



Comprehensive genetic diagnosis of patients with Duchenne/Becker muscular dystrophy (DMD/BMD) and pathogenicity analysis of splice site variants in the *DMD* gene^{*#}

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Abstract: Duchenne muscular dystrophy (DMD) and Becker muscular dystrophy (BMD) are caused by mutations in the *DMD* gene. The aim of this study is to identify pathogenic *DMD* variants in probands and reduce the risk of recurrence of the disease in affected families. Variations in 100 unrelated DMD/BMD patients were detected by multiplex ligation-dependent probe amplification (MLPA) and next-generation sequencing (NGS). Pathogenic variants in *DMD* were successfully identified in all cases, and 11 of them were novel. The most common mutations were intragenic deletions (69%), with two hotspots located in the 5' end (exons 2–19) and the central of the *DMD* gene (exons 45–55), while point mutations were observed in 22% patients. Further, c.1149+1G>A and c.1150–2A>G were confirmed by hybrid minigene splicing assay (HMSA). This two splice site mutations would lead to two aberrant *DMD* isoforms which give rise to severely truncated protein. Therefore, the clinical use of MLPA, NGS, and HMSA is an effective strategy to identify variants. Importantly, eight embryos were terminated pregnancies according to prenatal diagnosis and a healthy boy was successfully delivered by preimplantation genetic diagnosis (PGD). Early and accurate genetic diagnosis is essential for prenatal diagnosis/PGD to reduce the risk of recurrence of DMD in affected families.

Key words: Dystrophin gene; Variation; Genetic diagnosis; Splice site mutation; Hybrid minigene splicing assay
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1 Introduction


Dystrophinopathies are common neuromuscular disorders in childhood. There are two main pheno-

types: Duchenne muscular dystrophy (DMD, OMIM: 310200) and Becker muscular dystrophy (BMD, OMIM: 300376). DMD, with an approximate incidence of 1/3500 in live male births, is characterized by early-onset, rapidly progressive muscle weakness and being wheel-chair-dependent before age 13, while BMD presents milder clinical features, later-onset and slower progression (Jefferies et al., 2005). Both DMD and BMD are X-linked recessive neuromuscular diseases due to *DMD* gene (OMIM: 300377) mutations. This is the largest gene in the human genome (Muntoni et al., 2003). The *DMD* gene spans more than 2.5 million base pairs (bp) of genomic

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DNA on chromosome X p21.2-21.1 and consists of 79 exons. It encodes a 14 kilobases (kb) mRNA transcript and a 427 kDa full-length dystrophin protein comprising four domains (amino terminal domain, central rod domain, cysteine-rich domain, and carboxy terminal domain) (Muntoni et al., 2003). The dystrophin protein interacts with integral membrane proteins and they assemble into a dystrophin-glycoprotein complex, which plays an important role in stabilizing the sarcolemma and protecting muscle fibers from damage and necrosis (Rando, 2001).

Mutations of *DMD* include intragenic large deletions/duplications and point mutations. Intragenic deletions and duplications refer to one or more exons (Fairclough et al., 2013), whereas point mutations include nonsense mutations, small frame-shift deletions or insertions, missense, and splice site mutations (Roberts et al., 1994). Multiplex polymerase chain reaction (PCR) is used to be a standard diagnostic method. It could identify 98% of deletions in male patients, but neither duplication and point mutation nor female carriers are detectable (Beggs et al., 1990). Multiplex ligation-dependent probe amplification (MLPA) is currently the most widely used to detect exonic deletions and duplications of *DMD* both in male patients and female carriers (Schouten et al., 2002; Zimowski et al., 2014). Recently, with the dramatically reduced cost of sequencing, next-generation sequencing (NGS) has become clinically available for the detection of large deletions/duplications and point mutations (nonsense mutation, missense mutation, small insertions/deletions (indels) spanning several base pairs, and splice site mutation) throughout all the exons and flanking introns of *DMD* (Haas et al., 2011). Splicing regulation has been attracting much more attention since exon-skipping therapy began to appear (Echevarria et al., 2018). So far, a splicing pattern is essential for therapy and diagnosis of disease. Hybrid minigene splicing assay (HMSA) has allowed a relatively fast functional test to build connections between splicing and disease. Though the detection technologies develop rapidly, 1% to 2% of *DMD* cases remain undiagnosed (Bovolenta et al., 2008).

Identification of pathogenic *DMD* variants can confirm the diagnosis of *DMD*/*BMD* patients and determine the carrier status of their family members. Once the familial mutation is determined, prenatal

diagnosis or preimplantation genetic diagnosis (PGD) could be adopted for the family members to prevent the recurrence of the disease. Here, we combined MLPA, NGS, and Sanger sequencing to identify causative mutations in 100 unrelated *DMD* patients. Eleven novel mutations were detected and two splice site mutations were verified by HMSA. Prenatal diagnosis or PGD was performed on 50 families with known mutations.

2 Materials and methods

2.1 Patients

A total of 100 unrelated *DMD*/*BMD* families referred to the Department of Reproductive Genetics, Women's Hospital, School of Medicine, Zhejiang University (Hangzhou, China) were recruited. All subjects were Han Chinese. The diagnosis of *DMD*/*BMD* was based on serum creatine kinase (CK) measurements, muscle biopsy, electromyography, electrocardiogram, progression of the disease, and family history. There were 100 *DMD*/*BMD* probands and 100 mothers of probands in our study. This study was approved by the Ethical Committee of the Women's Hospital, School of Medicine, Zhejiang University. Informed consents were obtained from all participants.

2.2 Genomic DNA extraction

DNA was isolated from peripheral blood lymphocytes and amniocytes according to the manufacturer's standard protocol (QIAamp DNA Blood Mini Kit, Hilden, Germany). Amniotic fluids were obtained by an obstetrician through amniocentesis and then amniocytes were cultured for eleven days before DNA extraction.

2.3 MLPA

MLPA was used to screen all exons of *DMD* for all patients. The assay was performed with two independent MLPA kits SALSA P034 and P035 (MRC-Holland, Amsterdam, the Netherlands) according to the manufacturer's instruction and the PCR products were separated by ABI PRISM[®] 3100 Genetic Analyzer (Applied Biosystems, CA, USA). Then, the statistical and quantitative analyses were calculated by Coffalyser Net software (<http://www.coffalyser.net>).

2.4 NGS and Sanger sequencing

NGS was performed as previously described (Wei et al., 2013; Li et al., 2017). All primers were designed by Primer 5.0 (Premier Biosoft International, CA, USA) (Table S1). The sequencing data and the standard *DMD* reference sequence (GenBank accession number NM_004006.2) were aligned by Mutation Surveyor software (Soft Genetics, State College, PA, USA) to determine nucleotide variations. All mutations identified in this study were checked on the Human Gene Mutation Database (HGMD, <http://www.hgmd.cf.ac.uk>), the Leiden Open Variation Database (LOVD, <http://www.dmd.nl>), and the Universal Mutation Database (UMD, <http://www.umd.be>). Novel mutations were evaluated according to the American College of Medical Genetics and Genomics (ACMG) guidelines (Richards et al., 2015). Missense mutations were evaluated by Sorts Intolerant from Tolerant (SIFT, <http://sift.jcvi.org>) and PolyPhen-2 (<http://genetics.bwh.harvard.edu/pph2>). Splicing impact was scored using the Human Splicing Finder (HSF, <http://www.umd.be/HSF3>).

2.5 HMSA

To investigate the effects of the splice site mutations, HMSA including minigene construct, transfection, and reverse transcription PCR (RT-PCR) was performed as previously described (Xia et al., 2018). Human genomic DNA fragments covering from exon 10 to exon 11 were amplified using forward primer DMD-1149/50-F (5'-GATCCTCGAGctccctattgtctgtatctgc-3') and reverse primer DMD-1149/50-R (5'-GATCGGATCCtacacaatctctgtgcatgc-3'). The vector primers were as follows: SD6 (5'-TTGTCTACCCATGGACCCAGA-3') and SA2 (5'-CCCCCTGAACCTGAAACATAAAAT-3'). The PCR products were analyzed on 2% (0.02 g/mL) agarose gel and sequencing was performed.

2.6 PGD

In vitro fertilization (IVF) procedure was performed as previously described (Ye et al., 2014). Two or five trophocytes were aspirated from each blastocyst on Day 5 and transferred to PCR tube for whole genome amplification (WGA). One or two non-affected embryos were selected to be transferred. Clinical pregnancy was confirmed by serum β -human

chorionic gonadotrophin (β -hCG) and sonography. Amniocentesis was performed at 20 weeks of gestation. Multiple displacement amplification (MDA) was performed according to the manufacturer's instructions (REPLI-g Single Cell Kit for WGA, QIAGEN, Germany). The MDA products were used for PCR immediately or stored at -20°C . Preimplantation genetic haplotyping (PGH) was performed by NGS-based single nucleotide polymorphism (SNP) haplotyping. SNP markers located 1 Mb upstream and downstream of the *DMD* gene in the genomes from the 1000 Genomes Project and known mutation in *DMD* gene were used for NGS-based SNP haplotyping. The detailed procedure of NGS was performed according to the protocol as previously described (Chen et al., 2016). The data from NGS was further confirmed by standard PCR and Sanger sequencing. Sex determining region Y (*SRY*) gene was amplified by primers (SRY-F: AGTAAAGGCAACGTCCAGGAT; SRY-R: TTCCGACGAGGTCGATACTTA) and then the amplified products were analyzed by 1.5% (0.015 g/mL) agarose gel and Sanger sequencing.

3 Results

3.1 Deletion and duplication detection

In total, 69 deletions and 9 duplications were identified in this study (Tables S2 and S3). Notably, two deletion hotspots (exons 45–55 and exons 2–19) were observed (Fig. 1). The number of deleted or duplicated exons ranged widely from 1 to 47. Two or more continuous exon deletions could be easily and reliably determined by MLPA. For the cases with only one exon deletion, the results should be further confirmed by standard PCR and Sanger sequencing. Three-exon deletion/duplication was the most frequent (21.79%, 17/78), followed by single-exon (15.38%, 12/78), five-exon (10.26%, 8/78), and two-exon (8.97%, 7/78). As for the 12 single-exon deletion/duplication mutations, exon 51 was the commonest affected exon (41.67%, 5/12), followed by exon 50 (16.67%, 2/12). Among the 78 affected patients due to deletions/duplications, 47 of them (60.25%, 47/78) inherited the mutation from their mothers, while 31 (39.74%, 31/78) were de novo mutations.

site mutations could break the original splice site. A reported missense mutation c.497G>T was found in a patient. This mutation was predicted to be deleterious by SIFT (affecting protein function with a score of 0.00) and PolyPhen-2 (probably damaging with a score of 1.00).

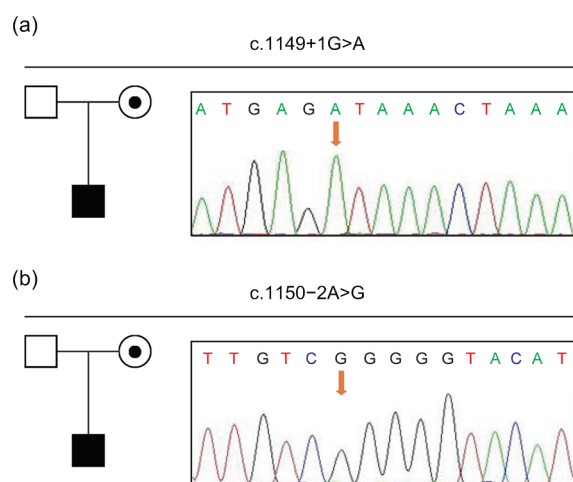


Fig. 2 Splice site mutations of DMD gene in the P99 (a) and P100 (b) families

Black boxes indicate affected males; dotted circles indicate female carriers; clear boxes indicate unaffected males. Partial sequencing chromatograms of genomic DNA from patients are shown. The arrows denote the positions of identified mutations

3.3 Splicing study by HMSA

HMSA was performed to investigate the effect of the two splice site mutations. The wide-type minigene construct was 1507 bp, across from partial intron 9 (152 bp), exon 10 (189 bp), intron 10 (650 bp), exon 11 (182 bp) to partial intron 11 (334 bp). A full length of 371 bp RT-PCR product (exclusive SD6 and SA2) was detected, which included exon 10 and exon 11 as expected. There was no product of normal size obtained for the mutant c.1149+1G>A minigene, but instead two abnormal larger fragments of 686 bp and 914 bp were detected resulting from two activations of cryptic donor splice sites in intron 10. Sequencing revealed that the two products contained 50 bp and 278 bp of intron 10, respectively (Fig. 3). They resulted from the activation of a cryptic splice site at different positions in the beginning of intron 10. Theoretically, both mutant isoforms would induce a premature termination codon (PTC) at amino acid 386. The motifs of two cryptic 5' splice sites (5'ss) activated were

ATGgcaagt and ATGgtattg, with the score 67.46 and 71.24 calculated by HSF, respectively.

Another minigene construct containing the c.1150-2A>G mutation yielded two shortened transcripts: a primary 454 bp transcript and a 614 bp transcript (Fig. 4). The 454 bp transcript was caused by complete skipping of exon 11 that led to the deletion of 182 bp. Thus, it included exon 10 (189 bp) and 265 bp fragment of exogenous pSPL3 vector by SD6 and SA2 primers. The skipping of exon 11 would cause frameshift that introduced stop codon 9 nucleotides downstream of the junction of exons 10 and 12. The 614 bp transcript resulted from the lack of a part of exon 11 (22 bp), which would cause frameshift that consequently introduced stop codon 46 nucleotides downstream of exon 11. The motif of cryptic 3' splice site (3'ss) activated was ggatttgacagCC, and the score of this cryptic 3'ss was 79.18 calculated by HSF.

3.4 Prenatal diagnosis and PGD

Prenatal diagnosis was performed on 50 mothers of probands (34 carriers and 16 non-carriers). Thirty normal females, 12 normal males, 5 female carriers, and 8 affected males were diagnosed (Table 1). The female carrier of exons 48–50 deletion (P30 family) and female carrier of c.1886C>G (P80 family) underwent PGD by haplotyping and gender determination. For the P30 family, biopsies were undertaken for four embryos: 1 and 4 were male, while embryos 2 and 3 were female. PGH identified 110 SNPs and 8 informative SNPs were selected. PGH and specific detection of deletions showed that all 4 embryos were normal (Fig. 5). Pregnancy was achieved after three cycles of embryo transfer. Amniocyte diagnosis confirmed the PGD results and then a healthy boy was delivered. In the P80 family, embryo biopsies were performed on 5 embryos. PGH identified 91 SNPs and 7 informative SNPs were selected (Fig. 5). Embryos 1, 2, and 4 demonstrated an affected haplotype inherited from the mother, whereas embryos 3 and 5 demonstrated an unaffected haplotype. PGH results were consistent with mutation and sex identification. Results indicated that embryos 1, 2, and 4 were female carriers, while embryos 3 and 5 were normal female and male, respectively. Finally, one embryo was transferred, resulting in a biochemical pregnancy. At 20 weeks of gestation, amniocyte diagnosis was performed and confirmed the PGD results.

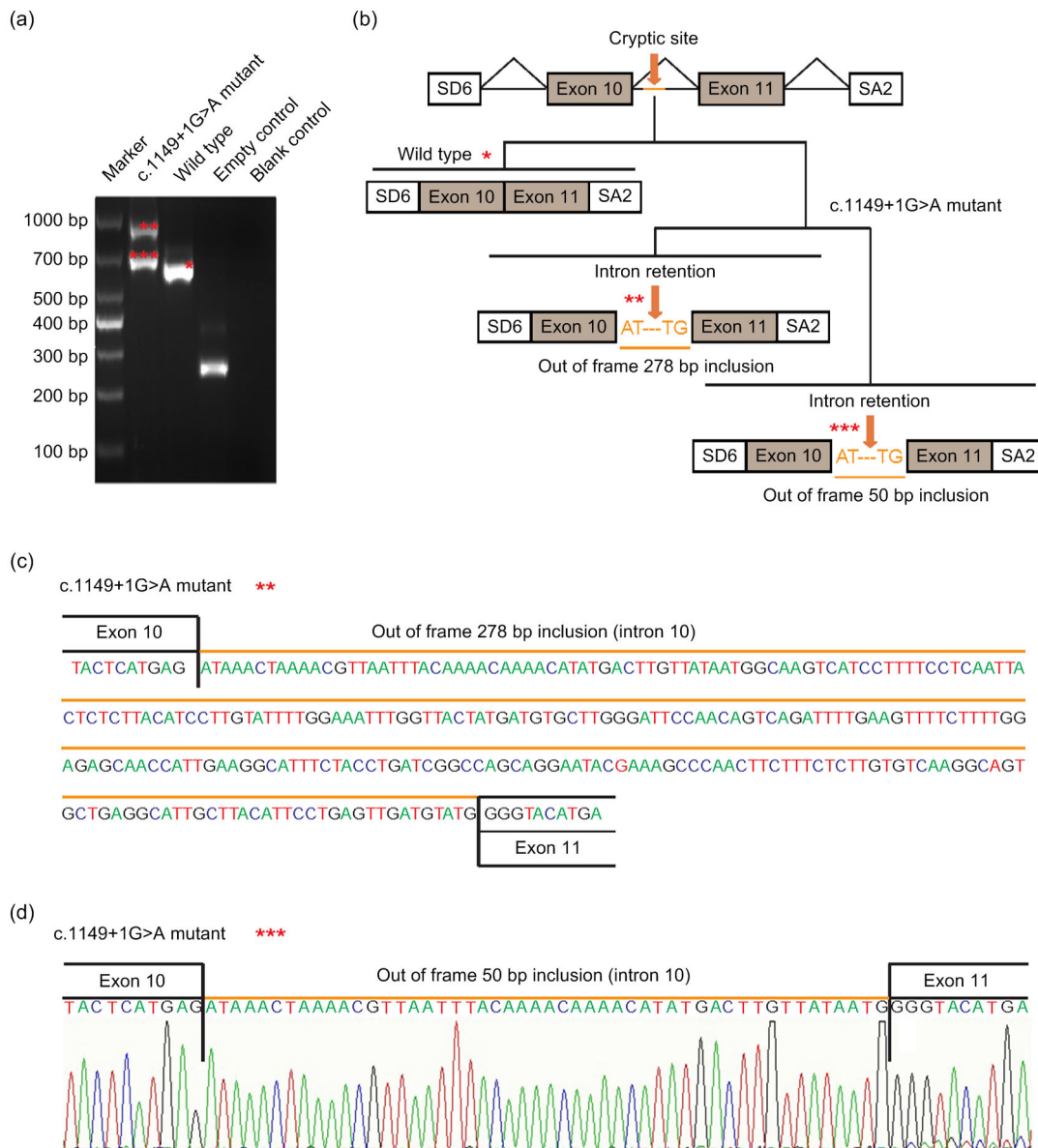


Fig. 3 Pathogenic analysis of *DMD*: c.1149+1G>A by HMSA

(a) Electrophoretogram of RT-PCR products. The mutant plasmid showed two types of splicing fragments of 686 bp (***) and 914 bp (**), while the wild-type plasmid showed a normal splicing fragment of 636 bp (*). The empty plasmid including SD6 and SA2 showed 265 bp. (b) Splicing models schematic representation. (c) Sequencing result of the mutated (aberrantly spliced) cDNA showing 278 bp retention of intron 10. (d) Sequencing result of the mutated (aberrantly spliced) cDNA showing 50 bp retention of intron 10

4 Discussion

In this study, all pathogenic variants in *DMD* were successfully identified in all 100 cases, and 11 variants were novel (Tables 2 and 3). Nonsense, indels and splice site mutations at $\pm 1/\pm 2$ were pathogenic, as evaluated according to ACMG guidelines (Richards,

et al., 2015). Our findings expanded the spectrum of the Human Mutation Database. MLPA was used as the first-line screening method and our results showed that the percentage of deletion and duplication detection by MLPA is 78%, which was similar to other studies (70%) (Lalic et al., 2005; Takeshima et al., 2010). As for the cases with negative MLPA results,

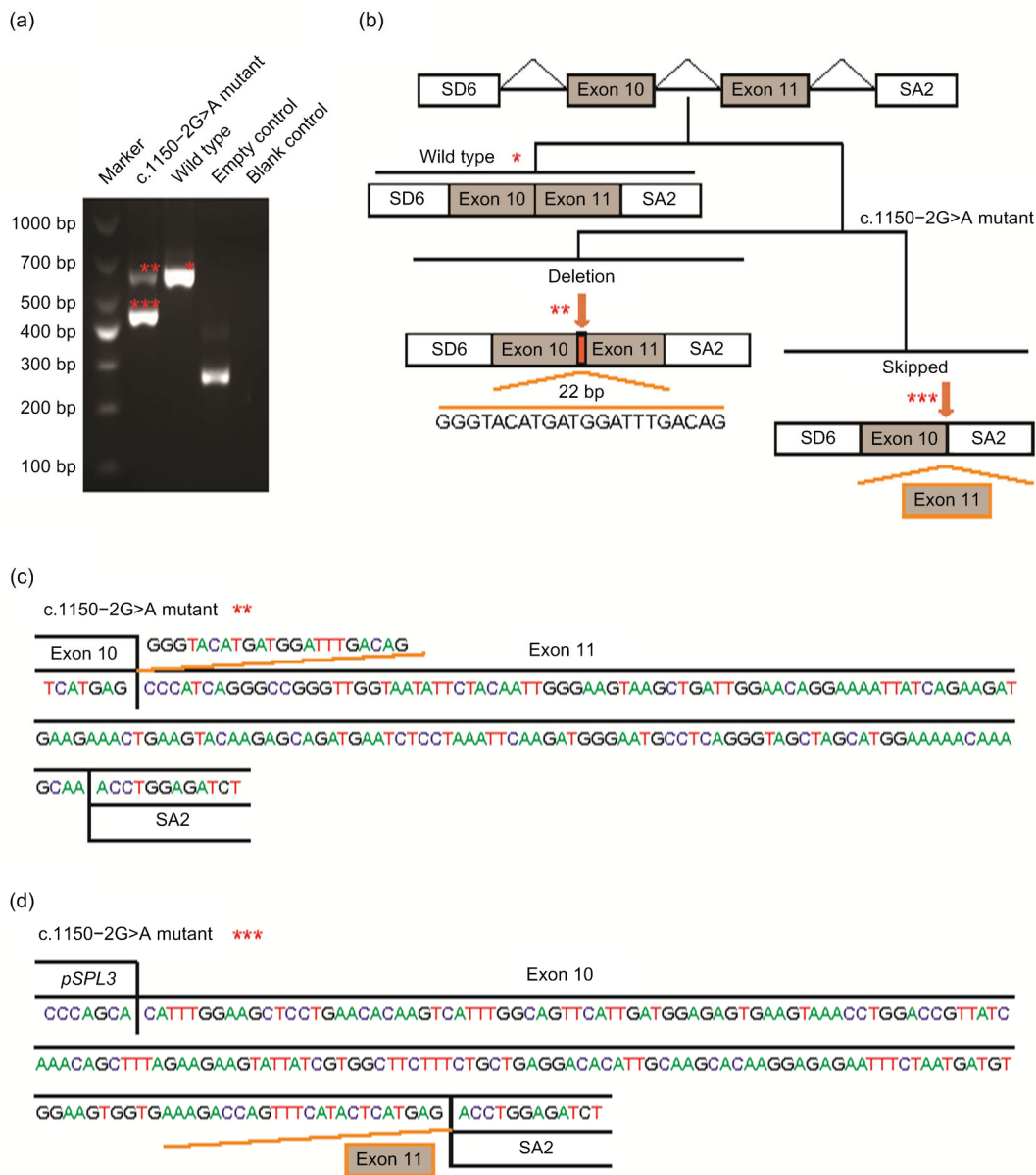


Fig. 4 Pathogenic analysis of DMD: c.1150-2A>G by HMSA

(a) Electrophoretogram of RT-PCR products. The mutant plasmid showed two types of splicing fragments of 454 bp (***) and 614 bp (**), while the wild-type plasmid showed a normal splicing fragment of 636 bp (*). The empty plasmid including SD6 and SA2 showed 265 bp. (b) Splicing models schematic representation. (c) Sequencing result of the mutated (aberrantly spliced) cDNA showing 22 bp lack of exon. (d) Sequencing result of the mutated (aberrantly spliced) cDNA showing skipping of exon 11

we further used NGS to detect possible point mutations (Flanigan et al., 2003). In total, 22 point mutations out of 100 cases (22%) were identified. Point mutations were dominated by nonsense mutation, which was consistent with previous studies (Tuffery-Giraud et al., 2009; Takeshima et al., 2010).

We identified a potential pathogenic missense mutation c.497G>T (p.Gly166Val) which was reported previously (Juan-Mateu et al., 2013). This mutation was located at highly conserved residues and was predicted to be pathogenic. In pedigree 81, there were three affected males who had hemizygote

Table 1 Prenatal diagnosis performed on 50 mothers of probands

Family No.	Carrier status of mother	Prenatal diagnosis	Family No.	Carrier status of mother	Prenatal diagnosis
P4	Yes	NF	P86	Yes	Patient
P91	No	dNF	P92	Yes	Patient
P27	No	NF	P94	Yes	NF
P35	No	NF	P95	Yes	NM
P36	No	NF	P96	Yes	NF
P48	No	NM	P97	Yes	Patient ¹ /Carrier ²
P51	No	NF	P31	Yes	NM
P52	No	NF	P39	Yes	dNF
P74	No	NM	P73	Yes	NF
P56	No	NF	P43	Yes	Patient
P57	No	NF	P49	Yes	Carrier
P60	No	NF	P50	Yes	Patient
P62	Yes	NF	P58	Yes	NF
P63	Yes	NM	P77	Yes	NM
P65	Yes	Carrier	P30	Yes	NM
P67	Yes	Carrier	P80	Yes	NF
P68	Yes	NF	P18	Yes	NF
P11	Yes	NM	P34	Yes	NF
P7	No	NF	P8	Yes	NM
P40	No	NF	P15	No	NM
P84	Yes	Patient	P33	Yes	Patient ¹ /NM ²
P46	No	NF ¹ /NM ²	P12	Yes	NF
P69	No	NF	P32	Yes	NF
P16	Yes	Patient	P76	Yes	NF
P20	Yes	NF	P82	Yes	Carrier

^{1/2}: number of pregnancy; NF: normal female fetuses; NM: normal male fetuses; d: double fetuses

Table 2 Characteristics of the detected mutations

Mutation type	Pathogenic	Known	Novel	De novo	Hereditary
Deletion	69	67	2	29	40
Duplication	9	8	1	2	7
Nonsense	13	9	4	3	10
Splicing	2	1	1	0	2
Missense	1	1	0	0	1
Indels	6	3	3	0	6
Total	100	89	11	34	66

Table 3 Eleven novel variants detected in this study

Patient No.	Variant	Inheritance
P4	EX5–6 deletion	Maternal
P43	EX12–33 deletion	Maternal
P77	EX56–70 duplication	Maternal
P79	c.3487C>T, p.(Gln1163Ter)	De novo
P82	c.8086_8087insC, p.(Leu2696ProfsX14)	Maternal
P85	c.9689delA, p.(Asp3230AlafsX53)	Maternal
P88	c.9669C>T, p.(Arg3223Ter)	Maternal
P89	c.2664 C>T, p.(Gln888Ter)	De novo
P92	c.7899G>A, p.(Trp2633Ter)	Maternal
P94	c.4131delA, p.(Lys1377AsnfsX5)	Maternal
P99	c.1149+1G>A	Maternal

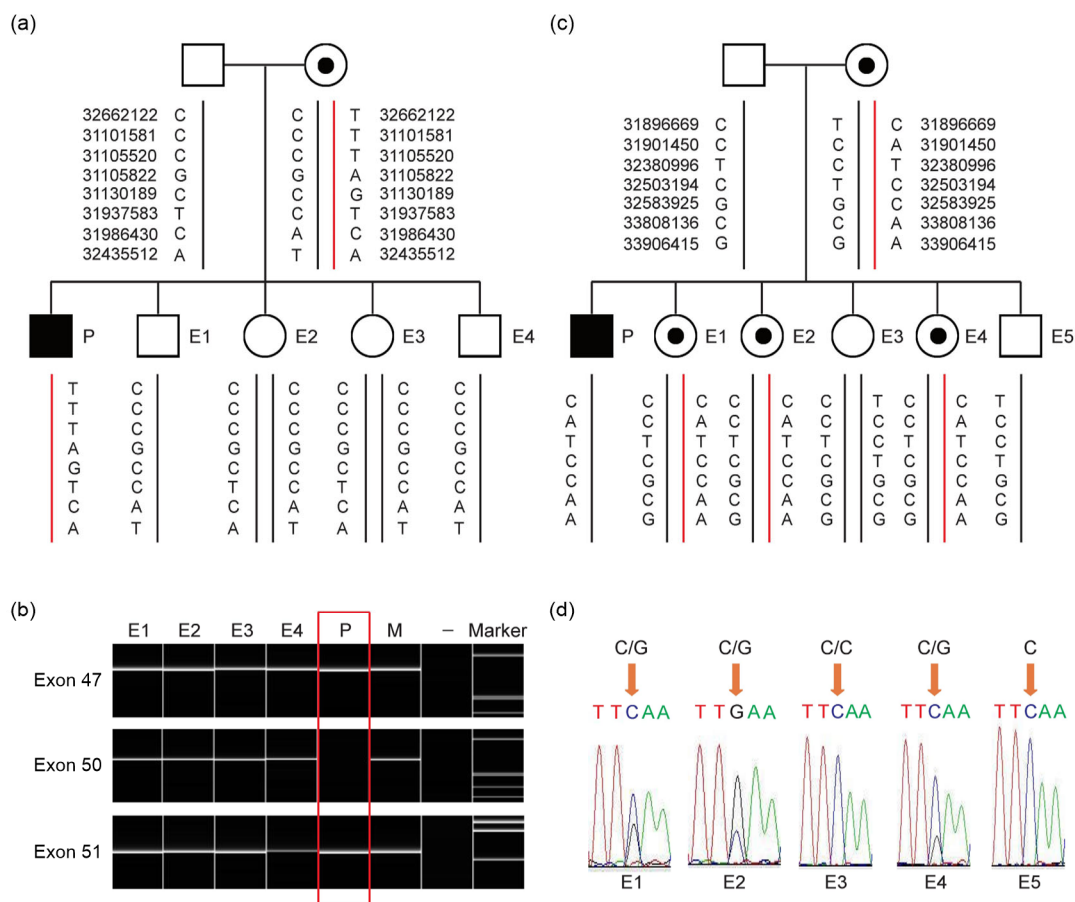


Fig. 5 PGD results of P30 and P80 families

(a) Haplotype analysis of P30 family. Diagram shows that all embryos have normal haplotype. (b) Direct mutation detection by amplification of exons 47, 50, and 51 of *DMD* for P30 family. All embryos had no deletion of exon 50. (c) Haplotype analysis of P80 family. E1, E2, and E4 demonstrated an affected haplotype pattern (red-line allele) inherited from mother, whereas E3 and E5 demonstrated an unaffected haplotype pattern (black-line allele). (d) Direct detection c.1886C/C in exon 16 of *DMD* for P80 family. E3 had wild homozygote c.1886C/C, whereas E5 had hemizygote. However, E1, E2, and E4 had heterozygous c.1886C>G (p.Ser629X). P: proband; M: proband's mother; E1–E5: embryos 1–5; -: negative control. Black boxes indicate affected males; dotted circles indicate female carriers; clear boxes and circles indicate unaffected males and females, respectively (Note: for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

c.497G>T. The first affected male had severe muscle weakness and died from respiratory failure at 20 years of age. The second one was early-onset and lost ambulation as disease progressed at 15 years of age, while the third one was 7-year-old now and suffered from progressive muscle weakness from 4 years of age. Juan-Mateu et al. (2013) had reported that mutation c.497G>T was found in an intermediate muscular dystrophy patient (loss of ambulation between 13 and 16 years of age), which was almost consistent with the patient's clinical phenotype in this study.

In DMD patients, prediction of splicing outcomes is essential for determining the phenotype. As

for novel mutation c.1149+1G>A, the HMSA results revealed that two abnormal transcripts of 50 bp and 278 bp retention partial intron 10 resulted from the activation of cryptic donor splice sites in intron 10 and both of them were out of frame. This was consistent with the patient's DMD phenotype (early-onset and wheel-chair-dependent at 8 years of age). The mutation c.1150-2A>G was previously reported once in a DMD case (Ma et al., 2018). However, no experimental evidence was available for this mutation. In our study, we not only verified that the mutation was maternal but the splicing outcome that arose from the mutation was conducted by HMSA. It revealed

that two abnormal transcripts of complete skipping of exon 11 and lack of 22 bp of exon 11. These two abnormal splicing outcomes were out of frame, which was consistent with the patient's DMD phenotype (early-onset and wheel-chair-dependent at 9 years of age).

Mutations involving GT and AG dinucleotide at the 5' (donor) and 3' (acceptor) splice sites would lead to disease (Pico et al., 2014). The major consequences of mutation at splice sites were exon skipping and cryptic splice site activation (Baralle and Baralle, 2005). The decision between two patterns of splicing outcomes was rather a matter of exon and intron length, exon flanking sequence, RNA secondary structure, open reading frame conservation, and DNA sequence environment (Roca et al., 2003; Buratti and Baralle, 2004; Zhang et al., 2005; Buratti et al., 2006; Hertel, 2008; Pico et al., 2014). Exon skipping was more common than cryptic donor splice site activation in the dystrophin gene mutations in cases of intron +1G>A, while cryptic splice site activation was likely only seen in strong exons (>170 bp) (Habara et al., 2009). As for the c.1149+1G>A case, it was suspected that cryptic splice site activation was influenced by the long length of exon 10 (189 bp). Minigene assay identified two cryptic 5'ss, and the scores calculated by HSF were lower than that of wild-type 5'ss, but higher than that of the mutant one. Actually, several potential 5'ss predicted by HSF were between the mutated authentic splice site and cryptic 5'ss. These potential 5'ss were completely silent and likely to be pseudo 5'ss. Roca et al. (2003) observed that the cryptic 5'ss activated were usually located close to the authentic 5'ss, whereas a few of cryptic 5'ss located further away were also activated. We suggested that the distance to the mutated splice site played an important role, but not the decisive factor for cryptic 5'ss activation. However, we observed the difference in splicing efficiency between these two cryptic 5'ss, which might be associated with proximity to the mutated splice site. It was interesting to note that one of cryptic splice sites activated at 50 bp downstream of exon 10 was activated, though the following nucleotides are "GC." The GT/AG splice sites were present in the majority of eukaryotic introns. In a database (SpliceDB, <http://www.softberry.com/spldb/SpliceDB.html>) of known mammalian splice sites, Burset et al. (2001) observed that non-canonical

GC sequence at 5'ss accounted for 0.56% and GC 5'ss possess a strong consensus sequence. Parada et al. (2014) uncovered that the GC/AG splice sites comprise about 0.889% of the total splice sites in humans. Although the percentage of non-canonical GC 5'ss was low, the GC 5'ss existed in various species, and were not aberrant splice sites. Also, a GC/AG splice sites pair existed at intron 30 of *DMD*. The factors promoting such weak site efficient selection are still poorly understood. Kralovicova et al. (2011) showed high density of GAA/CAA with splicing enhancers in exon making a contribution for efficient selection of GC 5'ss. In the absence of an alternative splice site, exon skipping was the preferred outcome at both donor and acceptor splice sites (Krawczak et al., 2007). As for c.1150-2A>G, exon 11 skipping was the major splicing outcome, and in contrast to the cryptic splice site was activated slightly. The sub-optimal, neighboring 3'ss activated was tggattgacag/CC and the score calculated by HSF was lower for this cryptic 3'ss with respect to wild-type 3'ss. The variation c.1150-2A>G was predicted to break ESE and ESS, which regulate premature mRNA splicing. These regulatory elements may play important roles in the pre-mRNA splicing process and have an impact on transcriptional efficiency. It was supposed that skipping of the adjacent exon was the preferred outcome when cryptic splice site was of low efficiency or not sufficient. So far, it is still a challenge to establish a rule to predict splicing outcomes. Though HMSA is an effective validation technique in the molecular laboratory, the appropriate RNA analysis ideally comes from affected tissue because of the tissue-specific dystrophin functions (Muntoni et al., 2003). So it is important to keep in mind that the splicing outcome would be different in artificial minigenes as compared to endogenous transcripts.

Early diagnosis of DMD and genetic confirmation of the causative mutation in patients are important. Once a mutation is identified, carrier analysis of female relatives can be performed. In our study, *DMD* gene mutation was inherited from the mother in 66% (66/100) of cases, whereas the remaining 34% (34/100) were de novo, which was consistent with a previous report (30%) (Sakthivel Murugan et al., 2013). However, it should be noted that a mother without any mutation in her peripheral blood lymphocytes is still at risk due to the possibility of

germinal mosaicism (Bakker et al., 1989; van Essen et al., 1992).

Prenatal diagnosis and PGD are valid tools to reduce the risk of having affected children. In 50 families with confirmed mutations, prenatal diagnoses were successfully performed by MLPA or Sanger sequencing. Eight fetuses were verified as affected boy, approximately theoretical value 25%, and five fetuses were carriers in 34 mother carriers. On the other hand, all fetuses were identified as unaffected in 16 mothers without mutation in their peripheral blood lymphocytes. In P30 family with deletion of exons 48–50, PGD was performed and a healthy boy was successfully delivered. Therefore, it is obvious that PGD is an alternative to prenatal diagnosis for a family at high risk of transmitting an inherited disease to offspring and avoiding the possible termination of pregnancy. Specific mutation detection (Girardet et al., 2003) and haplotype analysis (Lee et al., 1998) with gender determination have been universally used for PGD of DMD.

In conclusion, it is a great challenge to perform comprehensive analyses of causative mutations in *DMD* because of its large size and the variety of mutation types (Stockley et al., 2006). Our study provided a comprehensive combination of MLPA, NGS, and HMSA, which is an effective strategy to identify *DMD* pathogenic variants. Early and accurate genetic diagnosis and confirmation of variants are essential for therapy and prenatal diagnosis/PGD to reduce the risk of recurrence of DMD in affected families.

Contributors

Min-yue DONG set up the theme and examined the manuscript. Yan-mei YANG performed the experiments and wrote the manuscript. Kai YAN, Bei LIU, Li-ya WANG, and Ying-zhi HUANG performed the experiments. Min CHEN was responsible for editing the grammar of the manuscript. Ye-qing QIAN guided the modification process. Yi-xi SUN and Hong-ge LI were responsible for collecting the patients. All authors read and approved the final manuscript and, therefore, had full access to all the data in the study and take responsibility for the integrity and security of the data.

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Compliance with ethics guidelines

Yan-mei YANG, Kai YAN, Bei LIU, Min CHEN, Li-ya WANG, Ying-zhi HUANG, Ye-qing QIAN, Yi-xi SUN, Hong-ge LI, and Min-yue DONG declare that they have no conflict of interest.

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008 (5). Informed consent was obtained from all patients for being included in the study. Additional informed consent was obtained from all patients for whom identifying information is included in this article.

References

- Bakker E, Veenema H, den Dunnen JT, et al., 1989. Germinal mosaicism increases the recurrence risk for 'new' Duchenne muscular dystrophy mutations. *J Med Genet*, 26(9):553-559.
<https://doi.org/10.1136/jmg.26.9.553>
- Baralle D, Baralle M, 2005. Splicing in action: assessing disease causing sequence changes. *J Med Genet*, 42(10):737-748.
<https://doi.org/10.1136/jmg.2004.029538>
- Beggs AH, Koenig M, Boyce FM, et al., 1990. Detection of 98% of DMD/BMD gene deletions by polymerase chain reaction. *Hum Genet*, 86(1):45-48.
<https://doi.org/10.1007/BF00205170>
- Bovolenta M, Neri M, Fini S, et al., 2008. A novel custom high density-comparative genomic hybridization array detects common rearrangements as well as deep intronic mutations in dystrophinopathies. *BMC Genomics*, 9:572.
<https://doi.org/10.1186/1471-2164-9-572>
- Buratti E, Baralle FE, 2004. Influence of RNA secondary structure on the pre-mRNA splicing process. *Mol Cell Biol*, 24(24):10505-10514.
<https://doi.org/10.1128/MCB.24.24.10505-10514.2004>
- Buratti E, Baralle M, Baralle FE, 2006. Defective splicing, disease and therapy: searching for master checkpoints in exon definition. *Nucleic Acids Res*, 34(12):3494-3510.
<https://doi.org/10.1093/nar/gkl498>
- Burset M, Seledtsov IA, Solovyev VV, 2001. SpliceDB: database of canonical and non-canonical mammalian splice sites. *Nucleic Acids Res*, 29(1):255-259.
<https://doi.org/10.1093/nar/29.1.255>
- Chen LJ, Diao ZY, Xu ZP, et al., 2016. The clinical application of preimplantation genetic diagnosis for the patient affected by congenital contractural arachnodactyly and spinal and bulbar muscular atrophy. *J Assist Reprod Genet*, 33(11):1459-1466.
<https://doi.org/10.1007/s10815-016-0760-y>
- Echevarria L, Aupy P, Goyenvalle A, 2018. Exon-skipping advances for Duchenne muscular dystrophy. *Hum Mol Genet*, 27(R2):R163-R172.
<https://doi.org/10.1093/hmg/ddy171>

- Fairclough RJ, Wood MJ, Davies KE, 2013. Therapy for Duchenne muscular dystrophy: renewed optimism from genetic approaches. *Nat Rev Genet*, 14(6):373-378. <https://doi.org/10.1038/nrg3460>
- Flanigan KM, von Niederhausern A, Dunn DM, et al., 2003. Rapid direct sequence analysis of the dystrophin gene. *Am J Hum Genet*, 72(4):931-939. <https://doi.org/10.1086/374176>
- Girardet A, Hamamah S, Dechaud H, et al., 2003. Specific detection of deleted and non-deleted dystrophin exons together with gender assignment in preimplantation genetic diagnosis of Duchenne muscular dystrophy. *Mol Hum Reprod*, 9(7):421-427. <https://doi.org/10.1093/molehr/gag050>
- Haas J, Katus HA, Meder B, 2011. Next-generation sequencing entering the clinical arena. *Mol Cell Probes*, 25(5-6):206-211. <https://doi.org/10.1016/j.mcp.2011.08.005>
- Habara Y, Takeshima Y, Awano H, et al., 2009. In vitro splicing analysis showed that availability of a cryptic splice site is not a determinant for alternative splicing patterns caused by +1G→A mutations in introns of the dystrophin gene. *J Med Genet*, 46(8):542-547. <https://doi.org/10.1136/jmg.2008.061259>
- Hertel KJ, 2008. Combinatorial control of exon recognition. *J Biol Chem*, 283(3):1211-1215. <https://doi.org/10.1074/jbc.R700035200>
- Jefferies JL, Eidem BW, Belmont JW, et al., 2005. Genetic predictors and remodeling of dilated cardiomyopathy in muscular dystrophy. *Circulation*, 112(18):2799-2804. <https://doi.org/10.1161/CIRCULATIONAHA.104.528281>
- Juan-Mateu J, González-Querada L, Rodriguez MJ, et al., 2013. Interplay between *DMD* point mutations and splicing signals in dystrophinopathy phenotypes. *PLoS ONE*, 8(3):e59916. <https://doi.org/10.1371/journal.pone.0059916>
- Kralovicova J, Hwang G, Asplund AC, et al., 2011. Compensatory signals associated with the activation of human GC 5' splice sites. *Nucleic Acids Res*, 39(16):7077-7091. <https://doi.org/10.1093/nar/gkr306>
- Krawczak M, Thomas NST, Hundrieser B, et al., 2007. Single base-pair substitutions in exon-intron junctions of human genes: nature, distribution, and consequences for mRNA splicing. *Hum Mutat*, 28(2):150-158. <https://doi.org/10.1002/humu.20400>
- Lalic T, Vossen RHAM, Coffa J, et al., 2005. Deletion and duplication screening in the *DMD* gene using MLPA. *Eur J Hum Genet*, 13(11):1231-1234. <https://doi.org/10.1038/sj.ejhg.5201465>
- Lee SH, Kwak IP, Cha KE, et al., 1998. Preimplantation diagnosis of non-deletion Duchenne muscular dystrophy (DMD) by linkage polymerase chain reaction analysis. *Mol Hum Reprod*, 4(4):345-349. <https://doi.org/10.1093/molehr/4.4.345>
- Li Y, Pan Q, Gu YS, 2017. Phenotype-genotype correlation with Sanger sequencing identified retinol dehydrogenase 12 (*RDH12*) compound heterozygous variants in a Chinese family with Leber congenital amaurosis. *J Zhejiang Univ-Sci B (Biomed & Biotechnol)*, 18(5):421-429. <https://doi.org/10.1631/jzus.B1600156>
- Ma PP, Zhang S, Zhang H, et al., 2018. Comprehensive genetic characteristics of dystrophinopathies in China. *Orphanet J Rare Dis*, 13:109. <https://doi.org/10.1186/s13023-018-0853-z>
- Muntoni F, Torelli S, Ferlini A, 2003. Dystrophin and mutations: one gene, several proteins, multiple phenotypes. *Lancet Neurol*, 2(12):731-740. [https://doi.org/10.1016/S1474-4422\(03\)00585-4](https://doi.org/10.1016/S1474-4422(03)00585-4)
- Parada GE, Munita R, Cerda CA, et al., 2014. A comprehensive survey of non-canonical splice sites in the human transcriptome. *Nucleic Acids Res*, 42(16):10564-10578. <https://doi.org/10.1093/nar/gku744>
- Pico AR, Bader GD, Demchak B, et al., 2014. The Cytoscape app article collection. *F1000Res*, 3:138. <https://doi.org/10.12688/f1000research.4642.1>
- Rando TA, 2001. The dystrophin-glycoprotein complex, cellular signaling, and the regulation of cell survival in the muscular dystrophies. *Muscle Nerve*, 24(12):1575-1594. <https://doi.org/10.1002/mus.1192>
- Roberts RG, Gardner RJ, Bobrow M, 1994. Searching for the 1 in 2,400,000: a review of dystrophin gene point mutations. *Hum Mutat*, 4(1):1-11. <https://doi.org/10.1002/humu.1380040102>
- Roca X, Sachidanandam R, Krainer AR, 2003. Intrinsic differences between authentic and cryptic 5' splice sites. *Nucleic Acids Res*, 31(21):6321-6333. <https://doi.org/10.1093/nar/gkg830>
- Richards S, Aziz N, Bale S, et al., 2015. Standards and guidelines for the interpretation of sequence variants: a joint consensus recommendation of the American College of Medical Genetics and Genomics and the Association for Molecular Pathology. *Genet Med*, 17(5):405-424. <https://doi.org/10.1038/gim.2015.30>
- Sakthivel Murugan SM, Arthi C, Thilothammal N, et al., 2013. Carrier detection in Duchenne muscular dystrophy using molecular methods. *Indian J Med Res*, 137(6):1102-1110.
- Schouten JP, McElgunn CJ, Waaijer R, et al., 2002. Relative quantification of 40 nucleic acid sequences by multiplex ligation-dependent probe amplification. *Nucleic Acids Res*, 30(12):e57. <https://doi.org/10.1093/nar/gnf056>
- Stockley TL, Akber S, Bulgin N, et al., 2006. Strategy for comprehensive molecular testing for Duchenne and Becker muscular dystrophies. *Genet Test*, 10(4):229-243. <https://doi.org/10.1089/gte.2006.10.229>
- Takeshima Y, Yagi M, Okizuka Y, et al., 2010. Mutation spectrum of the dystrophin gene in 442 Duchenne/Becker muscular dystrophy cases from one Japanese referral center. *J Hum Genet*, 55(6):379-388. <https://doi.org/10.1038/jhg.2010.49>

- Tuffery-Giraud S, Bérout C, Leturcq F, et al., 2009. Genotype-phenotype analysis in 2,405 patients with a dystrophinopathy using the UMD-DMD database: a model of nationwide knowledgebase. *Hum Mutat*, 30(6):934-945. <https://doi.org/10.1002/humu.20976>
- van Essen AJ, Abbs S, Baiget M, et al., 1992. Parental origin and germline mosaicism of deletions and duplications of the dystrophin gene: a European study. *Hum Genet*, 88(3):249-257. <https://doi.org/10.1007/BF00197255>
- Wei XM, Dai Y, Yu P, et al., 2013. Targeted next-generation sequencing as a comprehensive test for patients with and female carriers of DMD/BMD: a multi-population diagnostic study. *Eur J Hum Genet*, 22(1):110-118. <https://doi.org/10.1038/ejhg.2013.82>
- Xia ZJ, Lin J, Lu LP, et al., 2018. An intronic mutation c.6430-3C>G in the *F8* gene causes splicing efficiency and premature termination in hemophilia A. *Blood Coagul Fibrinolysis*, 29(4):381-386. <https://doi.org/10.1097/MBC.0000000000000730>
- Ye Y, Yu P, Yong J, et al., 2014. Preimplantational genetic diagnosis and mutation detection in a family with duplication mutation of DMD gene. *Gynecol Obstet Invest*, 78(4):272-278. <https://doi.org/10.1159/000365083>
- Zhang XHF, Leslie CS, Chasin LA, 2005. Dichotomous splicing signals in exon flanks. *Genome Res*, 15(6):768-779. <https://doi.org/10.1101/gr.3217705>
- Zimowski JG, Massalska D, Holding M, et al., 2014. MLPA based detection of mutations in the dystrophin gene of 180 Polish families with Duchenne/Becker muscular dystrophy. *Neurol Neurochir Pol*, 48(6):416-422. <https://doi.org/10.1016/j.pjnns.2014.10.004>

List of electronic supplementary materials

- Table S1 Oligonucleotide primers for detection of mutations in *DMD* gene
- Table S2 Deletions in *DMD* gene detected by MLPA
- Table S3 Duplications in *DMD* gene detected by MLPA
- Table S4 Point mutations in *DMD* gene detected by NGS

中文概要

题目: 假肥大型肌营养不良症 (DMD/BMD) 遗传学诊断及剪接突变的致病性分析

目的: 针对 100 例无亲缘关系的假肥大型肌营养不良症 (DMD/BMD) 患者, 联合应用多种检测技术进行遗传学诊断, 并且建立个体化产前诊断及胚胎植入前遗传学诊断方案, 以最大限度地降低 DMD/BMD 患儿的出生。

创新点: 通过 minigene 剪接实验分析 *DMD*: c.1149+1G>A 和 c.1150-2A>G 突变是否导致剪接异常, 并确定剪接方式。

方法: 收集 100 例无亲缘关系 DMD/BMD 患者的临床资料, 应用多重连接依赖式探针扩增技术 (MLPA)、第二代测序 (NGS)、minigene 剪接实验 (HMSA) 进行遗传学诊断, 并通过单体型分析及性别鉴定进行胚胎植入前遗传学诊断。

结论: 联合应用多种检测技术可以尽早地对患者进行遗传学诊断, 为临床遗传咨询和产前诊断及胚胎植入前遗传学诊断提供了科学依据。

关键词: *DMD* 基因; 突变; 遗传学诊断; 剪接突变; Minigene 剪接实验