**TITLE:**

**Preparation of rAAV9 to Overexpress or Knockdown Genes in Mouse Hearts**

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**KEY WORDS:**

Gene delivery, cardiomyocyte, adeno-associated virus, gene overexpression, gene knockdown, subcutaneous injection.

**SHORT ABSTRACT:**

In this manuscript, a method to prepare recombinant adeno-associated virus 9 (rAAV9) vectors to manipulate gene expression in the mouse heart is described.

**LONG ABSTRACT:**

Controlling expression or activity of specific genes by myocardial delivery of genetic materials in murine models permits investigation of gene functions as well as their therapeutic potential in the heart. There are limited approaches for *in vivo* molecular intervention in the mouse heart. Recombinant adeno-associated virus (rAAV)-based genome engineering has been utilized as an essential tool for *in vivo* cardiac gene manipulation. The specific advantages of this technology include high efficiency, high specificity, low genomic integration rate, minimalimmunogenicity, and minimal pathogenicity. Here, a detailed procedure to construct, package, and purify the rAAV9 vectors is described. Subcutaneous injection of rAAV9 into neonatal pups results in robust expression or efficient knockdown of the gene(s) of interest in the mouse heart, but not in the liver and other tissues. Using the cardiac specific TnnT2 promoter, high expression of the GFP gene in the heart was obtained. Additionally, target mRNA was inhibited in the heart when a rAAV9-U6-shRNA was utilized. Working knowledge of rAAV9 technology may serve the scientist in cardiovascular investigations.

**INTRODUCTION:**

Controlling expression or activity of specific genes in various biological systems has become a valuable strategy in the study of gene function1. A direct means of accomplishing this goal is to manipulate nucleotide sequences and generate mutant alleles. Although **making precise, targeted changes to the genome of living cells is still** a time-consuming and **labor-intensive** practice, **the development of the powerful TALEN and Crispr/Cas9 tools has opened** a new era of genome editing2-5. A more routine laboratory method for gene manipulation has focused on the introduction of genetic materials (DNAs and RNAs containing coding sequences or siRNAs/shRNAs) into the cells to express or knockdown the gene(s) of interest1,6.

In many cases, the major bottleneck for gene manipulation is the delivery of DNA, RNA, or protein into the cells. With regard to *in vitro* studies, efficient transfection systems have been established in many cultured cell lines. With reference to the mouse model in particular, *in vivo* gene delivery is more challenging. There are a series of extra- and intracellular barriers need to be bypassed in order to achieve efficient cellular uptake of the exogenous reagents. Additional obstacles include the rapid clearance and the short duration of the delivered materials7,8. One strategy to circumvent these issues is to use viral vectors as “carriers” or “vehicles” for *in vivo* gene delivery. The naturally evolved transduction properties of viruses allow the efficient delivery of a gene of interest into cells7,9,10. Numerous types of viral vectors have been developed and enable flexible *in vivo* gene manipulation in different cell types and organs in mice.

The most commonly used viral systems include Retrovirus, Lentivirus, Adenovirus and Adeno-associated virus (AAV)11. Retroviruses are single-stranded RNA viruses and can introduce their genetic material to the host cell genome in a stable manner during mitotic division, providing potential for lifelong expression of the transduced genes in the target cells and organs12-14. However, many types of retroviruses only infect dividing cells, and their efficacy in non-dividing cells is very low15. This limits their utility for gene delivery. Lentivirus is a genus of the viruses of *Retroviridae* family. Different from other retroviruses, Lentivirus can infect both dividing and non-dividing cells, and has been widely used for gene transfer into post-mitotic and highly differentiated cells16. The life cycle of Lentivirus also involves integration of vector DNA into the host genomes. Thus, Lentivirus-mediated gene delivery enables stable and long-duration expression of the transduced genetic elements16-18. However, this feature may represent a double-edged sword in the use of these viruses to manipulate gene expression, as integration of vector DNA may lead to insertional mutagenesisin the host cells and can cause artefactual effects. Adenovirus is another widely used gene delivery system. Unlike retroviruses and lentiviruses, Adenoviruses are non-integrated, and do not interfere with the genomic integrity of host cells8,10,11,19. In addition, Adenoviruses can transfect DNA into many cell types, and infection is not dependent upon active cell division19. Another important characteristic of Adenoviruses is the ease of vector purification, as the viral vectors have the ability to be replicated19,20. However, the major caveat of this system is that Adenovirus infection can trigger strong immune responses in target cells and organs19, restricting its use in many investigations, particularly in gene therapy studies.

Compared with these different types of viral vectors, recombinant Adeno-associated virus (rAAV) appears to be the ideal gene delivery system21,22. It exhibits minimal immunogenicity and pathogenicity23,24. In addition, rAAV infects a broad range of cell types, including both dividing and non-dividing cells. In most cases, rAAV does not integrate into host genomes, thus the risk of undesired genetic/genomic changes in target cells is low22.

Recently, rAAV systems have been successfully used for *in vivo* deliver of DNAs encoding proteins, miRNAs, shRNAs, and Crispr-gRNAs into mouse cardiac muscle23,25-29. This methodology has facilitated the fundamental investigations and gene therapy studies in the field of cardiovascular research. Here, the detailed procedure to generate rAAV9 vectors that efficiently overexpress or knockdown the genes of interest in mouse hearts, was described. The protocol provides a simple and effective method of manipulating cardiac gene expression in murine experimental models.

**PROTOCOL:**

All described steps were performed under protocols approved by Biosafety Committee and the Institutional Animal Care and Use Committee of Boston Children’s Hospital. Boston Children’s Hospital has pathogen free mouse facilities with regulated hour light/dark cycles and climate control. Veterinary and animal care staff change cages and ensure the health of the mice. The facilities are AAALAC certified and have active Animal Welfare Assurance certification (AAALAC Accreditation Granted on 2/24/1992. The Animal Welfare Assurance number: A3303-01). Mice were euthanized by CO2 delivered from a compressed gas source. Tissue samples were collected after confirming that heart rate, movement and breathing of animals have ceased. Neonatal rodents are resistant to CO2 euthanasia and were euthanized by decapitation using sharp scissors. These methods are consistent with the recommendations of the Panel on Euthanasia of the American Veterinary Medical Association.

**1. Generation of rAAV9 constructs by cloning cDNA or shRNA expression cassette into the plasmid backbone.**

Note: The rAAV9 plasmid, containing the inverted terminal repeats (ITRs) of AAV2, used for gene overexpression has been modified to harbor the chicken TNNT2promoter (rAAV9.cTNT), which enables cardiomyocyte-specific expression of transduced genes25,26,29. Unique NheI and KpnI sites have been introduced into the plasmid and downstream of the promoter. The cDNA fragments encoding genes of interest can be cloned into the rAAV9 backbone using these two restriction sites25,26,29. Here, as an example, the rAAV9 vector for overexpression of GFP gene in mouse hearts was generated. The resulting plasmid contains cTNT::GFP cassette flanked by two ITR sites (**Figure 1**). rAAV9.U6::shRNA constructs were used for gene knockdown25. Design shRNAs using online shRNA design servers. rAAV9.U6::shRNA can be generated either by annealing and ligating DNA oligos containing shRNA sequences into the restriction enzyme-digested rAAV9 vectors harboring U6 promoter, or by long-range PCR and intra-molecular Gibson assembly-based “seamless” construction30. The resulting plasmid should contain U6-shRNA cassette flanked by two ITR sites (**Figure 2**). Here, as an example, the rAAV9.U6::shRNA vector was constructed to knockdown Trbp mRNA (Trbp shRNA sequence: GCAGTGATGGATATGCATCTTCTCGAGAAGATGCATATCCATCACTCG). A scramble shRNA was used as a negative control (CCTAAGGTTAAGTCGCCCTCGCTCGAGCGAGGGCGACTTAACCTTAGG)

1.1) Clone cDNA or shRNA expression cassette into rAAV9 plasmid backbone. Transform the DNA into competent *E. Coli* cells.

Note: Use stbl2 or stbl3 *E. coli* cells for rAAV9 DNA transformation to minimize undesired ITR recombination.

1.2) Pick up the positive clone from the transformed *E. Coli* cells. Amplify the culture in 500ml Lilly－Barnett **medium** and extract the rAAV9 plasmid from the bacterial cells.

Note: Midi/Maxi prep rAAV9 plasmid to obtain high amount of DNA (>100 g). Before generating the virus, always analyze the sequence integrity of the AAV plasmids by restriction digestion and agarose gel electrophoresis as previously described (http://www.vvf.uzh.ch/cloningservice/11bpdeletion/itrintegrity.html).

**2. Transfection of HEK293 cells with rAAV9 plasmids**

2.1) Prepare 1 g/l linear polyethylenimine (PEI) solution: Dissolve PEI powder in endotoxin-free dH2O that has been heated to 70-80 °C. After cooling down to room temperature, neutralize the solution to pH7.0 with 1 M HCl. Filter sterilize (0.22 m) the solution. Aliquot the 1 g/l PEI stock solution (1400 L/tube) and store the solution at -20 °C.

2.2) Culture HEK293 cells in Dulbecco’s Modified Eagle Medium (DMEM) with 10% Fetal Bovine Serum (FBS) and 1% penicillin/streptomycin. Culture the cells in a 37 °C incubator with 5 ± 0.5 % carbon dioxide (CO2).

2.3) At day 0, plate HEK293 cells in ten 150 mm dishes 18-20 h before transfection by splitting >90% confluent cells at a 1:2 dilution.

Note: At day 1, the cells should reach 90% confluence.

2.4) At day 1, transfect HEK293 with rAAV9 plasmid (*ex.* rAAV9.cTNT::GFP or rAAV6.U6::shRNA constructs), Ad-Helper plasmid and AAV-Rep/Cap plasmid using PEI25,26,29.

2.4.1) For 10 dishes of cells at 90% confluence, mix 70 g AAV-Rep/Cap plasmid, 70 g rAAV9 plasmid and 200 g Ad-Helper plasmid in a 50 mL centrifuge tube.

2.4.2) If the cells are less confluent, adjust the DNA amount proportionally. For instance, if the cells are at 75% confluent, reduce the DNA amount proportionally (75/90 of the amount shown in step 2.4.1): mix 70X75/90=58.3 g AAV-Rep/Cap plasmid, 70X75/90 = 58.3 g rAAV9 plasmid and 200X75/90=166.7 g Ad-Helper plasmid in a 50 mL centrifuge tube.

2.4.3) Add 49 mL room temperature DMEM (without FBS) to the 50 mL tube, and mix well.

2.4.4) Add 1360 l PEI solution to make the PEI: DNA ratio (v/w) be 4:1. Mix well. Incubate at room temperature for 15-30 min.

2.4.5) Add 5 mL of the mixture prepared in step 2.4.4 to each 150 mm dish (50 mL mixture for 10 150 mm dishes).

2.5) Culture the cells in a 37 °C incubator with 5 ± 0.5 % CO2 for 60-72 h.

**3. Harvest of transfected HEK293 cells and purification of rAAV9 vectors**

3.1) Harvest the cells 60-72 h after transfection. Dislodge and suspend the cells in the dishes by pipetting up and down with the culture medium. Transfer all the cell suspensions to sterile 50 mL tubes.

3.2) Centrifuge the cells at 500 X g for 5 min. Resuspend the cell pellet with 5 mL PBS in each tube, and combine all the cell suspensions into one 50 mL tube.

3.3) Centrifuge the cells at 500 X g for 5 min. Discard supernatant. At this step, store the cell pellet at -80 °C, or purify the AAV from the pellet immediately as described in steps 3.4-3.15.

3.4) Prepare lysis buffer: 150 mM NaCl, 20 mM Tris-HCl, pH 8.0. Filter sterilize (0.22 M). Store the buffer at 4 °C.

3.5) Resuspend the pellet with 10 mL lysis buffer.

3.6) Freeze the lysate at -80 °C or in the dry ice/ethanol bath, then thaw it at 37 °C. Vortex for 10 min. Freeze and thaw the lysate 3 times.

3.7) Add MgCl2 solution to thawed-lysate (make the final concentration of MgCl2 in the lysate be 1 mM). Add nuclease to a final concentration of 250 U/mL. Incubate at 37 °C for 15 min to dissolve the DNA/protein aggregation.

Note: If the DNA/protein aggregation does not get dissolved after Benzonase treatment, dounce homogenize the lysates 20 times).

3.8) Centrifuge the sample at 4800 X g for 20 min at 4 °C. Collect the supernatant.

3.9) Meanwhile, prepare Iodixanol gradient:

3.9.1) Prepare 17% Iodixanol solution by mixing 5 mL 10X PBS, 0.05 mL 1 M MgCl2, 0.125 mL 1 M KCl, 10 mL 5 M NaCl and 12.5 mL of density gradient medium such as Optiprep. Adjust the total volume to 50 mL with H2O.

3.9.2) Prepare 25% solution by mixing 5 mL 10X PBS, 0.05 mL 1 M MgCl2 , 0.125 mL 1 M KCl, 20 mL density gradient medium and 0.2 mL 0.5% (w/v) Phenol Red. Adjust the total volume to 50 mL with H2O.

3.9.3) Prepare 40% solution by mixing 5 mL 10X PBS, 0.05 mL 1 M MgCl2, 0.125 mL 1 M KCl and 33.3 mL of density gradient medium. Adjust the total volume to 50 mL with H2O.

3.9.4) Prepare 60% solution by mixing 0.05 mL 1 M MgCl2, 0.125 mL 1 M KCl, 50 mL density gradient medium and 0.1 mL 0.5% (w/v) Phenol Red.

3.10) Load the Iodixanol gradient solution to the polypropylene tube in the order of 5 mL 17%, 5 mL 25%, 5 mL40% and 5 mL 60% from the bottom with a needle and syringe. Load all the lysate obtained from step 3.8 (14-16 mL) on the top of the gradient. The eventual gradient from the bottom to top is 60%, 40%, 25% and 17%, and lysate layer. Fill the tube to full with lysis buffer. Cover the tube with the cork.

3.11) Centrifuge at 185,000 X g for 90 min at 16 °C.

3.12) Harvest the viral fraction (40% layer) with syringe. Insert the needle (21 gauge) into the intersection between 40% and 60% fractions, only aspirating the 40% layer.

Note: Avoid aspirating ANY of the 25% layer.

3.13) Mix the viral fraction w/ sterilized polyoxyethylene-polyoxypropylene block copolymer PBS solution (10% polyoxyethylene-polyoxypropylene block copolymer stock 1:10000 diluted in PBS) up to total volume 15 mL. Load the mixture to the filter tube (Cut-off MW=100kD). Centrifuge at 2000 X g for 30 min at 4 °C.

3.14) Discard the solution at the bottom. Refill the filter tube with polyoxyethylene-polyoxypropylene block copolymer PBS solution to a total volume of 15 mL. Centrifuge at 2000 X g for 20 min at 4 °C. Repeat this step two more times. Collect the purified rAAV9 virus (the fraction above the filter).

3.15) Transfer purified rAAV9 in the filter tube to 1.7 mL tubes. Aliquot purified rAAV9 (100 - 400 l/ tube, depending on the volume and titer of the AAV) and store the virus at -80 °C.

Note: Avoid repeated freeze-thaws.

**4. Measure the titer of rAAV9**

4.1) Prepare standard DNA samples.

4.1.1) Design specific and efficient PCR primers for rAAV9 vectors, and optimize the PCR condition.

Note: The primers used in this study are “Forward: TCGGGATAAAAGCAGTCTGG; Reverse: TCGGACGGAGATACGTGAGT”. The PCR reaction was performed with the following conditions: initial denaturing at 95°C for 3 min, followed by 35 cycles of 95 °C for 20 sec, 60 °C for 15 sec 72 °C for 10 sec. The final extension was performed at 72 °C for 10 min. However, the optimized primers and PCR conditions is plasmid-specific, as the inset sequence in rAAV9 vector may affect the specificity and efficiency of PCR31.

4.1.2) Perform PCR reaction with the conditions shown in step 4.1.1. Purify the PCR product with gel extraction kit.

4.1.3) Measure the concentration of purified DNA with spectrophotometers. Calculate the concentration in DNA molecular numbers based on the molecular weight/length of PCR product.

4.1.3.1) Calculate the molecular concentration using the following equation: molecular concentration (DNA molecules or fragments/mL) = 6.23 X 1023 mol-1 X Con. X 10-6/Mw. Note: (6.23 X 1023 mol-1 is Avagadro's Number; Con.:DNA concentration in g/mL; Mw.: molecular weight in g/mol). For instance, if the obtained concentration of the PCR product is 100 g/mL, and its length is 200 bp, the molecular weight of the double-strand DNA is 2 X 200 X 310 = 124000 (The average molecular weight of each nucleotide in the single strand DNA is about 310 g/mol). The molecular concentration (DNA molecules/mL) = 6.23 X 1023 mol-1 X 100 g/ mL X 10-6 /124000 g/mol = 5.18 X 1014 DNA molecules/mL.

4.1.4) Perform dilution series of the DNA fragment, and prepare the standard samples with the concentration of 1013 molecules /mL, 1012 molecules /mL, 1011 molecules /mL, 1010 molecules /mL, 109 molecules /mL, 108 molecules /mL, 107 molecules /mL. Use 1 l solution for each standard samples for quantitative PCR (qPCR, in step 4.6).

4.2) Mix 5 l purified rAAV9 solution with 5 l 10X DNAse buffer, 1 l DNAse 10000 U/ml), and 39 l ddH2O. The total volume is 50 l.

4.3) Incubate the vial at 37 °C for 30 min to remove residual unpackaged plasmid DNA.

4.4) Inactivate DNAse at 95 °C for 10 min. Cool down the solution, add 44 l H2O, 5 l 10 X DNAse buffer and 1 l Proteinase K stock (10 mg/mL).

4.5) Incubate the solution at 50 °C for 2 h. Stop the reaction and inactivate Proteinase K at 95 °C for 10 min.

4.6) Use 1 l sample for quantitative PCR (qPCR) assay. Calculate the titer.

4.6.1) Run quantitative PCR (qPCR) using samples from step 4.1.4 (standard samples) and from step 4.5 (samples to be measured), with the primers designed in step 4.1.1.

4.6.1.1) For each reaction, mix 10 l 2X SybrGreen master mix (containing Taq polymerase, dNTP mix, buffer, MgCl2 and SYBR Green), 0.5 l forward primer (5 M), 0.5 l reverse primer (5 M), 8 l H2O and 1 l sample to be measured. Perform qPCR with the following conditions: holding the samples at 50 °C for 2 min and 95 °C for 10 min; followed by 40 cycles of 95 °C for 15 sec, 60 °C for 1 min; for melt stage, incubate the samples at 95 °C for 30 sec and 60 °C for 15 sec. Generate the standard curve based on the CT numbers of the standard samples (**Figure 3**).

4.6.2) Calculate the molecular concentration/titer of the AAV sample against the standard curve. The rAAV9 has single-strand DNA genome, so the molecular concentration should be 2 fold higher than the calculated value (2Xpower (10, y), **Figure 3B**). In addition, the titer of the purified rAAV9 will be 20 fold higher than what is obtained from the calculation, due to the 1:20 dilution of the virus in DNAse and Proteinase K reactions (5 l in 100 l total).

**5. rAAV9 injection in neonatal mice and gene expression assays in the heart**

5.1) Prepare rAAV9 working solutions in polyoxyethylene-polyoxypropylene block copolymer PBS solution. Make the virus stock with the titers of 1-7 X 1012 particles/mL.

Note: Deliver 50-70 l rAAV9 solution into each postnatal day 0.5-1.5 mice by subcutaneous injection. To achieve efficient gene overexpression or knockdown, it is recommended to perform a pilot test for each study to optimize the amount of injected AAV. Use the same amount of rAAV9.cTNT::Luc or rAAV9.U6::scramble controls for each study to minimize the bias. (We use 1–1.5 × 1011 particles/pup for overexpression, 2.5–5 × 1011 particles/pup for knockdown, for postnatal day 0.5 - 1.5 mice).

5.2) Treat Neonatal mice with rAAV9 at P0.5 – P2.5 by subcutaneous injection.

5.2.1) Pre-fill 29G1/2, 0.33 X 12.7 mm insulin syringe with the rAAV9 solution. Be careful to remove air bubbles.

5.2.2) Hold the pup in one hand with thumb and forefinger. Prior to injection, swipe the back skin of the pup with swab stick saturated with 70% isopropyl alcohol to maintain the sterile condition. Insert the syringe needle into anterior-dorsal subcutis of the animal at an angle of 5 to 10 degrees. Inject 50-70 l rAAV9 solution with the insulin syringe.

Note: rAAV9 can also be delivered to the mouse via intraperitoneal or intravenous injection26,27. Efficient expression of the delivered genes in the heart can be obtained. However, intraperitoneal injection sometimes may result in leaky expression in the liver. After injection, condition of the pups was monitored every day.

5.3) The level of gene expression in the heart can be monitored with qPCR, immunofluorescence, or western blot (representative results are shown in **Figure 4 and 5**)25,26.

Note: Mice were euthanized by CO2 delivered from a compressed gas source. Tissue samples were collected after confirming that heart rate, movement and breathing of animals have ceased. Neonatal rodents are resistant to CO2 euthanasia and were euthanized by decapitation using sharp scissors. The method is consistent with the recommendations of the Panel on Euthanasia of the American Veterinary Medical Association.

**REPRESENTATIVE RESULTS:**

The strategies for rAAV9 to construct rAAV9.cTNT::GFP or rAAV9.U6::shRNA plasmids are shown in Figure 1 and Figure 2, respectively. As the examples, the rAAV9 vector was generated to overexpress GFP gene in mouse hearts. The resulting plasmid contains cTNT::GFP cassette flanked by two ITR sites (**Figure 1**). The rAAV9.U6::shRNA vector was constructed to knockdown Trbp mRNA (**Figure 2**)

The standard curve for rAAV9 titration was generated with the qPCR data by linear regression. The manipulated variable y represents the Log10 value of DNA molecular concentration of each standard sample, and the corresponding variable x represents the CT value. The Log10 (concentration) values (y) and CT numbers (x) exhibit a nice linear correlation (R2= 0.9971) and fit with the equation y = -0.2832x + 14.616 (**Figure 3A**). Titers of rAAV9 samples were calculated based on linear equation (**Figure 3B**). With the method described in the protocol (step 4.6.2, and **Figure 3B**), high titer of rAAV9 vectors (50-200 l, >6 X 1013 particles/mL) was obtained in the representative study.

To monitor the efficiency and tissue specificity of rAAV9.cTNT vectors, P0.5 pups were treated with same amount (1X1011 particles/pup) of rAAV9.cTNT::Luciferase (AAV-Luc) or rAAV9.cTNT::GFP (AAV-GFP) by subcutaneous injection. Two weeks after injection, GFP signal was monitored in various tissues of the mice. Robust expression of GFP was detected in the heart, but not in other organs (**Figure 4,** n>3). Thus efficient and heart-specific gene expression was achieved with rAAV9.cTNT vector.

To monitor the knockdown efficiency and tissue specificity of rAAV9.U6 vectors, P0.5 mice were treated with same amount (3X1011 particles/pup) of rAAV9.U6::Scramble (AAV-Scramble) or rAAV9.U6::Trbp shRNA (AAV-shTrbp) by subcutaneous injection. Two weeks after injection, expression of Trbp in various tissues of was monitored by qPCR (**Figure 5,** n=3). The mRNA level of Trbp in the heart was substantially reduced by rAAV9.U6::shTrbp (68% downregulation, *P* = 0.0004452). Down regulation of Trbp was also detected in the liver tissue from rAAV9.U6::shTrbp-treated mice. However, the fold change is much lower.

**FIGURE LEGENDS:**

**Figure 1. The strategies to construct rAAV9.cTNT::GFP plasmid**. (A) The scheme of cTNT::GFP cassette. (B) The rAAV9 plasmid has been modified to harbor the chicken *TNNT2* promoter (rAAV9.cTNT) followed by the two unique restriction sites (NheI and KpnI). The GFP open reading frame was cloned into the rAAV9.cTNT vector by restriction sites-mediated ligation to generate the rAAV9.cTNT::GFP plasmid. (B) rAAV9.cTNT::GFP plasmid can be constructed by Gibson assembly.

**Figure 2. The strategies to construct rAAV9.U6::shRNA plasmid**. (A) The scheme of U6::shRNA cassette is shown. Expression of shRNA is driven by U6 promoter (Blue). (B) rAAV9-U6-shRNA cassettes can be generated by annealing and ligating DNA oligos containing shRNA sequences into the restriction enzyme-digested rAAV9 vectors harboring U6 promoter. (C) rAAV9.U6::shRNA cassettes can be generated by long-range PCR and intra-molecular Gibson assembly-based “seamless” construction. The 5’ arm, loop, and 3’ arm of shRNA are shown in green, orange, and red, respectively.

**Figure 3. Calculation of rAAV9 titer.** (A) The standard curve for rAAV9 titration was generated with the qPCR data by linear regression. The manipulated variable *y* represents the Log10 value of DNA molecular concentration of each standard sample, and the corresponding variable *x* represents the CT value. (B) Titers of rAAV9 samples are calculated based on linear equation of the standard curve.

**Figure 4. Expression pattern of rAAV9.cTNT::GFP in mice tissues**. P0.5 pups were treated with same amount (1 X 1011 particles/pup) of rAAV9.cTNT::Luciferase (AAV-Luc, negative control) or rAAV9.cTNT::GFP (AAV-GFP) by subcutaneous injection. Two weeks after injection, the tissue samples were harvested. Expression of GFP was monitored under fluorescent dissection scope. Both bright field and fluorescence images are presented. The experiments have been repeated for more than 3 times (n>3). Bar = 2.0 mm. SkM, skeletal muscle.

**Figure 5. Knockdown gene expression with AAV-shRNA.** P0.5 mice were treated with same amount (3 X 1011 particles/pup) of rAAV9.U6::Scramble (AAV-Scramble) or rAAV9.U6::Trbp shRNA (AAV-shTrbp) by subcutaneous injection. Two weeks after injection, the mRNA levels of Trbp in various tissues were monitored by qPCR (n=3). Data are presented as Mean ± SEM. The cut-off P value is 0.05. NS, P>0.05, not significant. \*\*, P < 0.01. SkM, skeletal muscle.

**DISCUSSION:**

It is important to minimize undesired ITR recombination during plasmid construction. Before generating the virus, one must always monitor the ITR integrity of the AAV plasmids by restriction digestion and agarose gel electrophoresis. It is impossible to obtain 100% intact plasmid, but the recombination ratio should be minimized to as low as possible. Less than 20% is acceptable for successful rAAV9 packaging. Of note, culturing the bacteria at lower temperature (30 °C) with a lower shaking speed (180-200 rpm) can reduce the chance of ITR recombination.

It is essential to ensure that the HEK293 cells are healthy for successful transfection and rAAV9 packaging. “Healthy” cells are usually highly proliferative and grow fast. However, rapid proliferation and growth of HEK293 cells does not necessarily guarantee the high efficiency of rAAV9 packaging. Thus, it is important to start the experiments with fresh cells. It is recommended to use low-passage HEK293 cells (<10 passages, the cells are passaged every 2-3 days) for rAAV9 packaging. Of note, other serotypes of rAAV may need to be purified using different procedures32.

The investigator is granted flexibility in the generation of rAAV9 plasmids. Either restriction sites-mediated ligation or Gibson assembly can be used30. For rAAV9.U6::shRNA construction, the intra-molecular Gibson assembly-based strategy is an effective method (Figures 1 and 2). Multiple AAV-shRNA plasmids or pooled AAV-shRNAs can be rapidly constructed. To overexpress genes using rAAV9, there exists a size limitation for inserted cDNA sequences. Generally, the size fragment between ITRs needs to be smaller than 5 kb3[3](#_ENREF_31). Inteins-catalyzed protein splicing can be used to circumvent the packaging size limit of rAAV9 vectors34.

Other viral systems including retrovirus, lentivirus and adenovirus have also been developed and enable flexible gene manipulation. Compared with these different types of viral vectors, rAAV has t: Thus,rAAV-based genome engineering is emerging as an ideal tool for *in vivo* gene manipulation.

Previous studies have shown that the rAAV9 systems enable efficient expression of delivered genes *in vivo*. With the cTNT (chicken TnnT2) promoter, heart specific gene expression was obtained (Figure 4)[25](#_ENREF_25),[26](#_ENREF_26). Although the U6 promoter is ubiquitously active in mouse tissues, a most striking inhibition of target mRNA (Trbp) by rAAV9.U6::shRNA was observed in the heart, but not in other organs (Figure 5). The liver is the most common organ transduced by different serotypes of rAAV35,36. However, the knockdown efficiency (36% reduction of mRNA level) in the liver is much lower than that in the heart (68% reduction of mRNA level). This is consistent with the previous study showing that despite higher viral genome presence in the liver, systemic delivery of shRNA by rAAV9 provides more efficient gene knockdown in the heart[35](#_ENREF_33). It is possible that hepatocytes are more proliferative than cardiomyocytes and are more actively undergoing cell division after rAAV9 administration at the neonatal ages, which results in substantial vector genome dilution in the liver tissue. However, this also suggests that the serotype of rAAV9 may more efficiently transduce cardiomyocytes in comparison to other cell types. As demonstrated by Lovric *et al*., in differentiated myocytes, the DNA damage response MRN complex proteins are repressed. MRN complex proteins bind AAV genomes and inhibit AAV transduction through transcriptional silencing. Thus, permissivity to AAV transduction can be induced by the terminal differentiation of cardiomyocytes36, making the rAAV9 systems, comparing to other viral vectors, very suitable for gene manipulation in the heart. To further minimize the undesired knockdown effects in other organs (*e.g.* liver), one also can use cardiac-specific cTNT promoter-driven miR-30a-based shmiR to repress the genes of interest in the heart29. This manuscript provided the reader with the specific technicalities of capitalizing upon the rAAV9 technology in cardiovascular investigations.

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The authors have nothing to disclose.

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