Durable Exon Skipping and Dystrophin Production With Endosomal Escape Vehicle (EEV™)–Oligonucleotide Conjugates in Preclinical Models of Duchenne Muscular Dystrophy

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INTRODUCTION

- Currently approved phosphorodiamidate morpholino oligomer (PMO) therapies for Duchenne muscular dystrophy (DMD) are designed to restore the messenger RNA (mRNA) reading frame and produce dystrophin by exon skipping, but have shown modest improvements.[1,2]
  - Intracellular delivery of oligonucleotides is challenging because of poor cell entry and limited escape from the endosome in the target cell.[3,4]
- To enhance PMO delivery to target tissues, we designed a family of proprietary cyclic cell-penetrating peptides that form the core of the Endosomal Escape Vehicle (EEV™) platform[5] **(Figure 1)**.
  - Results of preliminary studies in *mdx* and D2-*mdx* mice demonstrated that EEV-PMO constructs dosed monthly produce dystrophin in skeletal and cardiac muscle by exon skipping.[6,7]

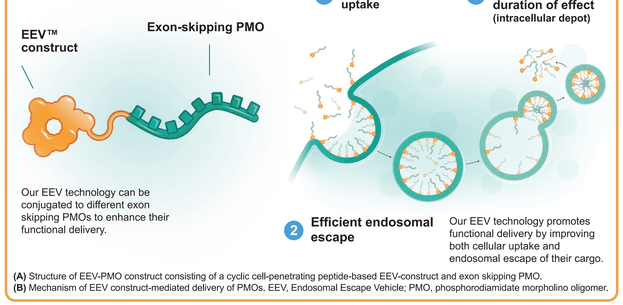
OBJECTIVE

- To assess the durable efficacy and therapeutic potential of exon skipping EEV-PMO constructs with less frequent dosing in preclinical models of DMD.

MATERIALS AND METHODS

- EEV-PMO-23, a DMD exon 23 skipping PMO conjugated to the EEV platform, was administered as an intravenous (IV) injection every 6 weeks (Q6W) to assess exon skipping, dystrophin production, and muscle contractility in D2-*mdx*[8] mice (**Figures 2–4**). These mice carry a nonsense mutation in exon 23.
- del44hDMD.*mdx* are human dystrophin (hDMD)–expressing mice engineered with a deletion in the hDMD exon 44 transgene on the *mdx* background, resulting in an exon 45 skip–amenable mouse line. These mice were treated with a human exon 45 skipping EEV-PMO construct (EEV-PMO-45) (**Figure 5**).
- del45hDMD.*mdx* are hDMD-expressing mice engineered with a deletion in the hDMD exon 45 transgene on the *mdx* background, resulting in an exon 44 skip–amenable mouse line. These mice were treated with a human exon 44 skipping EEV-PMO construct (EEV-PMO-44) (**Figure 6**).
- Exon-skipping efficiency was analyzed by either reverse-transcriptase polymerase chain reaction (RT-PCR) and LabChip (Perkin Elmer, Santa Clara, CA) (**Figure 2**) or digital droplet RT-PCR (**Figures 5 and 6**). Dystrophin restoration was evaluated by Simple Western Jess (Bio-Techne, Minneapolis, MN).
- Maximum tetanic muscle force and resistance towards eccentric-induced muscle damage via repeated eccentric (ECC) contractions were measured in the tibialis anterior muscle using a 3-in-1 Whole Animal Muscle Physiology system from Aurora Scientific (Aurora, ON, Canada).

Figure 1. EEV-PMO Construct Structure and Mechanism of Action.



(A) Structure of EEV-PMO construct consisting of a cyclic cell-penetrating peptide-based EEV-construct and exon skipping PMO. **(B)** Mechanism of EEV construct-mediated delivery of PMOs. EEV, Endosomal Escape Vehicle; PMO, phosphorodiamidate morpholino oligomer.

CONCLUSIONS

- EEV-PMO constructs produced robust and durable exon skipping and dystrophin production following 6-week dosing in preclinical models of DMD.
- Preliminary studies with exon 45 and 44 skipping EEV-PMO constructs showed robust exon skipping and dystrophin production in mouse models harboring exon 45 and 44 skip–amenable mutations, respectively.
- These findings support earlier studies demonstrating the preclinical efficacy of ENTR-601-44 and ENTR-601-45 and support further study of these EEV-PMO constructs in patients with exon 44 and 45 skip–amenable DMD, respectively.
  - A phase 1 clinical trial of ENTR-601-44 in healthy volunteers is ongoing with an estimated completion date in the second half of 2024.

ACKNOWLEDGMENTS

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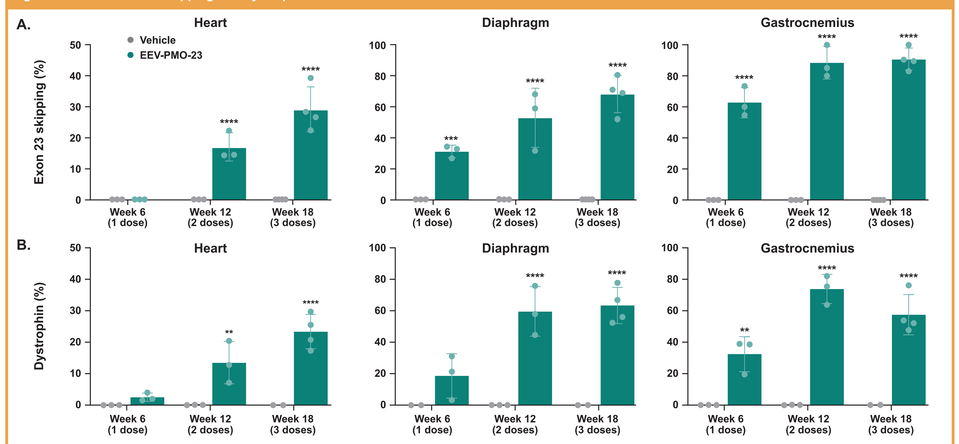
RESULTS

Exon Skipping and Dystrophin Production With EEV-PMO-23 in D2-mdx Mouse Model of DMD

- Significant mouse exon 23 skipping (**Figure 2A**) and dystrophin production (**Figure 2B**) were observed in cardiac and skeletal muscle following three Q6W doses of EEV-PMO-23.
  - Improvements over vehicle-treated mice were observed after the first dose in skeletal muscle and after the second dose in cardiac muscle.

Figure 2. Mouse Exon 23 Skipping and Dystrophin Production With EEV-PMO-23 in D2-*mdx* Mice.

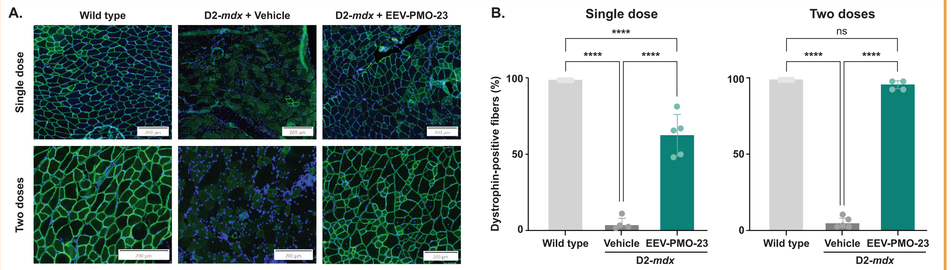


D2-*mdx* mice were treated with 80 mg/kg EEV-PMO-23 or vehicle Q6W. Exon skipping **(A)** and dystrophin production **(B)** were analyzed 6 weeks after each dose. Data shown as mean ± SD. One-way ANOVA was used for statistical comparison; ***p*<0.01, ****p*<0.001,*****p*<0.0001 vs. vehicle. ANOVA, analysis of variance; EEV, Endosomal Escape Vehicle; PMO, phosphorodiamidate morpholino oligomer; Q6W, every 6 weeks; SD, standard deviation.

Dystrophin Restoration With EEV-PMO-23 in D2-mdx Mouse Model of DMD

- Two Q6W doses of EEV-PMO-23 significantly increased dystrophin protein restoration via immunohistochemistry in the skeletal muscle of D2-*mdx* mice to similar levels observed in wild type mice with highly significant, evenly distributed, and correctly localized dystrophin protein restoration seen 6 weeks after one dose (**Figure 3**).

Figure 3. Dystrophin Expression With EEV-PMO-23 in D2-*mdx* Mice.

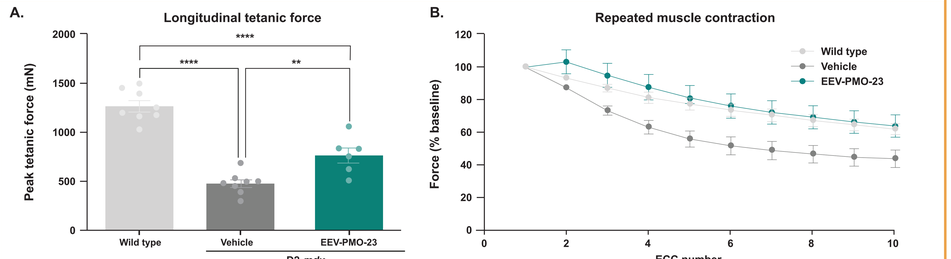


D2-*mdx* mice were treated with 80 mg/kg EEV-PMO-23 or vehicle Q6W. Gastrocnemius muscle was assessed for dystrophin expression 6 weeks after each dose. **(A)** Immunofluorescence showing dystrophin in green and DAPI in blue after one or 2 doses. **(B)** Quantification of dystrophin-positive fibers. Data shown as mean ± SD. One-way ANOVA was used for statistical comparison; *****p*<0.0001 vs. vehicle. ANOVA, analysis of variance; DAPI, 4',6-diamidino-2-phenylindole; EEV, Endosomal Escape Vehicle; ns, not significant; PMO, phosphorodiamidate morpholino oligomer; Q6W, every 6 weeks; SD, standard deviation.

EEV-PMO-23 Improves Muscle Contractile Function in D2-mdx Mouse Model of DMD

- Skeletal muscle contractile function was significantly improved following two Q6W doses of EEV-PMO-23 (**Figure 4**).

Figure 4. Muscle Contractility With EEV-PMO-23 in D2-*mdx* Mice.

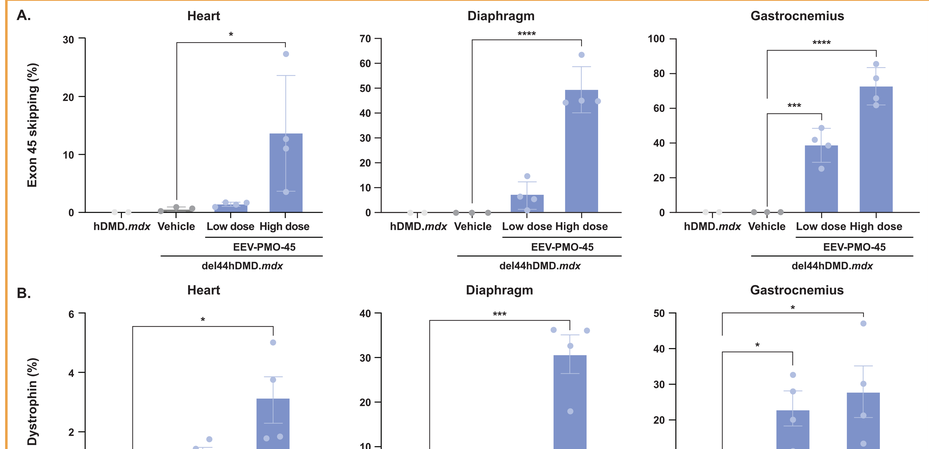


D2-*mdx* mice were treated with 80 mg/kg EEV-PMO-23 or vehicle Q6W. Muscle contractility of the tibialis anterior muscle was assessed 6 weeks after the second dose via **(A)** maximum tetanic force and **(B)** ECC-induced muscle force loss generated by repeated ECC contraction. Data shown as mean ± SEM. One-way ANOVA was used for statistical comparison; ***p*<0.01, *****p*<0.0001. ANOVA, analysis of variance; ECC, eccentric force; EEV, Endosomal Escape Vehicle; PMO, phosphorodiamidate morpholino oligomer; Q6W, every 6 weeks; SEM, standard error of the mean.

Exon Skipping and Dystrophin Production in Mutation-Specific Murine Models

- EEV-PMO-45 produced robust human exon 45 skipping and human dystrophin production in del44hDMD.*mdx* mice harboring an exon 45 skip–amenable mutation (**Figure 5**).

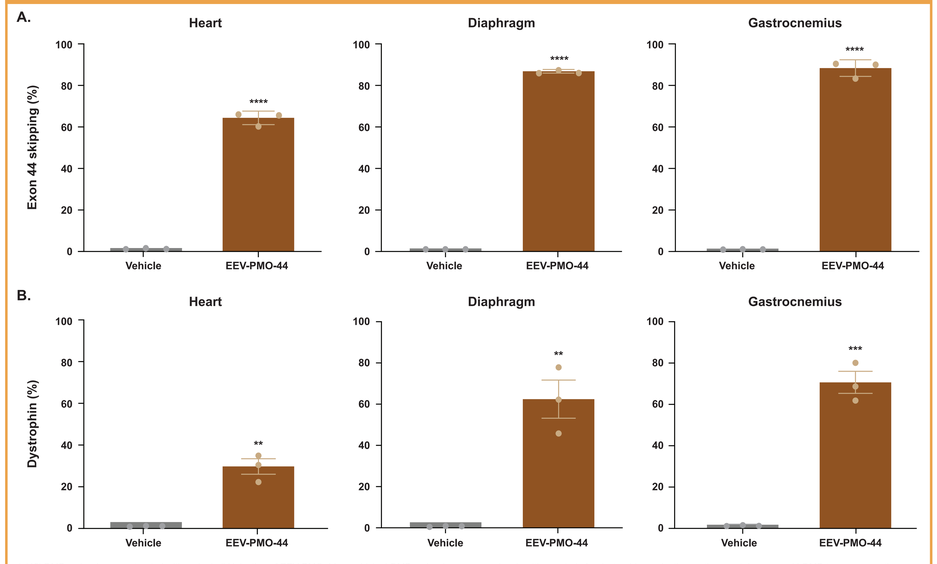
Figure 5. Efficacy of EEV-PMO-45 in del44hDMD.*mdx* Mice With an Exon 45 Skip–Amenable Mutation.



del44hDMD.*mdx* mice were treated with a single IV injection of EEV-PMO-45 or vehicle. hDMD.*mdx* mice were used as healthy controls for dystrophin production as they contain a normal hDMD transgene on the *mdx* background. Human exon 45 skipping **(A)** and dystrophin protein expression **(B)** were analyzed in the gastrocnemius, diaphragm, and heart 2 weeks after dosing. Data shown as mean ± SD. One-way ANOVA was used for statistical comparison; **p*<0.05, ****p*<0.001,*****p*<0.0001 vs. vehicle. ANOVA, analysis of variance; EEV, Endosomal Escape Vehicle; hDMD, human dystrophin; IV, intravenous; PMO, phosphorodiamidate morpholino oligomer; SD, standard deviation.

- A single IV dose of EEV-PMO-44 produced robust human exon 44 skipping and human dystrophin production in del45hDMD.*mdx* mice harboring an exon 44 skip–amenable mutation (**Figure 6**).

Figure 6. Efficacy of EEV-PMO-44 in del45hDMD.*mdx* Mice With an Exon 44 Skip–Amenable Mutation.



del45hDMD.*mdx* mice were treated with a single IV injection of EEV-PMO-44 or vehicle. hDMD.*mdx* mice were used as healthy controls for dystrophin production as they contain a normal hDMD transgene on the *mdx* background. Human exon 44 skipping **(A)** and dystrophin protein expression **(B)** were analyzed in the gastrocnemius, diaphragm, and heart 2 weeks after dosing. Data shown as mean ± SD. One-way ANOVA was used for statistical comparison; *****p*<0.0001 vs. vehicle. ANOVA, analysis of variance; EEV, Endosomal Escape Vehicle; hDMD, human dystrophin; PMO, phosphorodiamidate morpholino oligomer; SD, standard deviation.