–expressing cells in the skin (8, 9). The results were confirmed in P2 at the RNA level (data not shown), but no material was available from P1. Notably, in both patients, the same reversion mechanism (i.e., a single nucleotide deletion restoring the number of bases in the direct repeats) was found in all revertant patches, suggestive of a high propensity of the sequence to mutational events through slipped mispairing (12).

(Figure 1, D and E). Kindlin-1 immunofluorescence was negative in the affected skin, but positive (comparable to control skin) in 2 normal-appearing patches (Figure 2, D and E, and Supplemental Table 1).

In both P1 and P2, restored kindlin-1 expression visibly improved skin morphology (i.e., preservation of rete ridges, epidermal thickness, and keratinocyte proliferation; Figure 2, C and E). Collagen VII staining was used to evaluate the integrity of the DEJ. In normal-appearing areas with positive kindlin-1 immunostaining, a linear collagen VII signal was seen that contrasted the irregular pattern in affected areas (Figure 2, B–E), which indicated that restoration of kindlin-1 normalized the DEJ.

These results strongly supported the hypothesis that the normal-appearing kindlin-1–positive spots represent areas in which the inherited mutations had reverted. To test this, we used laser dissection microscopy (LDM) to collect keratinocytes from areas with altered or normal DEJ. DNA was extracted, and FERMT1 exons 4 and 5 were sequenced in P1 and P2, respectively. In both patients, the mutations were found in a heterozygous state in keratinocytes derived from all normal-appearing patches, whereas in diseased skin, the mutations were present in a homozygous state, similar to lymphocytes (Figure 3 and Supplemental Table 1).

Figure 1
Clinical features indicative of revertant mosaicism in KS. (A–C) P1 exhibited numerous normal-appearing skin patches of several mm² to 15 cm² on the entire integument, which remained constant over the 3-year observation period. Shown are the right axilla, upper thorax, and right arm (A); the left arm (B); and the left leg (C). (D and E) P2 had normal-appearing skin patches on the right hand (D) and the right lower leg (E). Revertant areas investigated here are outlined in black; biopsy sites are circled in blue or directly visible.

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Surprisingly, in both P1 and P2, the homozygous wild-type sequence was also disclosed in some areas of the normal-appearing skin samples (Figure 3), suggestive of a second mutational event in the revertant heterozygous keratinocytes — either a second back mutation, or mitotic recombination. To investigate this, we genotyped SNPs around FERMT1 in DNA extracted from lymphocytes of P1 and P2 and identified the borders of the homozygous regions, which spanned about 1.1 and 1.4 Mb, respectively. In the revertant patches with the homozygous wild-type FERMT1 sequences, recombination was confirmed by loss of heterozygosity of the SNP rs261360, located outside these homozygous regions (Supplemental Table 2).

These results demonstrated restoration of the FERMT1 reading frame, kindlin-1 expression, and skin structure in the revertant patches. Revertant keratinocytes proliferated normally, having a selective advantage compared with kindlin-1-negative cells (Figure 2), allowing them to expand. Nevertheless, large reverted areas (~15 cm²) may represent confluence of multiple overlapping or neighboring revertant events.

The slipped mispairing model involves the misalignment of short direct repeats during DNA replication and represents a common mutational mechanism (13–15), which has previously been elucidated in microorganisms (16–18). The primer strand containing the newly synthesized repeat dissociates from the template strand and misaligns, leading to either insertion or deletion of 1 or more direct repeats in the continued DNA synthesis. The fidelity of DNA replication is dependent on the local sequence environment and the DNA polymerase (19). PolyA and polyC repeats, as observed in our patients, are known hotspots for microdeletions and microinsertions (20, 21). Prior meta-analysis of the sequence vicinity of a large number of microdeletions and microinsertions in different genes revealed that short oligonucleotide motifs significantly correlate with the occurrence of both mutational events (12). Such motifs — GA⁶ and A⁶G, or AC⁶ and C⁶A — were present close to the mutations in our patients (Figure 3). Additionally, the DNA polymerase β frameshift hotspot AAAA, and the topoisomerase II consensus cleavage site CCCAG, which are potentially involved in site-specific recombination and putative deletion/insertion hot-
spots, were close to the mutations. Based on the identical molecular event in all analyzed spots and the finding that of our cohort of 26, all 6 KS patients with duplicating insertions exhibited multifocal revertant mosaicism, we strongly favor this mechanism as the cause of reversion. A recent report of an 8-year-old boy homozygous for c.676dupC and having a normal-appearing skin patch on his hand (5) strengthens our findings. Recognition of multiple patches in young children is difficult (22), since small normal-appearing areas may only become visible with age, against the progressive poikiloderma (ref. 7 and Supplemental Figure 2).

The multifocal mosaic pattern in KS is similar to the rare disorder ichthyosis with confetti, which is caused by dominant KRT10 mutations. In this disorder, multiple normal-appearing patches represent revertant areas in which the inherited mutation is rescued by different mitotic recombination events (6). In our cases, recombination occurred as a secondary mutational event, after the back mutation had already reverted the recessive condition.

These findings may open therapeutic perspectives for KS and other genodermatoses. The advantages of a therapy using revertant keratinocytes are the natural correction of the mutation and the lack of immune response. Grafting revertant keratinocytes in junctional epidermolysis bullosa demonstrated that the procedure is easy and well-tolerated by the patient, but cultivation of the reverted cells must be improved before it becomes clinically applicable (23).

Methods

Samples. EDTA blood was obtained from patients and parents. 4-mm punch skin biopsies were obtained from P1 and P2 (Supplemental Table 1 and Figure 1).

Immunohistochemical analysis. H&E, immunohistochemistry, and indirect immunofluorescence staining of the skin was performed as described previously (8), using primary antibodies to kindlin-1 (8), Ki-67 (MIB-1; Dako), and collagen VII (LH7.2; Millipore) and the AEC (3-amino-9-ethylcarbazole) system (Dako) or Alexa Fluor 488–conjugated goat anti-rabbit IgG (Dako) for secondary staining. Scale bars: 50 μm.
and -mouse IgGs (Invitrogen). Nuclei were visualized with hematoxylin or DAPI. Stained sections were observed with light microscopy (Nikon 80i) or confocal laser scanning microscopy (LSM510; Carl Zeiss).

Mutation detection. Mutation detection on DNA extracted from EDTA blood (Qiagen kit) was performed as described previously (24). At least 15 exons and adjacent junctions of FERMT1 were amplified and sequenced in an ABI 3130XL genetic analyzer using Big Dye Terminator Chemistry (Applied Biosystems). DNA sequences were compared with the NCBI reference (NC_000020.10) using Mutation Surveyor DNA (2.6.1 Softgenetics). Mutations were verified by sequencing in both directions from independent PCRs. Additionally, 34 SNPs covering 7 Mb around FERMT1 were genotyped by direct sequencing from the patients’ lymphocytes (Supplemental Table 2).

Nested PCR was used to detect mutations in DNA from microdissected tissue (Supplemental Table 3). All PCRs were repeated with templates from at least 3 separate DNA isolations obtained by LDM, and all products were sequenced in both directions.

DNA and RNA isolation from skin sections. For DNA recovery by LDM, 5-μm skin cryosections were mounted on 1.0-mm PEN membrane–covered slides (Zeiss). Collagen VII staining was used to visualize the DEJ because the signal is strong enough not to be bleached under LDM. Approximately 200 cells from affected and reverted areas were dissected with the Laser Robot Microbeam System (P.A.L.M. Microlaser Technology AG) and separately collected in the caps of 0.5-ml thin-walled tubes (Zeiss). For protein isolation, 20 cells from affected and reverted areas were dissected with the Laser Robot Microbeam System. Protein was extracted from these cells by boiling in Laemmli sample buffer (12.5% SDS, 50 mM Tris, pH 6.8, 10 mM DTT, 1% β-mercaptoethanol). Protein samples were separated by SDS-PAGE followed by Western blotting using antibodies against Collagen VII (Abcam) or laminin γ1 (Millipore). Nuclei were visualized with hematoxylin or -mouse IgGs (Invitrogen). Nuclei were visualized with hematoxylin or DAPI. Stained sections were observed with light microscopy (Nikon 80i) or confocal laser scanning microscopy (LSM510; Carl Zeiss).