

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Array-Comparative Genomic Hybridization Analysis in Fetuses with Major Congenital Malformations Reveals that 24% of Cases Have Pathogenic Deletions/Duplications

This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1563470> since 2017-12-02T23:11:08Z

Published version:

DOI:10.1159/000442308

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)



UNIVERSITÀ DEGLI STUDI DI TORINO

This is an author version of the contribution published on:

Questa è la versione dell'autore dell'opera:

[Cytogenet Genome Res. 2015;147(1):10-6. doi: 10.1159/000442308]

The definitive version is available at:

La versione definitiva è disponibile alla URL:

[<http://www.karger.com/Article/FullText/442308>]

ORIGINAL ARTICLE

Array-CGH analysis in fetuses with major congenital malformations reveals that 24% of cases have pathogenic deletions/duplications.

Eleonora Di Gregorio^{a,b*}, Giorgia Gai^{b*}, Giovanni Botta^c, Alessandro Calcia^a, Patrizia Pappi^b, Flavia Talarico^b, Elisa Savin^b, Marisa Ribotta^c, Andrea Zonta^b, Cecilia Mancini^a, Elisa Giorgio^a, Simona Cavalieri^a, Gabriella Restagno^b, Giovanni Battista Ferrero^d, Elsa Viora^e, Barbara Pasini^{a,b}, Enrico Grosso^b, Alfredo Brusco^{a,b*}, Alessandro Brussino^{a*}

^a University of Torino, Department of Medical Sciences, Turin, 10126, Italy

^b Città della Salute e della Scienza University Hospital, Medical Genetics Unit, Turin, 10126, Italy

^c Città della Salute e della Scienza University Hospital, Department of Pathology, Turin, 10126, Italy

^d University of Torino, Department of Public Health and Pediatrics, Turin, 10126, Italy

^e Città della Salute e della Scienza University Hospital, Department of Gynecology and Obstetrics, Ultrasound and Prenatal diagnosis Unit, Turin, 10126, Italy

Corresponding author: Alfredo Brusco, University of Torino, Department of Medical Sciences, via Santena 19, 10126, Torino, Italy. Fax +390116706582; e-mail: alfredo.brusco@unito.it

*These authors equally contributed to the work

Keywords: array-CGH, copy number variants, fetal malformations, genomic rearrangement, multiple chromosomal rearrangements

Running title: Array-CGH analysis in fetuses

ABSTRACT

Karyotype and array Comparative Genomic Hybridization (a-CGH) are routinely used to identify genetic determinants of major congenital malformations (MCMs) in fetal deaths or terminations of pregnancy after prenatal diagnosis. Pathogenic rearrangements are found with a variable rate of 9 to 39% for a-CGH. We collected 33 fetuses, nine with a single MCM and 24 with MCMs involving two to four organ systems. Array-CGH revealed Copy Number Variants (CNVs) in 14 out of 33 (42%) cases. Eight were classified as pathogenic: this equals a detection rate of 24% (8/33) considering fetuses with one or more MCMs, and 33% (8/24) taking into account fetuses with multiple malformations only. Three of the pathogenic variants were known microdeletion syndromes [22q11.21 deletion, central chromosome 22q11.21 deletion and Thrombocytopenia Absent Radius (TAR) syndrome] and five were large rearrangements, amounting up to >11 Mb per subject, and spanning strong phenotype-related genes. One of those was a *de novo* complex rearrangement. The remaining four duplications and two deletions were 130-900 kb in size, containing 1 to 7 genes, and were classified as variants of unknown clinical significance (VOUS). Our study confirms a-CGH as a powerful technique to ascertain the genetic etiology of fetal major congenital malformations.

INTRODUCTION

There is no consensus for defining major and minor Congenital Malformations (CMs). Commonly accepted definitions describe major anomalies (MCM) as “anatomic abnormalities that are severe enough to reduce life expectancy or compromise normal function”. Minor anomalies are “unusual morphologic features that are of no serious medical or cosmetic consequence to the patient”. They may be indicative of a more generalized altered morphogenesis or may represent a valuable indication for identifying a specific malformative syndromes (Kennet 2005; Kumar and Burton 2007).

Data from the EUROCAT network established a prevalence of MCMs in Europe of 2.6% between 2008 and 2012, including live births (2.1%), and fetal deaths/terminations of pregnancy after prenatal diagnosis (0.5%). Around 18% of MCMs were ascribed to known genetic conditions (<http://www.eurocat-network.eu>).

The genetic etiology of MCMs is widely variable: monogenic syndromes are estimated to account for 2-10% of cases, whereas chromosomal abnormalities are found in 10-15% of liveborn with MCMs (Stevenson 2006) and in 9-39% of fetuses with abnormal ultrasound findings, depending on the presence of a single anomaly or multiple malformations (Rizzo et al. 1996; Saldarriaga et al. 2015; Tseng et al. 2006; Wilson et al. 1992; Yashwanth et al. 2010). Subtelomeric deletions are present in around 5% of patients with multiple CMs associated with mental retardation (Koolen et al. 2004). Retrospective studies using array-Comparative Genomic Hybridization (a-CGH) in fetuses with multiple malformations report a detection rate of pathogenic chromosomal imbalances from 8 to 18% and a 10%-increase in the diagnostic yield of chromosomal microarray over karyotyping (95% confidence interval)(de Wit et al. 2014; Hillman et al. 2013; Le Caignec et al. 2005; Schaeffer et al. 2004; Tyreman et al. 2009; Vialard et al. 2009). It is estimated that ~50% of CMs have an unknown etiology (Rajangam and Nanjappa 2007).

In this work, we evaluated the detection rate of a-CGH analysis in identifying pathogenic chromosomal deletions/duplication in a group of fetuses with single or multiple CMs.

Materials and Methods

Cases and anatomopathological evaluation

Between January 2010 and September 2013 at the “Città della Salute e della Scienza di Torino” University Hospital, approximately 960 fetuses underwent autopsy following spontaneous abortions, intrauterine/neonatal deaths, and Termination Of Pregnancy for Fetal Anomalies (TOPFA). Fetal autopsy included evaluation of external appearance, measurement of morphometric parameters, examination of thorax and abdominal anatomy, and histological examination of main organs and pathological tissues. Skeletal X-ray analysis was performed on each fetus. Fetuses with suspicious infective causes of anomalies were excluded by placental examination. Excluding cases suggestive of a monogenic disease or a non-genetic origin, we selected 49 fetuses with MCMs. Sixteen a-CGH analyses failed due to the inadequate quality of genomic DNA. The remaining 33 analyses were performed on 9 fetuses with one major malformation and 24 with two or more major malformations. The study was approved by the Internal Review Board, and informed consent was obtained from parents of the analyzed fetuses.

Karyotyping and array-CGH analysis

Karyotyping on GTG-banded chromosomes (≥ 400 bands) was performed on chorionic villus sampling, amniotic fluid, or fibroblasts. Genomic DNA was extracted from fetal frozen tissues using the DNeasy Blood & Tissue kit (Qiagen, Hilden, Germany) following the manufacturer’s instructions. Array-CGH was performed using a 60K whole-genome oligonucleotide microarray following the manufacturer’s protocol (Agilent Technologies, Santa Clara, California, USA). Slides were scanned using a G2565BA scanner, and analyzed using Agilent CGH Analytics software ver.

4.0.81 (Agilent Technologies Inc.) with the statistical algorithm ADM-2 and a sensitivity threshold of 6.0. Significant copy-number changes were identified by at least three consecutive aberrant probes. Reference human genomic DNA was GRCh37/hg19. We followed pathogenicity criteria for CNVs as reported in the reference (Kearney et al. 2011).

Sequencing analysis

In patient DGT300197, we screened two SNPs in the 5-prime UTR (rs139428292: G>A) and in the first intron (rs201779890: G>C) of the RNA binding motif protein 8A (*RBM8A*) gene by Sanger sequencing. The following PCR conditions were used: 10 µMol primers (5'- gcctttgattggtcagcttg; 5'- aagggggcggaatctctaat), 200 µMol dNTPs, 60 ng of genomic DNA, and 0.5 unit of KAPA-fast 2G kit (Kapa Biosystems, Inc., MA, USA) in a 25 µl final volume under standard amplification conditions (56°C annealing temperature). PCR products were purified using Agencourt AMPure XP-PCR Purification (Beckman Coulter, Miami, FL, USA) and sequenced with the Big Dye v3.1 kit (Applied Biosystems, Foster City, CA, USA). Products were purified using Agencourt CleanSEQ-Dye Terminator Removal (Beckman Coulter) and run on an ABI-3730 platform, using the POP7 polymer (Applied Biosystems).

Results

Standard karyotype analysis was negative on fetal tissue samples, with the exception of nine in which the analysis was not possible due to culture failure. Using a-CGH, we identified one or more Copy Number Variants (CNVs) in 14 cases (14/33, 42%). Eight were classified as pathogenic: this equals to a detection rate of 24% (8/33) considering fetuses with one or more CMs, and 33% (8/24) taking in account fetuses with multiple malformations only. Among the eight pathogenic variants, three were associated with known microdeletion syndromes: a chromosome 22q11.21 deletion syndrome (MIM 188400), a central chromosome 22q11.21 deletion syndrome (Rump et al. 2014),

and a Thrombocytopenia Absent-Radius (TAR) syndrome (MIM 274000; Table 1, cases 1-3). The majority of TAR patients are compound heterozygous for a deletion on 1q21.1 encompassing the *RBM8A* causative gene, and a low-functioning SNP in either its 5'UTR or intron 1 (Albers et al. 2012). By sequencing analysis in our TAR case, we identified one of those variants, the hypomorphic "C" allele at SNP rs#201779890 on intron 1 of the non-deleted allele.

In the other five pathogenic CNVs, the extension of the total rearrangements per subject (11-41 Mb), and the number and the type of genes involved allowed the clear classification of the CNV as pathogenic (Table 1, subjects 4-8).

Cases 4 and 5 are already detailed in (Di Gregorio et al. 2014) as examples of cryptic large CNVs (>6 Mb) undetectable by conventional karyotyping.

Briefly, fetus 4 showed a complex phenotype, displaying partially overlapping features with Cornelia de Lange syndrome (MIM 122470). We found two large telomeric rearrangements: a 3q29 duplication (13.4 Mb) associated with the Cornelia de Lange phenotype (Dundar et al. 2011; Holder et al. 1994), and a 15q26.1q26.3 deletion (11.5 Mb) encompassing the minimal region of the 15q26-qter deletion syndrome (MIM 612626).

Case 5 carried two duplications on chromosome 7p22.3p22.2 and 7p22.1p21.2, and a deletion of chromosome 11q24.1q25. The duplication of the short arm of chromosome 7 causes a characteristic pattern of malformations including developmental, craniofacial, skeletal and cardiovascular anomalies, the severity of which depends on the size of the duplication (Papadopoulou et al. 2006). The neuronal migration defect could be explained by the deletion of Cell Adhesion Molecule-Related/Downregulated By Oncogenes (*CDON*, MIM 608707) and Kin of IRRE-like 3 (*KIRREL3*, MIM 607761) on chromosome 11, which are two genes involved in the control of neuronal migration and axon guidance (Bhalla et al. 2008; Okada et al. 2006). The cardiac phenotype (hypoplastic left heart) is likely to be part of the Jacobsen syndrome spectrum (MIM 147791), due to the 11q23 deletion (Grossfeld et al. 2009).

In case 6, we found six *de novo* duplications ranging from 37 kb to 4.8 Mb, with a total of 15.9 Mb, involving six different chromosomes. Among these, the 2q31.1 duplication spanned the *HOXD* gene cluster, a family of highly conserved transcription factors involved in the antero-posterior development of the limb and in the specification of fingers (Johnson et al. 2003; Johnson et al. 1998; Kessel and Gruss 1990), and could explain the polydactyly and digital shape anomalies in the fetus. Over-expression of *HOXD10* in mice cause polydactyly, whereas the duplication of the *HOXD* gene cluster modifies finger-shape and number in mice (Sheth et al. 2007; Tarchini et al. 2006; Zakany et al. 2004). The other five identified rearrangements could not be clearly related to the remaining clinical features. Moreover, a-CGH analysis in parents showed a 1.8 Mb duplication on chromosome 2q12.3q13 in his father.

Case 7 carried a large 13.5 Mb deletion of chromosome 15q25.3q26.3, partially overlapping with the 15q26-qter deletion syndrome region (MIM 612626). This fetus and patients carrying 15q26-qter deletion show micrognathia, which is part of the Robin sequence (Roback et al. 1991; Tonnie et al. 2001). Furthermore, the same region is associated with diaphragmatic hernia, also present in our case (MIM 142340)(Castiglia et al. 2005; Klaassens et al. 2007; Klaassens et al. 2005; Mosca et al. 2011). *IGF1R* and *ARRDC4* have been identified as the strongest candidates for this phenotype, because both are expressed in the developing diaphragm. Nasal bone agenesis could be explained by genes in the centromeric segment non-overlapping 15q26-qter deletion.

Case 8 showed a 11.4 Mb deletion on chromosome 3p14.2p13. One of his key features was the presence of a congenital heart defect (CHD, Table 1): assessing the pathogenicity of a CNV associated with CHD is not always straightforward, as many deletions/duplications encompass genes that are not clearly related to cardiac development (Richards and Garg 2010). A notable gene present in the deleted region was Forkhead Box P1 (*FOXP1*, MIM 605515), which is critical for heart development and was found to be deleted in a patient with an atrioventricular septal defect (Chang et al. 2013). Moreover, a rare contiguous gene syndrome has been described in patients

carrying a chromosome 3p14 deletion: key features of this syndrome include short stature, dysmorphisms, CHD, developmental delay, urogenital and neurological problems (Dimitrov et al. 2015). Interestingly, scrotal hypoplasia in the fetus might be explained by the deletion of the Prokineticin 2 gene (*PROK2*, MIM 607002), whose point mutations cause Kallmann syndrome type 4 (Dode et al. 2006), a disease featuring hypogonadotropic hypogonadism with testicular/scrotal atrophy (MIM 610628). A second candidate was the testis-expressed G-protein coupled receptor 27 (*GPR27*, MIM 605187), whose function is still poorly defined. Clenched hands in the fetus could be explained by the deletion of Forkhead Box Protein P1 (*FOXPI*) as hypothesized in a patient with limb contractures, speech delay, hypertonia and blepharophimosis carrying a 785-kb *de novo* 3p14 deletion: *FOXPI* haploinsufficiency may be involved in defects of motor neuron development resulting in limb contractures (Pariani et al. 2009).

Among the analyzed fetuses 6/33 (18%) carried CNVs ranging from 130-900 kb (four duplications and one deletion), classified as variants of unknown clinical significance (VOUS), which contained 1-7 genes. Segregation of the identified variants could not be assessed. In these regions, no obvious candidate gene could be associated with fetuses clinical features.

Discussion

In the recent years, about twenty studies have examined the potential impact/pathogenicity of CNVs in fetal malformations in prenatal diagnostic setting or after terminations of pregnancy (de Wit et al. 2014; Papoulidis et al. 2015; Srebniak et al. 2015). The proportion of clinically relevant findings is highly variable (from 4.3 to 18%) (de Wit et al. 2014; Papoulidis et al. 2015; Srebniak et al. 2015) reaching 24% with our study. Discrepancies among studies may be due to different technical platforms, different selection criteria, the size of the sample or the inclusion of VOUS among the identified CNVs. Based on the reported data, selection criteria are particular relevant: among our 24

cases with multisystem anomalies (2 to 4 organ systems), we found 13 cases with a positive a-CGH result (54%), and eight of these had true pathogenic variants (33%).

Notably, four of the eight cases carried at least one rearrangements above 10 Mb, which was undetected by conventional chromosomal analysis. Their loss may be due to the low karyotype resolution on chorionic villi or fetal fibroblasts, or to cryptic rearrangements as described by (Di Gregorio et al. 2014). Indeed, in a recent meta-analysis such large anomalies were excluded from the reported results, lowering the percentage of a-CGH detection (de Wit et al. 2014). Using these criteria, we would estimate a 15% of pathogenic copy number variations detected by a-CGH, in line with published data.

We classified as VOUS all the rearrangements without obvious biological effect, absent in the DGV database, and/or those for which it was not possible to perform segregation analysis.

Our results showed a higher percentage of VOUS in comparison to reported studies, where the detection rate ranged from 0.5 to 1.7% (Brady et al. 2014; Papoulidis et al. 2015). This discrepancy may be due to: 1) VOUS definition, considering that some group does not report rearrangements containing no genes (Brady et al. 2014); 2) array resolution (e.g., BAC array vs. oligonucleotide-array); 3) lack of knowledge about *de novo* vs. inherited VOUS, which are often considered benign if inherited from an healthy parent, especially if gene-devoid; 4) the presence of pathogenic copy number variants among VOUS: two of the detected VOUS were >500 kb, above an indicative limit of pathogenicity of 400 kb (Miller et al. 2010) and one contained 7 genes.

Genetic counseling to couples after termination of pregnancy due to a fetal malformation is particularly difficult. Phenotypic diagnosis is often impossible, and karyotype analysis has a limited detection rate.

Array-CGH data in our report demonstrate that the presence of pathogenic CNVs can allow a more precise evaluation of the recurrence risk. This was particularly important for cases in which the

derivative of a cryptic rearrangement present in one of the parents was identified (cases 4 and 5), or for the known 22q11.21 and TAR syndromes (cases 1, 2 and 3), which are associated with a significant recurrence risk, giving the possibility of an early prenatal test in subsequent pregnancies. Array-CGH using genomic DNA allows overcome tissue culture difficulties and the low resolution of prenatal/fetal karyotypes. Furthermore, balanced rearrangements undetectable at a-CGH (e.g., a translocations/insertions) are very unlikely causes of fetal malformations, suggesting this method to be suitable as a first tier analysis (Astbury et al. 2004). ~~However, given the high cost of the technique PCR-based Rapid Aneuploidy Detection should be recommended before a CGH.~~

In conclusion, we confirm a-CGH as a powerful technique to identify pathogenic chromosomal rearrangements in fetuses with MCMs, with a higher detection rate proportional to MCMs severity.

Acknowledgments

This work was funded by the Associazione Studio Malformazioni (to A. Brussino) and MURST 60% (to A. Brusco). This study utilizes data generated by the DECIPHER Consortium. A full list of centers who contributed to the generation of the data is available from <http://decipher.sanger.ac.uk> and via email from decipher@sanger.ac.uk; funding for the project was provided by the Wellcome Trust.

References

- Albers CA, Paul DS, Schulze H, Freson K, Stephens JC, Smethurst PA, Jolley JD, Cvejic A, Kostadima M, Bertone P, Breuning MH, Debili N, Deloukas P, Favier R, Fiedler J, Hobbs CM, Huang N, Hurles ME, Kiddle G, Krapels I, Nurden P, Ruivenkamp CA, Sambrook JG, Smith K, Stemple DL, Strauss G, Thys C, van Geet C, Newbury-Ecob R, Ouwehand WH, Ghevaert C: Compound inheritance of a low-frequency regulatory snp and a rare null mutation in exon-junction complex subunit *rbm8a* causes tar syndrome. *Nat Genet* 44:435-439, S431-432 (2012).
- Astbury C, Christ LA, Aughton DJ, Cassidy SB, Kumar A, Eichler EE, Schwartz S: Detection of deletions in de novo "balanced" chromosome rearrangements: Further evidence for their role in phenotypic abnormalities. *Genetics in medicine : official journal of the American College of Medical Genetics* 6:81-89 (2004).
- Bhalla K, Luo Y, Buchan T, Beachem MA, Guzauskas GF, Ladd S, Bratcher SJ, Schroer RJ, Balsamo J, DuPont BR, Lilien J, Srivastava AK: Alterations in *cdh15* and *kirrel3* in patients with mild to severe intellectual disability. *Am J Hum Genet* 83:703-713 (2008).
- Brady PD, Delle Chiaie B, Christenhusz G, Dierickx K, Van Den Bogaert K, Menten B, Janssens S, Defoort P, Roets E, Sleurs E, Keymolen K, De Catte L, Deprest J, de Ravel T, Van Esch H, Fryns JP, Devriendt K, Vermeesch JR: A prospective study of the clinical utility of prenatal chromosomal microarray analysis in fetuses with ultrasound abnormalities and an exploration of a framework for reporting unclassified variants and risk factors. *Genetics in medicine : official journal of the American College of Medical Genetics* 16:469-476 (2014).
- Castiglia L, Fichera M, Romano C, Galesi O, Grillo L, Sturnio M, Failla P: Narrowing the candidate region for congenital diaphragmatic hernia in chromosome 15q26: Contradictory results. *Am J Hum Genet* 77:892-894; author reply 894-895 (2005).
- Chang SW, Mislankar M, Misra C, Huang N, Dajusta DG, Harrison SM, McBride KL, Baker LA, Garg V: Genetic abnormalities in *foxp1* are associated with congenital heart defects. *Human mutation* 34:1226-1230 (2013).
- de Wit MC, Srebniak MI, Govaerts LC, Van Opstal D, Galjaard RJ, Go AT: Additional value of prenatal genomic array testing in fetuses with isolated structural ultrasound abnormalities and a normal karyotype: A systematic review of the literature. *Ultrasound Obstet Gynecol* 43:139-146 (2014).
- Di Gregorio E, Savin E, Biamino E, Belligni EF, Naretto VG, D'Alessandro G, Gai G, Fiocchi F, Calcia A, Mancini C, Giorgio E, Cavalieri S, Talarico F, Pappi P, Gandione M, Grosso M, Asnaghi V, Restagno G, Mandrile G, Botta G, Silengo MC, Grosso E, Ferrero GB, Brusco A: Large cryptic genomic rearrangements with apparently normal karyotypes detected by array-cgh. *Mol Cytogenet* 7:82 (2014).
- Dimitrov BI, Ogilvie C, Wiczorek D, Wakeling E, Sikkema-Raddatz B, van Ravenswaaij-Arts CM, Josifova D: 3p14 deletion is a rare contiguous gene syndrome: Report of 2 new patients and an overview of 14 patients. *Am J Med Genet A* 167:1223-1230 (2015).
- Dode C, Teixeira L, Levilliers J, Fouveaut C, Bouchard P, Kottler ML, Lespinasse J, Lienhardt-Roussie A, Mathieu M, Moerman A, Morgan G, Murat A, Toub Blanc JE, Wolczynski S, Delpech M, Petit C, Young J, Hardelin JP: Kallmann syndrome: Mutations in the genes encoding prokineticin-2 and prokineticin receptor-2. *PLoS Genet* 2:e175 (2006).
- Dundar M, Uzak A, Erdogan M, Saatci C, Akdeniz S, Luleci G, Keser I, Karauzum S: Partial trisomy 3q in a child with sacrococcygeal teratoma and cornelia de lange syndrome phenotype. *Genet Couns* 22:199-205 (2011).
- Grossfeld P, Ye M, Harvey R: Hypoplastic left heart syndrome: New genetic insights. *J Am Coll Cardiol* 53:1072-1074 (2009).
- Hillman SC, McMullan DJ, Hall G, Togneri FS, James N, Maher EJ, Meller CH, Williams D, Wapner RJ, Maher ER, Kilby MD: Use of prenatal chromosomal microarray: Prospective cohort study and systematic review and meta-analysis. *Ultrasound Obstet Gynecol* 41:610-620 (2013).
- Holder SE, Grimsley LM, Palmer RW, Butler LJ, Baraitser M: Partial trisomy 3q causing mild cornelia de lange phenotype. *J Med Genet* 31:150-152 (1994).

Johnson D, Kan SH, Oldridge M, Trembath RC, Roche P, Esnouf RM, Giele H, Wilkie AO: Missense mutations in the homeodomain of *hoxd13* are associated with brachydactyly types d and e. *Am J Hum Genet* 72:984-997 (2003).

Johnson KR, Sweet HO, Donahue LR, Ward-Bailey P, Bronson RT, Davisson MT: A new spontaneous mouse mutation of *hoxd13* with a polyalanine expansion and phenotype similar to human synpolydactyly. *Hum Mol Genet* 7:1033-1038 (1998).

Kearney HM, South ST, Wolff DJ, Lamb A, Hamosh A, Rao KW, Working Group of the American College of Medical G: American college of medical genetics recommendations for the design and performance expectations for clinical genomic copy number microarrays intended for use in the postnatal setting for detection of constitutional abnormalities. *Genetics in medicine : official journal of the American College of Medical Genetics* 13:676-679 (2011).

Kennet J: *Smith's recognizable patterns of human malformation* ed 6th. (Saunders, 2005).

Kessel M, Gruss P: Murine developmental control genes. *Science* 249:374-379 (1990).

Klaassens M, Galjaard RJ, Scott DA, Bruggenwirth HT, van Opstal D, Fox MV, Higgins RR, Cohen-Overbeek TE, Schoonderwaldt EM, Lee B, Tibboel D, de Klein A: Prenatal detection and outcome of congenital diaphragmatic hernia (*cdh*) associated with deletion of chromosome 15q26: Two patients and review of the literature. *Am J Med Genet A* 143A:2204-2212 (2007).

Klaassens M, van Dooren M, Eussen HJ, Douben H, den Dekker AT, Lee C, Donahoe PK, Galjaard RJ, Goemaere N, de Krijger RR, Wouters C, Wauters J, Oostra BA, Tibboel D, de Klein A: Congenital diaphragmatic hernia and chromosome 15q26: Determination of a candidate region by use of fluorescent in situ hybridization and array-based comparative genomic hybridization. *Am J Hum Genet* 76:877-882 (2005).

Koolen DA, Nillesen WM, Versteeg MH, Merx GF, Knoers NV, Kets M, Vermeer S, van Ravenswaaij CM, de Kovel CG, Brunner HG, Smeets D, de Vries BB, Sistermans EA: Screening for subtelomeric rearrangements in 210 patients with unexplained mental retardation using multiplex ligation dependent probe amplification (*mlpa*). *J Med Genet* 41:892-899 (2004).

Kumar P, Burton B: *Congenital malformations: Evidence-based evaluation and management*. (McGraw-Hill Education, 2007).

Le Caignec C, Boceno M, Saugier-veber P, Jacquemont S, Joubert M, David A, Frebourg T, Rival JM: Detection of genomic imbalances by array based comparative genomic hybridisation in fetuses with multiple malformations. *J Med Genet* 42:121-128 (2005).

Miller DT, Adam MP, Aradhya S, Biesecker LG, Brothman AR, Carter NP, Church DM, Crolla JA, Eichler EE, Epstein CJ, Faucett WA, Feuk L, Friedman JM, Hamosh A, Jackson L, Kaminsky EB, Kok K, Krantz ID, Kuhn RM, Lee C, Ostell JM, Rosenberg C, Scherer SW, Spinner NB, Stavropoulos DJ, Tepperberg JH, Thorland EC, Vermeesch JR, Waggoner DJ, Watson MS, Martin CL, Ledbetter DH: Consensus statement: Chromosomal microarray is a first-tier clinical diagnostic test for individuals with developmental disabilities or congenital anomalies. *Am J Hum Genet* 86:749-764 (2010).

Mosca AL, Pinson L, Andrieux J, Copin H, Bigi N, Puechberty J, Sarda P, Receveur A, Sevestre H, Pigeonnat S, Marle N, Payet M, Ragon C, Rousseau T, Thauvin-Robinet C, Masurel-Paulet A, Schneider A, Laurent N, Sagot P, Mugneret F, Lefort G, Faivre L, Callier P: Refining the critical region for congenital diaphragmatic hernia on chromosome 15q26 from the study of four fetuses. *Prenat Diagn* 31:912-914 (2011).

Okada A, Charron F, Morin S, Shin DS, Wong K, Fabre PJ, Tessier-Lavigne M, McConnell SK: *Boc* is a receptor for sonic hedgehog in the guidance of commissural axons. *Nature* 444:369-373 (2006).

Papadopoulou E, Sifakis S, Sarri C, Gyftodimou J, Liehr T, Mrasek K, Kalmanti M, Petersen MB: A report of pure 7p duplication syndrome and review of the literature. *Am J Med Genet A* 140:2802-2806 (2006).

Papoulidis I, Sotiriadis A, Siomou E, Papageorgiou E, Eleftheriades M, Papadopoulos V, Oikonomidou E, Orru S, Manolakos E, Athanasiadis A: Routine use of array comparative genomic hybridization (*acgh*) as standard approach for prenatal diagnosis of chromosomal abnormalities. Clinical experience of 1,763 prenatal cases. *Prenat Diagn* (2015).

Pariani MJ, Spencer A, Graham JM, Jr., Rimoin DL: A 785kb deletion of 3p14.1p13, including the *foxp1* gene, associated with speech delay, contractures, hypertonia and blepharophimosis. *Eur J Med Genet* 52:123-127 (2009).

Rajangam S, Nanjappa L: Cytogenetic studies in amenorrhea. *Saudi Med J* 28:187-192 (2007).

Richards AA, Garg V: Genetics of congenital heart disease. *Curr Cardiol Rev* 6:91-97 (2010).

Rizzo N, Pittalis MC, Pilu G, Perolo A, Banzi C, Visentin A, Bovicelli L: Distribution of abnormal karyotypes among malformed fetuses detected by ultrasound throughout gestation. *Prenat Diagn* 16:159-163 (1996).

Roback EW, Barakat AJ, Dev VG, Mbikay M, Chretien M, Butler MG: An infant with deletion of the distal long arm of chromosome 15 (q26.1----qter) and loss of insulin-like growth factor 1 receptor gene. *Am J Med Genet* 38:74-79 (1991).

Rump P, de Leeuw N, van Essen AJ, Verschuuren-Bemelmans CC, Veenstra-Knol HE, Swinkels ME, Oostdijk W, Ruivenkamp C, Reardon W, de Munnik S, Ruiter M, Frumkin A, Lev D, Evers C, Sikkema-Raddatz B, Dijkhuizen T, van Ravenswaaij-Arts CM: Central 22q11.2 deletions. *Am J Med Genet A* 164A:2707-2723 (2014).

Saldarriaga W, Garcia-Perdomo HA, Arango-Pineda J, Fonseca J: Karyotype versus genomic hybridization for the prenatal diagnosis of chromosomal abnormalities: A metaanalysis. *American journal of obstetrics and gynecology* 212:330 e331-310 (2015).

Schaeffer AJ, Chung J, Heretis K, Wong A, Ledbetter DH, Lese Martin C: Comparative genomic hybridization-array analysis enhances the detection of aneuploidies and submicroscopic imbalances in spontaneous miscarriages. *Am J Hum Genet* 74:1168-1174 (2004).

Sheth R, Bastida MF, Ros M: Hoxd and gli3 interactions modulate digit number in the amniote limb. *Developmental biology* 310:430-441 (2007).

Srebniak MI, Diderich KE, Joosten M, Govaerts LC, Knijnenburg J, de Vries FA, Boter M, Lont D, Knapen MF, de Wit MC, Go AT, Galjaard RH, Van Opstal D: Prenatal snp array testing in 1000 fetuses with ultrasound anomalies: Causative, unexpected and susceptibility cnvs. *Eur J Hum Genet* (2015).

Stevenson R: Genetic causes of malformations, in Stevenson R, Hall J (eds): *Human malformations and related anomalies* (Oxford University Press, New York 2006).

Tarchini B, Duboule D, Kmita M: Regulatory constraints in the evolution of the tetrapod limb anterior-posterior polarity. *Nature* 443:985-988 (2006).

Tonnies H, Schulze I, Hennies H, Neumann LM, Keitzer R, Neitzel H: De novo terminal deletion of chromosome 15q26.1 characterised by comparative genomic hybridisation and fish with locus specific probes. *J Med Genet* 38:617-621 (2001).

Tseng JJ, Chou MM, Lo FC, Lai HY, Chen MH, Ho ES: Detection of chromosome aberrations in the second trimester using genetic amniocentesis: Experience during 1995-2004. *Taiwan J Obstet Gynecol* 45:39-41 (2006).

Tyremen M, Abbott KM, Willatt LR, Nash R, Lees C, Whittaker J, Simonic I: High resolution array analysis: Diagnosing pregnancies with abnormal ultrasound findings. *J Med Genet* 46:531-541 (2009).

Vialard F, Molina Gomes D, Leroy B, Quarello E, Escalona A, Le Sciellour C, Serazin V, Roume J, Ville Y, de Mazancourt P, Selva J: Array comparative genomic hybridization in prenatal diagnosis: Another experience. *Fetal Diagn Ther* 25:277-284 (2009).

Wilson RD, Chitayat D, McGillivray BC: Fetal ultrasound abnormalities: Correlation with fetal karyotype, autopsy findings, and postnatal outcome--five-year prospective study. *Am J Med Genet* 44:586-590 (1992).

Yashwanth R, Chandra N, Gopinath PM: Chromosomal abnormalities among children with congenital malformations. *International Journal of Human Genetics* 10:57-63 (2010).

Zakany J, Kmita M, Duboule D: A dual role for hox genes in limb anterior-posterior asymmetry. *Science* 304:1669-1672 (2004).

Patient Decipher code	Prenatal Echography / Autopsy	Karyotype	a-CGH result	Size	MIM genes / phenotypes	Clinical significance
1 DGT308537	No echography / Pericerebellar and intraventricular hemorrhage, Situs ambiguous, Complex cardiopathy	46,XX	arr 22q11.21(18,919,942-21,440,514)x1	2.5 Mb	40/7	Known syndrome
2 DGT308539	Oligohydramnios, Right renal agenesis, Multicystic left kidney dysplasia / Potter facies, Right renal agenesis, Multicystic left kidney dysplasia	46,XY	arr 22q11.21(20,754,422-21,440,514)x1	0.8 Mb	11/3	Known syndrome
3 DGT300197	Bilateral upper limb bone malformations with agenesis of radius and ulna, Hands hyperflexion / Brain micro-hemorrhagic foci, Dysmorphic features, Bilateral upper limb bone malformations (radius agenesis, dysplastic and shorten ulna), Scoliosis, Supernumerary ribs	46,XY	arr 1q21.1(145,413,388-145,747,269)x1	0.3 Mb	8/2	Known syndrome
4 DGT283329	Intrauterine growth retardation, Abnormality of the ventricular septum, Cardiomegaly, Hyperechogenic bowel / Possible lissencephaly, Lower lip protrusion, Micrognathia, Abnormality of the ventricular septum, Ventriculomegaly, Arm hypoplasia	46,XX	arr 3q27.1q29(184,428,168 - 197,840,339)x3	13.4 Mb	75/18	Pathogenic
			arr 15q26.1q26.3(90,857,664 - 102,383,473)x1	11.5 Mb	27/10	
5 DGT290945	No echography / Agenesis of corpus callosum, Abnormality of neuronal migration, Abnormality of vertebrae, Flat nose, Low set ears, Hypertelorism, Aortic arch hypoplasia, Hypoplastic left heart, Hypoplastic long bones	46,XX	arr 7p22.3p22.2 (92,532-4,176,031)x3	4 Mb	26/5	Pathogenic
			arr 7p22.1p21.2 (7,044,310-15,709,683)x3	8.6 Mb	16/2	
			arr 11q24.1q25(122,467,330-134,868,407)x1	12.4 Mb	57/18	
6 DGT308533	Ambiguous genitalia, Penoscrotal hypospadias / Hypoplasia of the mandible, Hand polydactyly, Kidney dysplasia, Ambiguous genitalia with male gonads, Periorbital fibrosis, Pancreatic hyperplasia, Anal atresia	46,XY	arr 2q31.1(176,958,852-176,996,671)x3	37 Kb	-	Pathogenic
			arr 8q24.3(142,205,751-145,747,468)x3	3.5 Mb	58/13	
			arr 10q26.3(133,749,950-135,276,555)x3	1.5 Mb	16/2	
			arr 11p15.5p15.4(218,365-3,243,604)x3	3 Mb	68/19	
			arr 16p13.3(106,271-4,902,543)x3	4.8 Mb	131/24	
			arr 20q13.3(60,112,364-62,893,189)x3	2.7 Mb	51/7	
7 DGT308538	No echography / Pierre-Robin sequence, Agenesis of the nasal bone, Left diaphragmatic hernia	46,XX	arr 15q25.3q26.3(87,344,281-100,872,951) x1	13.5 Mb	46/12	Pathogenic

8 DGT308536	Truncus arteriosus, Abnormality of the ventricular septum / Truncus arteriosus, Abnormality of the ventricular septum, Hand clenching, Scrotal hypoplasia	46,XY	arr 3p14.2p13(61,067,122-72,423,962)x1	11.4 Mb	23/6	Pathogenic
9 DGT301136	Intrauterine growth retardation / Dysmorphic features, Abnormality of vertebrae, Pulmonary hypoplasia, Bilateral renal agenesis, Aplasia of the uterus, Talipes equinovarus	No (culture failure)	arr 1p31.1(77,444,894-77,578,846)x3	0.13 Mb	2/0	VOUS
10 DGT301192	No echography / Potter facies, Patent ductus arteriosus, Vertebral fusion, Anal atresia	46,XY	arr 2p22.2(38,523,015-38,570,650)x3	0.47 Mb	1/0	VOUS
11 DGT301190	No echography / Potter facies, Lower limbs hypoplasia, Tibial torsion, Fibular aplasia, Talipes equinovarus and oligodactyly	46,XY	arr 2p23.1(30,814,684-30,832,151)x1	0.18 Mb	1/0	VOUS
12 DGT301184	Anhydramnios, Bilateral renal agenesis / Bilateral renal agenesis, Patent ductus arteriosus, Abnormality of the ventricular septum, Lower limbs hyperextension	46,XX	arr 3q25.1(150,651,708-151,542,568)x3	0.9 Mb	7/2	VOUS
13 DGT308540	No Echography / Dysmorphic features, Complex cardiac malformation, Polysplenia, Unilateral renal agenesis, Aplasia of the bladder, Ambiguous genitalia, Arms malformations, Anal atresia, Limb malformations, Oligodactyly, Syndactyly	46,XY	arr 5p11q11.1 (49,690,172-50,123,913)x3	0.5 Mb	2/0	VOUS
14 DGT312082	No Echography / Cerebellar vermis hypoplasia, Rhombencephalosynapsis, Subcutaneous edema, Aortic arch and aortic ductus defect	46,XY	arr 22q11.23(25.664.618-25.799.582)x1	0.14 Mb	2/0	VOUS