Close linkage of a gene for X linked deafness to three microsatellite repeats at Xq21 in radiologically normal and abnormal families

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Abstract
We have used three highly polymorphic microsatellite repeats from Xq21 to type families in whom a gene for X linked deafness with perilymphatic gusher (DFN 3) was segregating. All three markers were tightly linked to the disease in its radiologically normal and abnormal forms, with a maximum lod score of 10.37 with DXS995 and 8.44 with DXS986 at zero recombination, and 14.03 with DXS1002 at $\theta = 0.01$. In an isolated case of deafness of this type, DXS995 indicated either the first recombination observed between the marker and the disease gene or a new mutation in the proband. Southern blotting using a cosmid fragment from the candidate region has confirmed a de novo mutation by showing a deletion in the proband which is not present in his mother as judged by dosage analysis. We also describe a family with a paracentric inversion associated with a microdeletion and discuss how deletion mapping using these and other markers in the region has helped to define a candidate region for the gene.

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In clinical practice, deafness can usefully be classified into non-syndromic (in which there are no extra-auditory features) and syndromic, of which there are over 400 entries in the London Dysmorphology Database. X linked deafness accounts for a small proportion of all non-syndromic genetic deafness, but it is nevertheless one of the best defined in terms of genetic and physical localisation. X linked deafness was initially classified into four groups on the basis of the pure tone audiogram, but recent work has questioned the basis of that classification and proposes a radiological classification instead. Phelps et al. described a unique abnormality on the CT scan of the petrous temporal bone in more than 50% of families with X linked deafness which consisted of dilatation of the internal auditory meati and deficiency of the bone between the basal turn of the cochlea and the internal auditory meatus. This abnormality has been shown to be consistent for affected males within each pedigree so that it was either present in all deaf males scanned or in none. The bony defect may explain the well described phenomenon of the perilymphatic “gusher” at stapes surgery since it proposes a communication between the cerebrospinal fluid and the perilymphatic space. Whether there are two genes in Xq21 causing deafness accounting for the two radiological types, normal and abnormal, or whether there is a single gene in which allelic mutations may cause different pathology, is a question that will only be satisfactorily answered once the gene(s) have been cloned. What is clear from previous linkage studies is that deaf males with the typical bony abnormality on CT scan have a mutation in a gene at Xq21 in what is designated the DFN 3 locus. Other non-syndromic forms of X linked deafness without distinctive bony changes show linkage heterogeneity, with only some mapping to Xq21. Of the two reported families that do not map to Xq21, one family maps to Xp11.3–21.1 and the other family maps to neither of these loci (unpublished data). Only families in whom the bony abnormality has been shown or families which have previously shown independent linkage to markers from Xq13–21 have been examined in this study.

Localisation of a major non-syndromic X linked deafness locus to the broad area Xq13–q21 is supported by linkage data from several groups, by analysis of cytogenetically visible male viable deletions with complex phenotypes, and the detection of microdeletions in unrelated male patients with X linked deafness. We now describe the use of three highly informative microsatellite repeats to type seven families with this condition and show tight linkage to the gene. One of these markers, DXS995, was used to type an additional small kindred in which a deaf male showed the radiological abnormality characteristic of X linked deafness. The result indicated either the first recombination seen with this marker and the disease gene or a de novo mutation in the proband. Southern blotting subsequently has confirmed that there is a deletion in this patient
Figure 1 Pedigree structure of family 8. Autoradiograph shows the band pattern observed with DXS995. The mother is heterozygous and both brothers have inherited the same allele.

which appears to be de novo, since dosage analysis indicates that it is not carried by the patient’s mother.

Materials and methods

PATIENTS

Eight families with X linked deafness were studied using the microsatellite repeats DXS995, DXS986, and DXS1002 and all were screened for deletions using PCR primers for DXS26, which Bach et al.6 have already shown is deleted in some patients with DFN 3.

Families 1 to 6 have been described previously7 as has family 7.3 Family 8 has not been reported previously and is shown in fig 1. All affected males in these pedigrees had severe to profound hearing loss of prelingual onset. In families 3, 4, and 5, hearing loss was mixed and in the remainder it was a pure sensorineural hearing loss. Syndromic forms of deafness were excluded on the basis of history and clinical examination. Several deaf males from pedigrees 1 to 6 had a CT scan of the petrous temporal bone. Affected males from pedigrees 2, 3, 5, and 6 showed the characteristic bony defect described by Phelps et al.4 The single male in family 7 who had a CT scan has shown the typical appearance.8 Blood was taken from one affected male from each family for cytogentic analysis.

Patient D209 with a cytogenetic deletion of band Xq21, deafness, choroideraemia, and developmental delay, was examined radiologically.

DNA ANALYSIS

DNA was extracted from peripheral blood lymphocytes by standard techniques.10 DNA was amplified in the polymerase chain reaction (PCR) by primers flanking dinucleotide repeat polymorphisms. Reaction mix consisted of 250 ng of genomic DNA, 50 pmol of each primer, buffer consisting of 1.5 mmol/l Tris pH 8.3, 1.5 mmol/l MgCl2, 50 mmol/l KCl, 0.2 mmol/l dGTP, dATP, dTTP, and 0.02 mmol/l dCTP, 1 μl of 32P-dCTP (3000 Ci/mmol) per 1 ml of reaction mix, and 1 unit of Taq polymerase (Bioline) in a reaction volume of 50 μl. Products were separated on a 6% acrylamide 7 mol/l urea denaturing gel at 60 W for two to three hours. Dried gels were exposed to x ray film (X-Omat, Kodak) for 24 hours.

Primer sequences for the three microsatellites are as follows: DXS995: 5’ AAGGGCGCTGATGATATAT 3’ (forward) and 5’ AATGCCCTCCCAATG 3’ (reverse). DXS1002: 5’ CTGCATCCTTTAGTTCTATGCTTC 3’ (forward) and 5’ TCCCATGTTCCTGCGA 3’ (reverse). DXS986: 5’ CCTAAGGATGATCATCCAGTAACTGCTGATGATTAT 3’ (forward) and 5’ AGCTCATATCCAAGTTGCTGA 3’ (reverse).

Conditions for thermal cycling consisted of denaturation at 95°C for five minutes, followed by 30 cycles of 58°C (DXS995 and DXS986) or 56°C (DXS1002) for 30 seconds, 72°C for 30 seconds, and 95°C for 30 seconds, followed by a final extension step of 72°C for 10 minutes. Primer sequences for DXS26 are: 5’ GGAGTTGTGGGTGTTGTTGD 3’ (forward) and 5’ GGACACTGATTCTTAGAGTA GAT 3’ (reverse). Cycling conditions consisted of initial denaturation at 95°C for five minutes, 30 cycles of 95°C for one minute, 58°C for 1.5 minutes, 72°C for one minute followed by a 10 minute final extension step of 72°C.

RADIOLOGY

Patient D20 and the proband from family 8 underwent high resolution CT scanning of the petrous temporal bones.

TWO POINT LINKAGE ANALYSIS

Maximum lod scores (Zmax), and the maximum likelihood estimate of the recombination fraction (θ (θmax)), were calculated for the deafness locus and each of the three markers DXS995, DXS1002, and DXS986 using the computer programme LIPED.11 Marker allele frequencies were taken from the Genome Data Base. The frequency of the deafness allele was taken as 0.001 with penetrance complete in males. Recombination fractions were converted to genetic distances by using Haldane’s mapping function.

SOUTHERN BLOTTING

DNA was digested according to the manufacturer’s instructions using EcoRI (NBL), separated using 0.8% agarose gels and blotted onto Hybond N+ (Amersham). Probes were labelled using random hexanucleotides to a specific activity of 1 x 106 cpm/ml with α-32P-dCTP (3000 Ci/mmol) and preammeled with human competitor DNA (Sigma) if necessary, as described by Blonden et al.12 Filters were washed in 3 x SSC/0.1% SDS for 20 minutes at room temperature, followed by a single wash with 0.1 x SSC/0.1% SDS at 65°C. Radioactive filters were exposed to phosphorimager screens for 24 to 96 hours and the radioactive signal
Table 1  Pairwise lod scores between the disease gene (DFN3) and marker loci in families with the characteristic radiological change

<table>
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<th>Marker locus</th>
<th>Recombination fraction θ</th>
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</tr>
<tr>
<td>DXS1002</td>
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Table 2  Pairwise lod scores between the disease gene and marker loci in families with normal radiology

<table>
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<tr>
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<td>DXS995</td>
<td>4.51</td>
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<td>DXS1002</td>
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Two point lod scores between each microsatellite repeat and the disease locus are given in tables 1 and 2. Results in table 1 refer to families who show the CT scan abnormality and table 2 refers to families who have a normal CT scan appearance. The maximum lod scores observed indicate that all these markers are tightly linked with the disease. No recombinations were observed between the disease and any of the markers in families with abnormal radiology, resulting in lod scores of 9.80 at θ = 0 for DXS1002, Zmax of 5.86 at θ = 0 for DXS995, and Zmax of 7.23 at θ = 0 for DXS986. In those families with normal radiology no recombinations were seen between DXS986 and DXS995 and the disease locus with lod scores of 1.21 and 4.51 respectively at θ = 0, and a single recombinant was observed between the disease and DXS1002 giving a Zmax of 4.71 at θ = 0.05.

Fig 1 shows the result of microsatellite analysis using DXS995 in family 8. Both brothers have inherited the same allele from their mother. On PCR analysis, DKS26 was not deleted in this family. None of the families was found to be deleted for DXS995, but all the affected males from one family, pedigree 7, failed to amplify using PCR primers for DKS26 (data not shown). Cytogenetic analysis has shown that a paracentric inversion (fig 2) at Xq13–21 segregates with the deafness in this family in five out of five deaf males, two out of two obligate carrier females, but not with one hearing male tested or a pregnant female at 50% risk of being a carrier. Chromosome preparations were examined without the knowledge of affected or obligate carrier status.

Patient D20 was found to be deleted for DXS995 and DXS1002 but not for DXS986. DNA showed no deletion of DXS26 by PCR. CT scan of the petrous temporal bone showed bulbus internal auditory meati and a deficiency of bone between the basal turn of the cochlea and the internal auditory meatus in patient D20 and the deaf male in family 8.

PROBES
Cosmid E1 is a subclone of a YAC which spans DKS26.10 Probe E1 is the 3.7 kb fragment of an EcoRI digest of cosmid E1 and required preannealing with sheared human placental DNA. Probe E3.9 is a control probe from chromosome 22.

DOSAGE
Dosage was determined by measuring the ratio of radioactive signals from the test probe, E1, and a control probe E3.9 using a phosphorimager. Normal males and normal females were used as controls for one and two copies of the X chromosome and the mean ratio of E1/E3.9 signal was calculated for female controls. The E1/E3.9 ratio values for all samples were then normalised to this mean female value. Ten females and 15 males were used as normal controls. Samples from four obligate carriers from family 7 were measured and the mother of the proband in family 8 was compared to all of these subjects.

Figure 2  Two partial karyotypes of the pair of X chromosomes in one of the obligate carrier females with the ISCN (International System for Human Cytogenetic Nomenclature) diagram showing the paracentric inversion (X) (q13.1q21.2).
normalised ratios of the relative intensities of probe E1 to control probe E3.9, for four obligate carriers from family 7, control subjects, and the mother of the proband in family 8 are shown in fig 4. The mean ratio for control females was 99-2% (SD=5-7) and the mean ratio for control males was 53-6% (SD=8-77). The value for the four obligate female carriers from family 7 lie within the control male range as expected for deletion carriers. In family 8, the mother’s value falls within the control female range indicating that she has two copies of that region of the X chromosome and that her son has a de novo deletion.

**Discussion**

We have used three polymorphic microsatellite repeats to type families in whom a gene for X linked deafness at Xq21 was segregating. The location of these markers in relation to markers used previously for linkage in this condition is shown in fig 5, which indicates the proximity of the microsatellites used here to the disease locus, based on physical data from deletion mapping. Although all three markers are tightly linked to the gene for X linked deafness, it is not possible to discern on linkage analysis alone which is the closer marker, since lod scores between both DXS995 and DXS986 and the deafness locus were maximum at zero recombination in both sets of families. The one recombination observed probably occurs between DXS1002 and the disease locus in II-1 in pedigree 1 (fig 6). Since I-2 is uninformative for the other two markers it is not possible to determine whether recombination has also occurred between the disease and one or both of the other two markers and therefore to place it with respect to all three markers by multipoint mapping.

Since it is not yet known whether there are two genes at Xq21 causing deafness, or a single gene in which allelic mutations can cause deaf-
ness with or without radiological change, we have considered our lod scores separately in these two groups of families. However, our data show that both groups are closely linked to Xq21 and cannot be distinguished on linkage analysis alone, as the maximum two point lod score is 5.86 with no recombinations in families with the radiological change, and 4.51 with no recombinations in families with normal radiology with the marker DXS995. Furthermore, one large family with normal radiology independently achieves a lod score greater than 3. Summation of the lod scores gives a Zmax of 10.37 at θ=0 with DXS995. The 95% confidence limits indicate that 0 < θ < 0.05 for DXS995 (or within 5 cM of the gene) and 0 < θ < 0.06 for DXS986 (or within 6 cM of the disease locus), calculated by subtracting one lod unit from the maximum lod score.17

What is clear from these data is that families with normal temporal bone radiology can link to Xq21. So although abnormal cochlear radiology indicates mutation in the DFN3 locus at Xq21, a normal scan in a family with an X-linked pattern of inheritance does not exclude mutation at this locus.

These markers may be useful for carrier ascertainment in families with a radiological change or a pedigree which is linked to Xq21, until such time as the gene is cloned and direct mutation detection becomes possible, or in those families in whom mutation detection is elusive. Haplotype analysis suggests that 16 females in our pedigrees would appear to be carrying the gene for X-linked deafness within these confidence intervals. Such information on carrier status is requested by women of child bearing age as illustrated by our experience with one female who enquired about further information on her carrier status after becoming pregnant. Advice from audiological colleagues regarding early testing, diagnosis, and provision of hearing aids in a child with severe hearing impairment and the subsequent improvement in language development has encouraged some of these females who may be carriers to seek more information. The possible use of these markers by gene tracking in the diagnosis of severe to profound deafness in the baby sons of carrier mothers may lead to early intervention and auditory training. The predictive value of these tightly linked markers has been well illustrated in family 8. As both brothers inherited the same maternal allele at DXS995, this either indicated the first recombination seen to date, or, as dosage studies now support, a de novo mutation.

The order of the three microsatellite markers has been determined by deletion mapping using cell lines, as cen – DXS986, DXS995, DXS1002, – tel.16 Affected males in family 7 were deleted for DXS26 using PCR, and this familial deletion has been confirmed here on Southern blotting using probe E1 (fig 4) and more extensively by hybridisation with a panel of cosmids from a contiguous region encompassing DXS26 must lie centromeric to DXS995 and DXS1002, as both of these microsatellite repeats are deleted in patient D20 who has the large cytogenetic deletion of band Xq21 but who shows no deletion of DXS26 on PCR (fig 5). This would place the disease locus for DFN3, the "gusher" form of X-linked deafness, between DXS995 and DXS26; however, the deletion seen in the proband from family 8 does not overlap with that of D20 who is not deleted for E1 (data not shown) which indicates that the gene must lie in the region encompassing DXS26 and DXS995.16

The remaining question of whether or not a single gene can give rise to both phenotypes, radiologically normal and abnormal, seen in non-syndromic X-linked deafness cannot be answered until the gene is cloned. Frenz et al19 provides in vitro evidence for an influence of the developing sensory epithelium on the formation of the otic capsule. It is conceivable that a protein produced in the epithelium plays roles dependent on different domains, one of which is concerned with induction of cartilage formation, the other with development of the sensory epithilium. Large deletions such as the contiguous gene case reported by Reardon et al2 are associated with the bony defect, so the prediction is that absence of the whole gene product gives this phenotype. It is possible that some mutant peptides just cause the sensorineural hearing loss.

Figure 6. Pedigree of family 1 showing haplotypes for markers DXS986, DXS995, and DXS1002. Recombination is seen between DXS1002 and the disease locus, probably in I-1.

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