Analysis of the p63 gene in classical EEC syndrome, related syndromes, and non-syndromic orofacial clefts

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L L Barrow, H van Bokhoven, S Daack-Hirsch, T Andersen, S E C van Beersum, R Gorlin, J C Murray

EEC syndrome is an autosomal dominant disorder with the cardinal signs of ectrodactyly, ectodermal dysplasia, and orofacial clefts. EEC syndrome has been linked to chromosome 3q27 and heterozygous p63 mutations were detected in unrelated EEC families. In addition, homozygous p63 null mice exhibit craniofacial abnormalities, limb truncations, and absence of epithelial appendages, such as hair follicles and tooth primordia. In this study, we screened 39 syndromic patients, including four with EEC syndrome, five with syndromes closely related to EEC syndrome, and 30 with other syndromic orofacial clefts and/or limb anomalies. We identified heterozygous p63 mutations in three unrelated cases of EEC syndrome, two Iowa white families and one sporadic case in a Filipino boy. One family is atypical for EEC and has features consistent with Hay-Wells syndrome. In this family, the mutation ablates a splice acceptor site and, in the other two, mutations produce amino acid substitutions, R280C and R304Q, which alter conserved DNA binding sites. Germline mosaicism was detected in the founder of the mutation in one case. These three cases show significant interfamilial and intrafamilial variability in expressivity. We also screened p63 in 62 patients with non-syndromic orofacial clefts, identifying an intrinsic single nucleotide polymorphism but finding no evidence of mutations that would explain even a subset of non-syndromic orofacial clefts. This study supports a common role for p63 in classical EEC syndrome, both familial and sporadic, but not in other related or non-syndromic forms of orofacial clefts.
MATERIALS AND METHODS

Subjects
Syndromic cases were identified at the University of Iowa Hospitals and Clinics and in the Philippines through Operation Smile. All cases had at least one affected family member examined by at least one clinical geneticist (JCM) or genetics clinical nurse specialist (SDH). Family histories were taken and blood or buccal swabs were collected for DNA analysis. Samples were obtained after signed informed consent following IRB approval both in the United States and in the Philippines. The identified cases consisted of five Iowa white cases and 34 Philippine cases. Previously described diagnostic criteria were used for EEC syndrome.

Two of three cardinal signs must be present in isolated cases. In a familial case, one of three cardinal signs and a first degree relative with unequivocal EEC syndrome must be present to make the diagnosis. Also, related but separate syndromes were excluded from the diagnosis of EEC syndrome. Two of five Iowa white patients and one of 34 Philippine patients met these criteria for diagnosis of classical EEC syndrome. Cases of limb reduction defects and amniotic band sequence were also included in the study. A possible association of amniotic bands and EEC syndrome has been previously proposed. The clinical information for the cases is summarised in table 1. The data for cases in which mutations were detected are given in greater elaboration. Cases of non-syndromic orofacial clefts were also identified, 31 white patients through the Iowa Birth Defects Registry and 31 Filipino cases through Operation Smile.

In case 1, three family members were affected in two generations of Iowa whites (fig 1). The affected family members (II.1, II.2, and III.1) all showed ectodermal dysplasia, with sparse to absent blonde hair, eyebrows, and eyelashes, dysplastic nails, palmar hyperkeratosis, and cone shaped teeth. All three also have renal abnormalities: an unspecified left renal abnormality (II.1), left renal agenesis (II.2), and right multicystic kidney and left dysplastic kidney (III.1). The proband (III.1) required a renal transplant following complications of peritoneal dialysis. The proband also has an isolated

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</table>

Complete table available [genetics.uiowa.edu].

M, male; F, female; cl/p, cleft lip and palate; bcl/p, bilateral cleft lip and palate; cpo, cleft palate only; lc/l/p, left cleft lip and palate; rcl, right cleft lip; AB (amniotic band).

Figure 1 Pedigrees of EEC cases 1, 2, and 3. Affected subjects are indicated by blackened squares and circles. Proband are indicated by arrows.
cleft of the soft palate, previously repaired. No other family member has a cleft and no family member has ectrodactyly nor lacrimal tract abnormalities. The father (II.2) does appear to have impairment of his lacrimal glands since he does not produce tears. The proband also has asthma requiring treatment with bronchodilators, chronic otitis media, and a repaired type I Arnold-Chiari malformation.

In case 2, three family members were again affected in two generations of white Iowans (fig 1). The affected family members (I.2, II.3, and II.4) all show ectodermal dysplasia with sparse blonde hair, eyebrows, and eyelashes, dry skin, diminished perspiration, dystrophic nails, and peg shaped teeth with delayed dentition. The mother (I.2) is missing her central lower incisors, her first molar on the lower left side, and all wisdom teeth. All three (I.2, II.3, and II.4) have limb abnormalities, and both children (II.3 and II.4) have ectrodactyly. The mother has shortening of the first digits of her hands and fifth digits on her feet. The boys (II.3 and II.4) have missing digits 2-3 and 4-5 syndactyly of the hands bilaterally as well as missing right toes 2-4 and 4-5 syndactyly of the left foot. All three (I.2, II.3, and II.4) have lacrimal duct obstruction. The proband’s brother (II.4) has a bifid uvula. No other orofacial cleft was detected. The brother also had hypoplasia. All three had clinically significant asthma requiring treatment with bronchodilators.

In case 3, the classical EEC triad occurred in the sporadic case of a Filipino boy (fig 1, fig 2). The boy had no sibs and neither parent was affected. He had bilateral ectrodactyly of the upper and lower extremities. He was missing digits 2-3 of the right hand and foot and missing digit 3 of the left hand and foot. He had sparse hair and hypodontia. He also had bilateral cleft lip and a cleft palate, which were subsequently repaired by Operation Smile. Lacrimal tract and urogenital abnormalities were not detected.

**Mutational analysis**

SSCP analysis was conducted with 16 primer pairs external to each exon and inclusive of the splice donor and acceptor sites. Product sizes ranged from 140 to 366 bp, and products longer than 300 bp were digested with an appropriate restriction enzyme to produce two fragments less than 300 bp for SSCP analysis. PCR was conducted in a Stratagene Robocycler 96 in 10 µl reactions containing 1.5 mmol/l Mg²⁺, 40-80 ng DNA, Biolase Reaction Buffer (Bioline), 0.25 mmol/l each dNTP, 0.6 µmol/l each oligodeoxynucleotide primer, and 1.5 units Biolase DNA polymerase (Bioline). Cycling profile was one cycle of 94°C for three minutes, 40 cycles of 94°C for 40 seconds, 55-58°C for 30 seconds, and 68°C for two minutes, and one cycle of 68°C for seven minutes. Products were amplified in microtitre plates, digested when greater than 300 bp, electrophoresed on MDE gels, and silver stained. Variant and control bands were cut from the stained gel, amplified, and purified from agarose gel with QIAquick Gel Extraction Kit (QIAGEN). Genomic DNA was isolated as well. Purified products were sequenced bidirectionally with an Applied Biosystems (ABI) 373 DNA Sequencer using ABI Prism Dye. The 20 µl reactions contained 5% DMSO, 1.0 ng/µl DNA per 100 bp sequence, and 0.32 µmol/l oligodeoxynucleotide primer. Cycling was conducted in a GeneAmp PCR System 9700 (Perkin-Elmer). Cycling profile was one cycle of 95°C for five
minutes, 99 cycles of 95°C for 20 seconds, 52-57°C for 20 seconds, and 62-67°C for four minutes. Sequence was analysed with Macintosh software including ABI Prism Sequencing Analysis 3.0 and Sequencher 3.1.1 (Gene Codes Corporation, Ann Arbor, MI).

RT-PCR
Total RNA was extracted from lymphoblastoid cell lines from affected subject III.1 of case 1 and from a control. cDNA was synthesised from 250 ng denatured RNA by random priming with random hexanucleotide primers (pd(N)6, Pharmacia) in a 20 µl reaction volume containing 5 mmol/l MgCl2, 10 mmol/l Tris base, 50 mmol/l KCl, 0.01% (w/v) gelatin, 1 mmol/l dNTPs, 2.5 U pd(N), 9 U RNA-guard RNase inhibitor (Pharmacia) and 1.25 U Taq polymerase (Life Technologies). Amplification was carried out in 35 cycles of 45 seconds at 95°C, 45 seconds at 50°C, and 90 seconds at 72°C. PCR products were analysed on 1.5% agarose gels. DNA fragments were excised with the above p63 specific oligonucleotides using the Big Dye terminator kit (PE). Sequence analysis was performed on an ABI3700 capillary sequencer (PE Applied Biosystems).

RESULTS
For p63 mutational analysis, we developed primer pairs external to each exon and inclusive of the splice sites based upon previous reports.7–11 SSCP was used to screen each proband for all 16 exons and all SSCP variants were directly sequenced. Additionally, all probands were directly sequenced for exons 5, 7, and 8 because these exons correspond to the highly conserved p53 DNA binding domain where 90% of the 10 000 mutations have been reported.7–11 Also, eight of nine previously reported p63 mutations were located in exons 5, 7, and 8.

Heterozygous p63 mutations were detected in three unrelated cases of EEC syndrome, two by SSCP and one by direct sequencing alone (fig 3). The mutation in case 1, AG to GG transition of splice acceptor site preceding exon 11. Case 2: CCG to CTG transition of exon 7 (R280C). Case 3: CGG to CAG transition of exon 8 (R304Q). Heterozygous nucleotides indicated by N.

Figure 3 Chromatograms of heterozygous p63 mutations in cases of EEC syndrome. Case 1: AG to GG transition of splice acceptor site preceding exon 11. Case 2: CCG to CTG transition of exon 7 (R280C). Case 3: CGG to CAG transition of exon 8 (R304Q). Heterozygous nucleotides indicated by N.
The effect of the splice site mutation in case 1 was investigated by analysis of p63 specific transcripts from a lymphoblastoid cell line of III.1 and from a control. RT-PCR was performed with exon specific primers in three combinations: exon 8 to exon 13, exon 8 to exon 12, and exon 10 to exon 12, which for the control yielded products of the expected sizes (fig 6). The same products were also obtained for patient III.1, but in addition products of smaller sizes were observed. The sizes of these smaller products corresponded with the expected sizes of products resulting from skipping of exon 11. The integrity of the products was verified by sequencing. Indeed, the amplicons from the control as well as the corresponding amplicons from patient III.1 contained wild type p63 sequences. In contrast, the smaller product observed for patient III.1 contained p63 sequences without the entire 158 bp sequences of exon 11 (fig 6). Thus, the A>G splice site mutation is predicted to give rise to truncated p63 protein by the skipping of exon 11.

DISCUSSION

An AG to GG heterozygous mutation of the splice acceptor site preceding exon 11 was found in case 1. This family has features consistent with Hay-Wells syndrome and its mutation is unusual by location and type from the previously reported EEC and split hand/split foot cases.

The previous reports of mutations in Hay-Wells syndrome all resulted from missense mutations in sterile alpha motif (SAM) encompassed by exons 13 and 14 and which might be affected by this frameshift in exon 11. Skipping of exon 11 results in a frameshift of the open reading frame. Transcripts lacking this exon could be easily detected in a lymphoblastoid cell line, indicating that mutant protein may be generated from it. Exon 11 is contained in only the α- and β-isotypes of p63, and deletion of this exon will produce truncated forms of these isotypes. A frameshift mutation resulting in a premature stop codon in exon 13 was identified previously in a patient with EEC syndrome.

Transactivation studies indicated that this truncated protein exhibited dominant negative properties towards wild type p63 isotypes. A similar dominant negative effect is expected for the protein products generated by the exon 11 lacking transcripts, because the tetramerisation domain is still normally present. ΔN-p63α, the predominant p63 isotype in epithelial basal cell layers, lacks transactivation capacity for p53 reporter genes in vitro. However, ΔN-p63α does show prominent dominant negative activity to suppress the transactivation of these p53 reporter genes by both p53 and...
Transactivation studies with mutant p63 isotypes and p53 reporter genes in vitro suggest that hetero-oligomer formation between mutant and wild type p63 isotypes may explain the dominant negative activity of the p63 missense mutations in EEC syndrome. Since the RNA intermediate of the splice acceptor site mutation in case 1 is likely to be rapidly degraded in vivo, it begs the question as to whether this case might be an example of haploinsufficiency in EEC syndrome, as opposed to dominant negative activity. This question is at present under investigation.

The two heterozygous p63 missense mutations detected in this study, Arg280Cys and Arg304Gln, result in amino acid substitutions in residues which are highly conserved in sequence comparison of the DNA binding domains of p53, p63, and p73. The p63 DNA binding domain shares approximately 60% and 85% amino acid identity with p53 and p73, respectively. Arg280 and Arg304 of p63 correspond to Arg249 and Arg273 of p53, which are among the six most frequently mutated p53 residues. In the established nomenclature of p53 mutations, Arg304Gln is a class I mutation of the transcription factor p63 which disrupts protein-DNA contact points and Arg280Cys is a class II mutation of p63 which alters a residue essential for proper orientation of the DNA binding surface. A previous study has reported Arg304Gln in EEC syndrome and Arg280Cys in non-syndromic ectrodactyly, suggesting in a previous study that amino acid residues not directly involved in DNA binding might cause non-syndromic ectrodactyly as opposed to EEC syndrome. In this study, however, classical EEC syndrome with Arg280Cys was found in case 2. The affected family members of case 1 had renal abnormalities, which were not present in the other cases. Other clinical findings among these three cases included lacrimal tract obstruction, impaired lacrimal gland function, asthma, hypospadias, chronic otitis media, and Arnold-Chiari malformation.

Some form of orofacial cleft was present in a family member of each of the three cases. The proband in case 1 had an isolated cleft palate, but the two affected members of the previous generation did not have any cleft. Also, the brother of the proband in case 1 and the two affected members of the previous generation did not have any cleft. The affected family members of case 1 also had cleft palate, but the two affected members of the previous generation did not have any cleft.

Figure 6  RT-PCR analysis of p63 transcripts in case 1 containing the 3′ splice site mutation in intron 10. (Above) Analysis of RT-PCR products on a 1.75% agarose gel. p63 derived transcripts from lymphoblastoid cells of a control (normal) and patient III.1 (mutant). The amplified exons are indicated on top of each lane. The expected sizes of the wild type amplicons are on the left, while sizes of mutant amplicons are on the right. The aberrant RT-PCR products are indicated by an asterisk. A 100 bp ladder is used as a marker (M). A summary of the amplification reactions and product sizes is given in the diagram. Mutant alleles lack the 158 bp exon 11. (Below) Sequence analysis of excised bands from the gel. The top panel is the sequence of 406 bp product from exon 10 to exon 12 from the control, whereas the lower panel is the sequence of the 248 bp band obtained with the same primers with RNA template from patient III.1. The sequence clearly shows that this 248 bp product is the result of skipping of exon 11.

TA-p63x. Transactivation studies with mutant p63 isotypes and p53 reporter genes in vitro suggest that hetero-oligomer formation between mutant and wild type p63 isotypes may explain the dominant negative activity of the p63 missense mutations in EEC syndrome. Since the RNA intermediate of the splice acceptor site mutation in case 1 is likely to be rapidly degraded in vivo, it begs the question as to whether this case might be an example of haploinsufficiency in EEC syndrome, as opposed to dominant negative activity. This question is at present under investigation.

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The affected family members of case 1 also had cleft palate, but the two affected members of the previous generation did not have any cleft. The affected family members of case 1 also had cleft palate, but the two affected members of the previous generation did not have any cleft.
proband in case 2 had a bidental uvula, but the proband and mother did not have a cleft. It is interesting to note that while the proband of case 1 had an isolated cleft of the soft palate and the proband in case 2 had a bidental uvula, the affected child in case 3 had bilateral cleft lip and a cleft palate. Genetics and embryology suggest that isolated clefts of the secondary (soft) palate may be a distinct clinical entity from clefts of the primary (hard) palate that involve the lip with or without the palate."

ACKNOWLEDGEMENTS

We thank the families who participated in this study. We thank Operation Smile for support. We also thank Bonnie Ludwig, Sarah O'Brien, and Nancy Newkirk for technical support. This study was supported by grants DE08559 and DE11948 (JCM) from the US National Institute of Dental Research, and grant NWO 901-02-232 (HV) from the Dutch Foundation for Scientific Research (NOW). Training was supported by US National Institutes of Deafness and Communication Disorders grant DC00040 (LLB), “Research Training Program for Oralotology Program”, administered by Dr Bruce Gantz.

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REFERENCES

ECHO

Coeliac disease in twins

The first large population study of coeliac disease (CD) among twins has confirmed that genetic makeup is more important than environmental influence in this disorder. Using twinship as the first selection criterion and CD as the second allowed the true extent of genetic influence to be determined.

Twenty twin pairs were monozygotic and 27 were dizygotic. The ratio of monozygotic pairs to dizygotic pairs of the same sex and to dizygotic pairs of opposite sex was very close to the expected population ratio, confirming a truly population based sample. Concordance for CD was 86% probandwise, 74% pairwise for monozygotic twins and 20% probandwise, 11% pairwise for dizygotic twins.

The odds of concordance in the non-index twin after adjusting for age, sex, number of shared HLA haplotypes, and zygosity were for genotype DQA1*0501/DQB1*0201, specifying the DQ2 heterodimer, 3.3 (95% confidence interval 0.4 to 30.0) and for DQA1*0301/DQB1*0302, specifying DQ8, 1.4 (0.0 to 41.0). In monozygotic pairs the odds when adjusted for DQ genotype were 17.0 (2.1 to 134.0), indicating another, separate genetic influence.

Patients were identified from the Italian Twin Registry—with 1.6m names—cross matched with approximately 6000 names listed in a large CD patient support group. Forty seven of 58 twin pairs were studied. Each pair was tested for antibody markers and had an intestinal biopsy, if necessary, to confirm CD status, and was tested for HLA type. Same sex pairs were tested to confirm their zygosity.

Previous studies in twins, based on volunteers or case series, have the disadvantage of recruiting bias.


