

## **Array-CGH analysis indicates a high prevalence of genomic rearrangements in holoprosencephaly: an updated map of candidate loci.**

Claude Bendavid, Lucie Rochard, Christèle Dubourg, Jonathan Seguin, Isabelle Gicquel, Laurent Pasquier, Jacqueline Vigneron, Annie Laquerrière, Pascale Marcorelles, Corinne Jeanne-Pasquier, et al.

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**Array-CGH analysis indicates a high prevalence of genomic rearrangements in Holoprosencephaly: an updated map of HPE candidate loci.**

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Key Words:	holoprosencephaly, CGH array, rearrangements, candidate loci



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## ABSTRACT

Holoprosencephaly (HPE) is the most frequent congenital malformation of the brain. Aetiology includes karyotype anomalies, environmental factors and genic forms that can be syndromic or isolated. Non-random structural chromosomal anomalies previously compiled from chromosomal HPE predicted at least 12 different HPE loci. To date, eight HPE genes have been identified from recurrent chromosomal rearrangements or from the sequencing of genes from Nodal and SHH pathways. Our cohort of isolated HPE presents a high genetic heterogeneity. Point mutations were found in *SHH*, *ZIC2*, *SIX3* and *TGIF* genes in about 20% of cases (with 10% in *SHH*). Submicroscopic deletions in these same genes were found in 7.5% and 4.4% presented with other subtelomeric gain or losses. Consequently molecular basis of HPE remains unknown in 70% of our cohort.

In order to detect new HPE candidate genes, we used array-CGH to refine the previous karyotype based HPE loci map. We analysed 111 HPE patients with high performance Agilent arrays made of 44K or 244K oligonucleotidic probes and found that 28 presented with submicroscopic anomalies involving known or new potential HPE loci located on different chromosomes but with poor redundancy. We observed 14 isolated deletions, 9 isolated duplications and 5 associated genomic losses and gains. Compiling these new data with frequencies of deletions in known HPE genes and of subtelomeric anomalies, we give evidence that microrearrangements could be a major molecular mechanism in HPE. Additionally, this study opens new insights on HPE candidate genes identification giving an updated HPE candidate loci map.

## INTRODUCTION

Holoprosencephaly (HPE; MIM 236100) is the most common forebrain developmental anomaly in humans, resulting from a complete or partial failure of cleavage of the forebrain during development. The clinical spectrum ranges from alobar HPE (absent interhemispheric fissure) to semilobar (posterior midline separation) and lobar HPE (continuity only across the frontal cortex) generally associated with facial anomalies. HPE is a severe pathology, associated with mental retardation in all affected live newborns, with poor or symptomatic treatment (Cohen, 2006). The genetic counselling in HPE families is very complex due to the extreme phenotypical variability, the genetic heterogeneity, and a high recurrence risk (13%) in apparently sporadic cases. Chronologically, non-random structural chromosomal anomalies previously compiled from chromosomal HPE predicted at least 12 different HPE loci, and out of these 12 loci, eight genes have been really implicated in HPE with mutations found in isolated HPE: Sonic hedgehog (SHH; 7q36; HPE3)(Belloni, et al., 1996; Roessler, et al., 1996), ZIC2 (13q32; HPE5)(Brown, et al., 1998), SIX3 (2p21; HPE2)(Wallis and Muenke, 1999), TGIF (18p11.3; HPE4)(Gripp, et al., 2000), PATCHED1 (9q22)(Ming and Muenke, 2002), TDGF1 (3p21.31)(de la Cruz, et al., 2002), FAST1 (8q34) (Ouspenskaia, et al., 2002) and GLI2 (2q24)(Roessler and Muenke, 2003). In total, these actors play a role either in the SHH pathway, or in the Nodal/Transforming Growth Factor beta (TGF $\beta$ ) pathway, or as transcription factors. Point mutations in the four major genes, *SHH*, *ZIC2*, *SIX3* and *TGIF*, were identified in 20% of our HPE patients. Among these genes, SHH appears to be the major one accounting for 50% of the identified mutations (Dubourg, et al., 2004).

Animal studies and rare human cases showed that double heterozygous mutations could be involved in HPE phenotype, introducing the multi-hit hypothesis in this developmental disorder (Ming and Muenke, 2002). This hypothesis helped in the understanding of the variable penetrance of familial mutations in the disease and led us to systematically screen the four genes, even if one mutation was initially found in the first sequenced gene. Additional work is focusing on environmental factors including low cholesterol levels (Edison, et al., 2007).

Since 2003, we also screened these genes for microrearrangements and proved for the first time the implication of gene deletions in 7.5% in holoprosencephaly (3.2% in

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3 SHH, 2% in ZIC2, 1.6% in SIX3 and 0.65% in TGIF) (Bendavid, et al., 2006a;  
4 Bendavid, et al., 2006b). When comparing the combined mutation and deletion  
5 results observed in the foetus cohort and in the live-born children, the total  
6 proportions of gene anomalies are close (28% and 24% respectively), but the rate of  
7 point mutations is much higher in live born children than in fetuses (23% versus  
8 14%) whereas submicroscopic deletions, which represent gross alterations, occur  
9 more frequently in fetuses (10% versus 5%) who generally have a more severe  
10 phenotype.

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12 Because of the HPE clinical and genetic heterogeneity, and the lack of informative  
13 families, a classical positional cloning strategy based on genome wide scan is not  
14 possible. Consequently, we were led to develop a strategy based on molecular  
15 biology and cytogenetics to identify candidate regions and thus candidate genes.  
16 This approach will complete the initial karyotype based study of recurrent  
17 chromosomal abnormalities which led to the identification of the first HPE genes  
18 (Belloni, et al., 1996) and HPE loci map (Roessler and Muenke, 1998).

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20 After screening of microdeletions or mutations in known HPE genes with  
21 QMPSF/MLPA or DHPLC plus sequencing respectively, we searched for  
22 submicroscopic rearrangements in subtelomeric chromosomal regions using the  
23 Multiplex Ligation Probe Amplification (MLPA) method (Hogervorst, et al., 2003).  
24 Indeed, subtelomeric aberrations were detected in 4,4% of our HPE patients with no  
25 known anomaly, showing either a single anomaly or an association between a  
26 deletion and a gain, these rearrangements were very heterogeneous, encompassing  
27 10 different subtelomeric regions. Some targeted regions known to be implicated in  
28 HPE (7q encompassing the SHH gene, 18p encompassing the TGIF gene, 21q  
29 including a candidate gene, LSS (Lanosterol Synthase)), but also new regions (1p,  
30 5q, 7p, 8p, 9q, 17q, 18q and 22q) were identified. Several samples, mainly foetal  
31 ones, consisted of an association between a duplication and a deletion in two  
32 chromosomal subtelomeres like (dup7pter; del7qter) or (dup20pter; del21qter).  
33 Moreover, rearrangements presented by fetuses generally implied known HPE loci,  
34 while those observed in live children encompassed regions not previously described  
35 (Bendavid, et al., 2007). But, even if we compile these large deletions, point  
36 mutations and deletions in the known genes, the combined rate of patients with  
37 identified molecular basis only reaches 30%, so more than 70% of the cases remain  
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3 unexplained, suggesting the involvement of many other genes in HPE (Dubourg, et  
4 al., 2007) and/or non genetic factors.

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7 The previous data showed the growing importance of microrearrangements in a  
8 complex genetic disease where mutations in the different genes have a variable  
9 penetrance and may need a second genetic event to give the disease. In order to  
10 identify new candidate loci and thus novel candidate genes, we decided to perform a  
11 genome wide screening for submicroscopic anomalies on isolated HPE patients,  
12 using Agilent array-CGH technology. We first tested the technique on 10 patients with  
13 known alterations in *SHH*, *TGIF*, *ZIC2*, *SIX3* or subtelomeres in order to better define  
14 the size of the rearrangement and the breakpoints. Then 111 samples (64 fetuses  
15 and 47 live-born children), with no known karyotypes alterations, were hybridized. We  
16 chose these patients with no regard to their mutational status for the main HPE  
17 genes, resulting in that 18% of this group were carrying a mutation.

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20 Confirming the growing importance of micro rearrangements, this study showed up  
21 an impressive rate of 28 patients among 111 with submicroscopic chromosomal  
22 anomalies. These defects involved known or new potential HPE loci located on  
23 different chromosomes but with poor redundancy. Added to the previous  
24 microdeletion findings in known HPE genes and subtelomeres, our data showed that  
25 microrearrangements could be the major molecular mechanism in HPE and strongly  
26 reinforce the multigenic origin in this developmental disorder.

## 27 28 29 30 31 32 33 34 35 36 37 38 39 40 **MATERIAL AND METHODS**

### 41 42 43 44 ***Patients and controls***

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47 The cohort consisted in 9 patients presenting with a known deletion already detected  
48 by qPCR or QMPSF in HPE genes (*SHH*, *TGIF*, *ZIC2* and *SIX3*) or telomeric  
49 rearrangements shown by MLPA experiments and 111 HPE patients (64 fetuses and  
50 47 live-born children) with normal karyotype. Out of this whole cohort, all foetuses  
51 had severe HPE (central nervous system (CNS) findings consistent with HPE)  
52 whereas 15 live-borns had severe HPE and 32 had a spectrum of HPE microsigns  
53 (midline defect without cerebral malformation, including facial clefting, single central  
54 maxillary incisor, hypotelorism).

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3 Twenty patients with already known point mutations in the four HPE genes were also  
4 included, 20 of them with an inherited mutation and a severe phenotype whereas the  
5 transmitting parent had a microform.  
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8 For only 21 cases with positive CGH result, we had both maternal and paternal DNA  
9 that could be investigated by array-CGH, MLPA or quantitative PCR to confirm de  
10 novo alterations.  
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15 In order to simplify the interpretation of the results and better characterize CNVs, we  
16 used genomic DNA from one well-characterized normal male 46,XY and 1 well-  
17 characterized normal female 46,XX as control. These two controls were regular blood  
18 donors that gave consent (to Etablissement Français du Sang) to use anonymously  
19 their DNA for diagnosis or research purposes.  
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26 This study was approved by the Institutional Review Board, and parents of all  
27 participants gave their informed consent.  
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### 31 32 ***Comparative Genomic Hybridization study*** 33

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35 Briefly, for live-born children, genomic DNA was extracted from peripheral whole  
36 blood by the Flexigene DNA kit from QIAGEN. For foetuses, DNA was extracted from  
37 tissues or cultured amniotic cells, using the QIAamp DNA minikit from QIAGEN. DNA  
38 concentration was determined using a NanoDrop Spectrophotometer (NanoDrop  
39 Technologies, Inc., Wilmington, DE).  
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47 Array-CGH analysis can be hampered by the large DNA input requirement: a  
48 minimum of 0.5 µg per sample are needed to process one array-CGH. Most of our  
49 samples were extracted from foetuses, and only a small amount of DNA is often  
50 available. So, when necessary, DNA samples were amplified using a whole genome  
51 amplification method. In this case, control DNA was also amplified in order not to co-  
52 hybridize a native DNA from a control with an amplified DNA from a patient.  
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59 DNA amplification  
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3 DNA samples were amplified using the GenomePlex WGA kit (Sigma product code  
4 WGA2) according to the protocol provided by Sigma. The amount of DNA input into  
5 WGA reactions was 50 ng.  
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#### 10 Array-CGH

11 Array-CGH was performed using the Agilent Human Genome Microarray Kit 44A and  
12 244A (Agilent Technologies, Santa Clara, CA, USA). These are high resolution 60-  
13 mer oligonucleotide based microarrays containing 44,000 or 244,000 60-mers probes  
14 respectively, spanning coding and non-coding genomic sequences with median  
15 spacing of 24 kb and 7.4 kb respectively.  
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19 When using native DNA, both patient and a sex-matched control's DNAs were  
20 separately digested with both AluI and RsaI (Promega, Madison, WI, USA) for 2 h at  
21 37C°. Quality of digestion was controlled on a 1% agarose gel.  
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26 When patient and control DNA were amplified digestion was not necessary as the  
27 WGA method already generates small fragments, and DNA was directly labelled after  
28 purification.  
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#### 33 Labelling

34 DNA concentration was re-controlled using Qubit quantification method (Invitrogen,  
35 Carlsbad, CA, USA) in order to use the same DNA input for the patient and the  
36 control labelling. According to the protocol provided by Agilent (Protocol v4.0, June  
37 2006), the native digested or WGA2 amplified DNA were labelled by random priming  
38 using the Agilent "Genomic DNA Labelling Kit Plus". Patient DNA and control DNA  
39 were labelled with Cy3-dUTP and Cy5-dUTP respectively. Labelled products were  
40 purified by Microcon YM-30 filters (Millipore, Billerica, MA, USA). Finally, patient and  
41 control DNAs were pooled based on equimolar DNA concentration measured with a  
42 Nanodrop ND-1000 spectrophotometer (Nanodrop Technologies, Rockland,  
43 Delaware, USA). The mix was denatured with Human Cot I DNA, and then  
44 hybridized on microarrays at 65 °C for 24 to 48 h in a hybridization oven with a rotator  
45 rack. Washing steps and acetonitrile rinsing were performed according to the Agilent  
46 protocol in an ozone free area. Arrays were analysed using the Agilent scanner  
47 G2565BA and the Agilent Feature Extraction software version 9.1(CGH-v4\_9.1  
48 protocol). The software removed outliers pixels and subtracted local background.  
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3 Normalisation of the data was achieved by linear dye normalisation and log<sub>2</sub> ratios of  
4 the dye-normalized signals were calculated.  
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### 8 **Bioinformatics**

9 Data were imported into Agilent CGHanalytics software version 3.4.27 for analysis.  
10 Identification of probes with a significant gain or loss was based on cut-off values of  
11 0.5 and -1 respectively. Based on CGHanalytics Quality control metrics (QCmetrics),  
12 the arrays included had a Derivative Log Ratio (DLR) spread score under 0,320. The  
13 DLR Spread metrics estimates the log ratio noise by calculating the spread of log  
14 ratio differences between consecutive probes along all chromosomes (Largo, et al.,  
15 2007). DNA sequence information from the software was linked to the public UCSC  
16 database (Human Genome Browser, May 2004 Assembly: Hg18). We only  
17 conserved gains or losses that encompassed at least 3 consecutive spots on the  
18 array. We didn't present in the result table the gains and losses corresponding to high  
19 frequency copy number variation (CNV).  
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29 Based on a quality score for the arrays, we classified them in two groups so that to  
30 select arrays that could enter a transversal analysis using the Nexus Copy Number  
31 software ([www.Biodiscovery.com](http://www.Biodiscovery.com)). Patient CGH files extracted from Feature  
32 extraction were uploaded into the Nexus Copy Number software. This software also  
33 gives a quality score: all arrays with a score under 0.180 (corresponding to 0.320 in  
34 CGH analytics) allowed the transversal analysis without strong interfering  
35 background (that could generate false positive gains or losses). Using this  
36 transversal analysis, we compiled all array data and gave a graphic view of the  
37 combined results (aggregate) where the frequencies of anomalies were represented  
38 by histograms. This aggregate easily pointed out small redundant rearrangements  
39 that resulted either from frequent CNV either from one anomaly of the control DNA  
40 (mirror image in most of the patients). Finally, all gains or losses could be compared  
41 to CNV listed in the database (monthly updated from TCAG) and exported in Tables  
42 (Tables 1, 2 and 3) and Figure 1.  
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54 The aim of this approach was to detect the redundancy of small regions and get a  
55 percentage value to compare with rare CNV frequencies for the same area when  
56 such CNV was already described in databases (TCAG human variation website:  
57 <http://projects.tcag.ca/variation/>).  
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## RESULTS

### ***Search for CNVs in control DNA***

Male and female control DNAs were co-hybridized on a 244K microarray in order to better characterize copy number variants (CNV) that could be present even in these phenotypically normal individuals.

Gains or losses observed in the two control genomic DNA were listed in order to be taken into account in the interpretation of patients' array-CGH results (data not shown).

### ***Array-CGH analysis in patients***

120 patients (70 fetuses and 50 live-born children) were analysed either on a 44K or a 244K Agilent oligonucleotide arrays.

Out of them, 9 presented with a known deletion already detected by qPCR or QMPSF on known genes (*SHH*, *TGIF*, *ZIC2* and *SIX3*) or subtelomeric rearrangements shown by MLPA experiments. They were analysed on 44K arrays.

A first cohort of 37 patients without any karyotypic alterations was also tested with 44K agilent array-CGH and another cohort of 74 HPE patients was secondarily tested on 244K array-CGH as soon as this platform became commercially available.

#### **Patients with known rearrangements**

Out of the 9 patients with known rearrangements analysed on 44K arrays, 7 were fetuses and 2 were live born children. 7 had severe HPE phenotype with alobar or semilobar form. These patients were known to present deletions in known genes like *SHH*, *TGIF*, *ZIC2* and *SIX3*, but array-CGH analysis could give the size of the losses which ranged from 1 gene to 30Mb, and showed that 4 of them had also gain of genomic DNA.

An overview of all imbalances is shown in Table 1.

#### **Patients analysed on 44K arrays**

A first array-CGH analysis on 37 HPE patients was performed, using oligonucleotide 44K Agilent® array. 19 cases were fetuses and 18 were live-born children. Sub microscopic chromosomal imbalances were detected in 9 (5 fetuses, 4 children) out

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3 of them, 6 had an isolated deletions and 3 had duplications. The size of the  
4 imbalances ranged from 50 Kb to 16.9 Mb. (Table 2)  
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### 9 **Patients analysed on 244K arrays**

10 Another cohort of 74 HPE (45 fetuses and 29 live-born children) was then analysed,  
11 using a higher resolution array (244K Agilent®).  
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13 19 patients (12 fetuses, 7 children) out of 74 (26%) presented copy number variations  
14 not described in the CNV databases. These rearrangements are more frequently  
15 deletions as 12 patients had an isolated or associated loss. 11 patients had isolated  
16 or associated duplications. The size's range of the imbalances is very large, from 300  
17 Kb to 16.5 Mb (Table 3).  
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### 24 ***Nexus study***

25 Compiling 90 arrays (quality score below 0,180) in the Nexus study, the aggregate  
26 pointed out 2 regions overlapping known CNV but with a higher recurrence than what  
27 was reported in CNV databases. The first locus included two genes: *MACROD2* and  
28 *FLRT3* in 20p12.1. The second one included the gene *TPPP* in 5p15.3.  
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## 34 **DISCUSSION**

35 This study is the first series of HPE patients to be screened for chromosomal  
36 imbalances with high resolution oligonucleotide microarrays. In a total of 111 patients  
37 with normal karyotype, 28 were detected with chromosomal imbalances (25%). This  
38 unexpected high frequency, whatever the size, location and redundancy of the  
39 rearrangements, demonstrates that CGH is mandatory to detect submicroscopic  
40 molecular defects; consequently, adding these anomalies to the results of the classic  
41 diagnosis screening of isolated HPE, the rate of identified molecular defects could  
42 exceed for the first time 50% of cases.  
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### 52 ***Methodology***

#### 53 **Control DNA**

54 We decided to use genomic DNA from one normal male 46,XY and one normal  
55 female 46,XX as controls. Indeed, it seemed to us that it was easier to validate the  
56 CNVs status of these two DNA samples and thus avoid false positive or negative  
57 results in our series. A similar strategy was chosen by Carter et al (Carter, 2007),  
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3 who selected NA15510, the source of fosmid library used to confirm genome  
4 assembly during the finishing of the human genome, and NA10851, a well  
5 characterized cell line DNA from the Hap-Map collection.  
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### 9 **CNV interference**

10 Results need to take into account the presence of potential copy number variants  
11 (CNV) present in the normal human genome. Indeed, the recent appreciation of  
12 widespread copy number variation in genomes of healthy subjects was a significant  
13 challenge for teams that wished to use array-CGH in order to correlate chromosomal  
14 imbalances and diagnosis of constitutional disorders. Public available databases that  
15 accumulate CNV data on hundreds of healthy individuals are now available. So we  
16 systematically compared our results to the Database of Genomic Variants (DGV)  
17 (<http://projects.tcag.ca/variations>), which in June 2008 contained 17641 CNVs entries  
18 from 49 different published studies using different array platforms and healthy human  
19 groups; most of these CNVs range from 40 to 100 kb (Carter, 2007). The referenced  
20 CNVs could account for over 20% of the human genome. Of course, this database  
21 should be considered with great caution, especially when these CNVs are reported  
22 only in a single individual out of hundreds what should definitely not deny any morbid  
23 role for such locus. Every month, new CNV data are described in the literature, so it  
24 is very difficult to consider all these data and to appreciate their accuracy. In our  
25 Nexus study, we pointed out two loci of interest based on a higher frequency than  
26 what could be found in CNV database:  
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28 A first chromosomal region presented 4 gains and 5 losses in HPE patients, covering  
29 mostly 150 Kb, in 5p15.3. This redundant rearranged region contains a candidate  
30 gene, TPPP, expressed in adult brain and often described in Alzheimer papers.  
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32 A second one was located in 20p. Indeed, among 110 HPE patients, 4 presented  
33 rearrangement at 20p12.1, 3 losses and 1 gain. These rearrangements spanned over  
34 several closed regions, all concerning one or several exons of *MACROD2* gene  
35 (*C20orf133*) (Figure 1) whose embryonic expression pattern in the mouse orthologue  
36 is compatible with a role in holoprosencephaly (Maas, et al., 2007). This gene  
37 contains a nested gene in its third exon, called *FLRT3*, coding a fibronectin leucin-  
38 rich repeat transmembrane protein, which could be a conserved Nodal target.  
39 Indeed, loss of function in the *FLRT3* gene leads to defects in ventral closure,  
40 headfold fusion and definitive endoderm migration (Maretto, et al., 2008).  
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3 A deletion of MACROD2 was previously found in one patient with Kabuki syndrome  
4 (KS) ; sequencing of 19 other KS patients did not reveal any mutation in MACROD2  
5 discarding this gene as a unique candidate gene for KS (Maas, et al., 2007).  
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8 To confirm that the rearrangements observed in our 4 patients were not benign CNV,  
9 the different database reporting these large-scale polymorphisms were investigated  
10 and unlike the Maas paper data, we could determine that they overlapped described  
11 CNVs. Moreover, Kuniba et al recently described the results of a deletion assay for  
12 the exon 5 in MACROD2 and a mutation analysis of MACROD2 and FLRT3 among  
13 43 patients with KS in Japan (Kuniba, et al., 2008). They also showed that 2 patients  
14 out of 18 presented copy number variations in this region, and concluded that  
15 MACROD2 and/or FLRT3 could not be the causative gene in most Japanese KS  
16 patients.  
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19 These two papers and our own analysis demonstrate that one should be very  
20 cautious about the involvement of genes in diseases without an achieved CNV  
21 database to analyze the results.  
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### 25 26 27 28 29 30 31 32 33 **Minimal size to be considered**

34 Currently available data suggest using a DNA size cut-off for a positive result. To  
35 avoid listing many anomalies (small CNV or background noise related to one or two  
36 consecutive spots on the array), we chose that all data presented in tables must  
37 result from three consecutive co-deleted or co-duplicated probes on the 44K or 244K  
38 arrays to produce strong evidence of any genomic defect; consequently their  
39 respective resolution can be estimated to 48kb and 14.8kb respectively.  
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43 This compromise is not perfect as this cut-off of 3 spots on the 44K array would have  
44 led us to discard a deletion located only on *SIX3* gene (Table 1) and involving only  
45 one spot, if we had not been aware of its existence based on previous specific  
46 studies (Bendavid, et al., 2006a).  
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### 55 **Impact of array resolution**

56 We used the oligonucleotide 44K Agilent® arrays to test 37 HPE patients (19  
57 fetuses and 18 live-born children). Sub microscopic chromosomal imbalances were  
58 detected in 9 out of them (24%), 6 deletions and 4 duplications (Table 2). Another  
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3 cohort of 74 HPE (45 fetuses and 29 live-born children) was then analysed, using  
4 244K Agilent® arrays. 19 patients out of 74 (26 %) presented rearrangements.

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6 When using the high resolution arrays, the rate of detected rearrangements modestly  
7 raises (26% versus 24%). This suggests that the resolution of the 44K arrays could  
8 be sufficient for routine screening of HPE patients. On the opposite, the higher rate of  
9 small deletions detected by 244K needs more data compiling (based on Nexus  
10 software to point out the more frequent anomalies and exclude putative CNV). In  
11 routine diagnosis, the cost of the 244K array versus its modest raise of the detection  
12 rate could certainly limit the CGH approach to the 44K array.  
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### 24 **Patient's results**

#### 25 26 **Identified loci were heterogeneous in size and poorly redundant, but** 27 **large anomalies were preferentially found in fetuses**

28 Previous data suggested that deletions in known genes (*SHH*, *SIX3*, *ZIC2* and *TGIF*)  
29 were more frequent in fetuses than in children, who, on the opposite, presented a  
30 higher rate of mutations (Bendavid, et al., 2006a; Bendavid, et al., 2006b). The  
31 present study corroborates this hypothesis as 17 chromosomal rearrangements were  
32 observed in fetuses (61%) versus 11 in children (39%).  
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38 The structural variations observed in our cohort present a wide range of sizes.

39 We first determined the precise size of rearrangements in samples known to be  
40 deleted for HPE genes (*SHH*, *TGIF*, *SIX3* and *ZIC2*) by qPCR, QMPSF or MLPA or  
41 by high resolution karyotype (Table 1). The patient (N°8) with a deletion of *TGIF* in  
42 18p shown by quantitative PCR (Bendavid, et al., 2006a) had in fact a 10 Mb loss of  
43 telomeric genomic DNA. Deletions in 13q including *ZIC2* ranged from 1.7 Mb to 30.7  
44 Mb, while those including *SHH* in 7q ranged from 3 Mb to 7 Mb. The severity of the  
45 phenotype seems to be correlated with the size of the deletion, if we consider that  
46 wider rearrangements are mostly found in fetuses with alobar or semi-lobar HPE,  
47 while the smaller ones (even concerning a single probe like the patient (N°1) with  
48 isolated *SIX3* deletion) were preferentially observed in live-born children, with lobar  
49 HPE accompanied with minor signs. Nevertheless, phenotype/genotype correlation is  
50 not straight as children with typical HPE do not have a higher rate of rearrangements  
51 than children with minor signs.  
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## Parental analysis

In our series, out of 28 patients with gains or losses, both parents could be tested in 21 cases (focusing on 26 rearrangements). The aim of this parental analysis was to further modulate the role of these rearrangements in phenotype onset based on their inheritance.

Therefore, we postulated first that all anomalies found isolated (not associated with a mutation) and that raised de novo in the proband would be the more likely to be involved in the phenotype. Second, all anomalies found isolated but inherited from one parent would be part from a genetic background and may only act with a variable penetrance or with an associated factor. Finally, if found associated with a mutation and inherited from one parent, the anomaly would more likely be a very minor modulator.

In our series, 9 patients had at least one gain or loss inherited from one parent; 8 were duplications whereas only 3 were deletions (patients N° 23, 30 and 32). In 6 patients (N° 18, 21, 27, 30, 32 and 37), rearrangements were associated to mutations. Therefore, no definitive conclusion about the involvement of these different regions can be given.

On the opposite, out of the 11 patients with de novo gains or losses, we had 9 deletions and only 4 duplications. 8 involved known HPE loci: 2p (SIX3), 7qter (SHH), 13q (ZIC2), 18pter (TGIF), 20pter and 21qter. This reinforces the implication of loci like 20pter or 21qter in HPE but also gives new candidate loci with regions not previously involved in the disease: 1q, 6q, 7p, 10q, 14q and 17q. The 14q del was already reported by Kamnasaran et al in 2005 as a putative HPE loci (Kamnasaran, et al., 2005). The two overlapping 6q del are also particularly interesting as they mapped a new locus that appeared twice de novo.

It's worth noting that one patient (N°25) presents a *SHH* locus duplication. This could be associated with a *SHH* gain of function, what has never been described before in HPE. Nevertheless, this defect was also found in the mother (normal phenotype). *SHH* gains of function are usually associated with basocellular carcinoma that have not been described to date in this family. On another hand, this rearrangement may cause a *SHH* loss of function based on the modification of the chromatin environment. Further investigations on *SHH* expression in this family should be overtaken.



### Update of HPE loci map

The major aim of our research is to identify candidate regions, map them (Figure 2) and thus extract new HPE candidate genes. Because of the large number of non redundant loci found and the large number of genes covered, it was not relevant to list every candidate gene that could be hypothesized out of these regions. Nevertheless, our results are a milestone in further genetic research and diagnosis in HPE. Effectively, an important bioinformatics investigation on these regions can therefore be performed, based on gene networks and known functional studies results in order to prioritize the best candidate regions and genes out of our data.

Today, only one region could be easily hypothesized as it showed a redundancy in 4 patients who presented a deletion of about 100Kb without overlap with CNVs in the TCAG database to date. This region is located in 10p12.1 and contains a candidate gene, *PATCHED3*, belonging to the *PATCHED* family, receptor of *SHH*, one of the main HPE genes. Nevertheless, we could investigate the parents for one case (N°30) and the deletion was inherited from the father, knowing that furthermore the father also transmitted a *SHH* mutation. Another case (N°27) with no parental study also had an associated *SHH* mutation. Consequently, a role for *PATCHED3* is questionable and it's difficult to consider it as a strong modulator making the fetus phenotype worse than his father's.

### CGH use in routine diagnosis

For diagnosis, this study demonstrates that the CGHarray approach must be another part of the molecular routine so that to get as much potential markers of the disease as possible to help the genetic counseling. In our experience, this method has been very helpful in the identification of unbalanced subtelomeric anomalies (as MLPA for subtelomeres but with the advantage of determining the breakpoints in the same time) and led to identification of parental cryptic balanced translocations by FISH.

Finally, this study also reinforces the multi-hit hypothesis showing 16 patients with associated gains and losses or rearrangements and mutations. The patients (with severe phenotype) with known mutations inherited from one parent (with mild phenotype) plus a gain and/or a loss are a strong example of what could be considered as a genetic background helping the mutation penetrance.

## Conclusion

This is the first study screening a large cohort of isolated HPE by CGHarray. Results demonstrated a high frequency of submicroscopic anomalies with yield of 25%. These anomalies are heterogeneous in size and poorly redundant, what give even more evidence of the multi and plurigenic origin of this developmental disorder. The map of these anomalies added to known candidate loci will certainly help to associate potential candidate genes from developmental research with the human disease. This study also demonstrates that CGH must be part of the molecular diagnosis algorithm to help clinicians to get more disease markers for the difficult HPE genetic counseling.

## Databases

Database of Genomic Variants (<http://projects.tcag.ca/variations>),  
Human Genome Browser, (May 2004 Assembly: Hg18).  
Nexus Copy Number software ([www.Biodiscovery.com](http://www.Biodiscovery.com))

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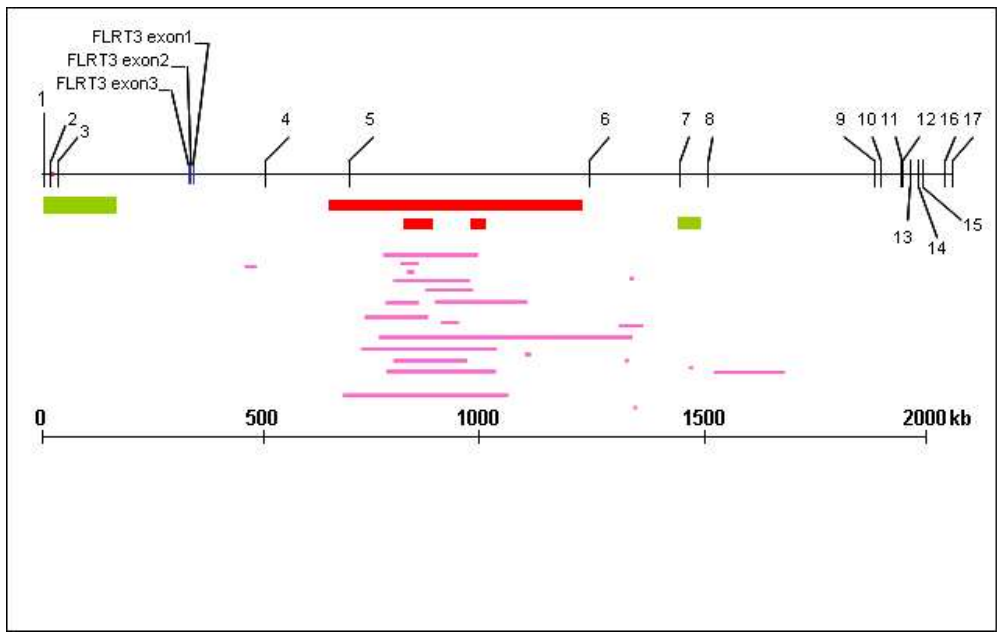
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**Figure 1:** Schematic view of the exons and introns of MACROD2 and FLRT3 genes. MACROD2 contains 17 exons and is 2057697 bp size. It contains in the third intron the FLRT3 gene. This three exons gene is 13628 bp in size. Red lines indicate deletion of patients, Green line indicate duplication. Positions of CNVs are represented by pink lines (updated in June 2008).

**Figure 2:** This figure represents all chromosome ideograms with: 1) in yellow, on the left of each ideogram, all related known HPE loci included in Roessler et al (1998) and 14q loci from Kamnasaran and al (2005) papers. 2) in green all gains found in our cohort 3) in red all losses found in our cohort. Gains and losses are associated with the patient numbers that can be found in tables 2, 3 and 4.

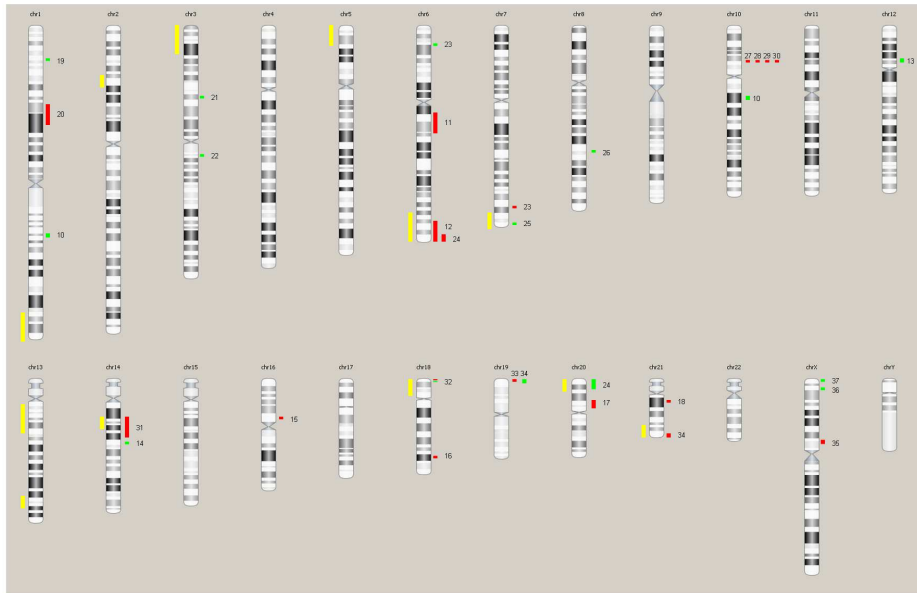
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: Schematic view of the exons and introns of MACROD2 and FLRT3 genes. MACROD2 contains 17 exons and is 2057697 bp size. It contains in the third intron the FLRT3 gene. This three exons gene is 13628 bp in size. Red lines indicate deletion of patients, Green line indicate duplication. Positions of CNVs are represented by pink lines (updated in June 2008).  
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**Table 1: CGH analysis in 9 patients with known defects**

Patient	Phenotype	F / C	Sexe	Anomalies	Start-End	size (Mb)	sequencing
1	lobar	C		Del 2p	45022541-45025894	Only six3 gene	
2	lobar	C	M	Del 5qter	177354922-ter	3,5	
				Dup 17q	70880633-ter	7,9	
3	alobar	F		Dup 7pter	0-6167900	7	
				Del 7qter	152087784-ter	7	
4	semi lobar	F	F	Del 7q	154943585- 1578473434	3	
				Dup 8p	0-409876	0.4	
5	syndromic HPE	F	F	Del 7qter	152232455-ter	6,2	
6	semi lobar	F	M	Del 13q	98323528-100026969	1,7	
7	alobar	F	M	Del 13q ter	83266096-ter	30,7	
8	semi lobar	F	M	Del 18pter	66272268-ter	10	
9	alobar	F	M	Del 20p	0-8268492	8,2	
	cardiac anomalies			Dup 21q	35804023-ter	11	

**Table 2: Summary of copy number changes detected by 44K array CGH (short clinical description and associated mutations in HPE genes)**

Patient	Phenotype	F / C	Sexe	Anomalies	Start-End	taille (Mb)	sequencing
10	semi lobar	F	F	Dup 1q	165319168-165662668	0,3	
				Dup 10q	59312961-60086986	0,8	
11	minor signs	C	M	Del 6q	69637936-86100038	16,9	
12	Semi lobar	F	F	Del 6q	155166802-ter	15,7	
13	semi lobar	C	M	Dup 12p	26727022-27427780	0,8	
14	lobar, polymalformations	F	M	Dup14q	49150663-49200220	0,05	
15	syndromic HPE	C	F	Del 16p	29407325-30255748	0,85	
16	semi lobar	F	M	Del 18q	62405035-63364892	1	
17	alobar	F	F	Del 20p	18377837-23793823	5,4	
18	semi lobar	C	F	Del 21q	19024763-20666763	1,6	Zic2 de novo



**Table 3: Summary of copy number changes detected by 244K array CGH (short clinical description and associated mutations in HPE genes)**

Patient	Phenotype	F / C	Sexe	Anomalies	Start-End	Size (Mb)	sequencing
19	lobar	C	M	Dup 1p	26866731-27930229	1,06	
20	minor signs	C	F	Del 1p	61656706-77968936	16,4	
21	semi lobar	F	M	Dup 3p	54969531-55519135	0,55	SHH paternal
22	alobar	F	F	Dup3q	101837302-101896892	0,6	
23	minor signs	C	F	Del 7q	142530842-142603299	0,7	
				Dup 6p	13251543-13558381	0,3	
24	minor signs	C	M	Del 6qter	165767853-ter	5,2	
				Dup 20pter	0-7967454	8	
25	semi lobar	F	M	Dup 7q	154623987-155557785	0,93	
26	minor signs	C	F	Dup 8q	98220486-98365015	0,15	
27	minor signs	C	M	Del 10p	27656534-27753830	0,10	SHH
28	lobar	F	M	Del 10p	27645595-27754606	0,11	
29	alobar	F	F	Del 10p	27645595-27754606	0,11	
30	lobar + familial form	F	M	Del 10p	27645595-27754606	0,11	SHH paternal
31	alobar	F	F	Del 14q	29960612-46532138	16,5	
32	alobar	F	M	Del 18p	0-602022	0,6	
				Dup 18p	1707459-1834111	0,13	Zic2 ( <i>de novo</i> )
33	semi lobar	F	M	Del 19p	0-402006	0,4	
34	minor signs	C	F	Dup 19p	0-1124473	1,1	
				Del 21q	44012487-ter	2,9	
35	semi lobar	F	F	Del Xp	48145179-52507792	4,4	
36	minor signs	F	F	DupXp	7542546-8091810	0,5	
37	alobar	F	M	Dup Xp	2709755-2923910	0,3	2 in Zic2

**Table 4: Study of inheritance in 21 probands (out of 31) whose both parents were available for analysis. Gene dosage was performed (QMPSF or MLPA or CGH) in the parents to check if the remaniement was inherited. Out of three patients with subtelomeric gain and loss, FISH was only performed in one case and confirmed a balanced translocation in one parent.**

Patient	anomalies	mutations		remaniement	
		father	mother	father	mother
10	Dup 1q	No	No	No	No
	Dup 10q	No	No	No	No
1	Del 2p	No	No	No	No
21	Dup 3p	Yes	no	Yes	No
22	Dup3q	No	No	Yes	No
23	Dup 6p	No	No	No	Yes
	Del 7q	No	No	No	Yes
11	Del 6q	No	No	No	No
12	Del 6q	No	No	No	No
3	Del 7qter	No	No	No	balanced
	Dup 7pter	No	No	No	balanced
25	Dup 7q	No	No	No	Yes
26	Dup 8q	No	No	No	Yes
30	Del 10p	Yes	No	Yes	No
13	Dup 12p	No	No	Yes	No
6	Del 13q	No	No	No	No
7	Del 13q ter	No	No	No	No
31	Del 14q	No	No	No	No
2	Dup 17q	No	No	No	No
32	Del 18p	No	No	Yes	No
	Dup 18p	No	No	Yes	No
8	Del 18pter	No	No	No	No
9	Del 20p	No	No	No	No
	Dup 21q	No	No	No	No
18	Del 21q	No	No	No	No
36	DupXp	No	No	Yes	No