

Video Article

Preparation of rAAV9 to Overexpress or Knockdown Genes in Mouse Hearts

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Abstract

Controlling the expression or activity of specific genes through the myocardial delivery of genetic materials in murine models permits the investigation of gene functions. Their therapeutic potential in the heart can also be determined. 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, minimal immunogenicity, 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 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 be useful for cardiovascular investigations.

Video Link

The video component of this article can be found at <https://www.jove.com/video/54787/>

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 Caspr/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 interest^{1,6}.

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. However, in the mouse model in particular, *in vivo* gene delivery is more challenging. There are a series of extra- and intracellular barriers that 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 materials^{7,8}. 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 cells^{7,9,10}. 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 the 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 *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 the integration of vector DNA into the host genome. 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 mutagenesis in 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 cells^{8,10,11,19}. 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 replicated^{19,20}. 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 system^{21,22}. It exhibits minimal immunogenicity and pathogenicity^{23,24}. 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 or genomic changes in the target cells is low²².

Recently, rAAV systems have been successfully used for the *in vivo* delivery of DNA encoding proteins, miRNAs, shRNAs, and Crispr-gRNAs into mouse cardiac muscle^{23,25-29}. This methodology has facilitated 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 the 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 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. 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 had 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 a 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 TNNT2 promoter (rAAV9.cTNT), which enables cardiomyocyte-specific expression of transduced genes^{25,26,29}. Unique NheI and KpnI sites have been introduced into the plasmid, downstream of the promoter. The cDNA fragments encoding the genes of interest can be cloned into the rAAV9 backbone using these two restriction sites^{25,26,29}. Here, as an example, the rAAV9 vector for overexpression of the GFP gene in mouse hearts was generated. The resulting plasmid contains the 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 the U6 promoter, or by long-range PCR and intra-molecular Gibson assembly-based "seamless" construction³⁰. The resulting plasmid should contain the 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. Clone the cDNA or shRNA expression cassette into the rAAV9 plasmid backbone. Transform the DNA into competent *E. Coli* cells²⁵.
NOTE: Use stbI2 or stbI3 *E. coli* cells for rAAV9 DNA transformation to minimize undesired ITR recombination.
2. Pick up the positive clone from the transformed *E. Coli* cells. Amplify the culture in 500 ml of Lilly-Barnett medium and extract the rAAV9 plasmid from the bacterial cells²⁵⁻³⁰.
NOTE: Midi/Maxi prep the rAAV9 plasmid to obtain a high amount of DNA (> 100 µg). 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

1. Prepare 1 µg/µl of linear polyethylenimine (PEI) solution. Dissolve PEI powder in endotoxin-free dH₂O that has been heated to 70-80 °C. After cooling down to RT, neutralize the solution to pH 7.0 with 1 M HCl. Filter sterilize (0.22 µm) the solution. Aliquot the 1 µg/µl PEI stock solution (1,400 µl/tube) and store the solution at -20 °C.
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).
3. At day 0, plate HEK293 cells in ten 150-mm dishes 18-20 hr before transfection by splitting > 90% confluent cells in a 1:2 dilution.
NOTE: At day 1, the cells should reach 90% confluence.
4. At day 1, transfect HEK293 cells with the rAAV9 plasmid (e.g., rAAV9.cTNT::GFP or rAAV6.U6::shRNA constructs), Ad-Helper plasmid, and AAV-Rep/Cap plasmid using PEI^{25,26,29}.
 1. For 10 dishes of cells at 90% confluence, mix 70 µg of AAV-Rep/Cap plasmid, 70 µg pf rAAV9 plasmid, and 200 µg of Ad-Helper plasmid in a 50-ml centrifuge tube.
 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 70 x 75/90 = 58.3 µg of AAV-Rep/Cap plasmid, 70 x 75/90 = 58.3 µg of rAAV9 plasmid, and 200 x 75/90 = 166.7 µg of Ad-Helper plasmid in a 50-ml centrifuge tube.
 3. Add 49 ml of RT DMEM (without FBS) to the 50-ml tube and mix well.
 4. Add 1,360 µl of PEI solution to make the PEI:DNA ratio (v/w) be 4:1. Mix well. Incubate at RT for 15 - 30 min.
 5. Add 5 ml of the mixture prepared in step 2.4.4 to each 150-mm dish (50 ml of the mixture for ten 150-mm dishes).

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

3. Harvest of Transfected HEK293 Cells and Purification of rAAV9 Vectors

1. Harvest the cells 60-72 hr 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.
2. Centrifuge the cells at 500 x g for 5 min. Resuspend the cell pellet with 5 ml of PBS in each tube and combine all the cell suspensions into one 50 ml tube.
3. Centrifuge the cells at 500 x g for 5 min. Discard the supernatant. At this step, store the cell pellet at -80 °C or immediately purify the AAV from the pellet, as described in steps 3.4-3.15.
4. Prepare the lysis buffer: 150 mM NaCl and 20 mM Tris-HCl, pH 8.0. Filter sterilize (0.22 µM). Store the buffer at 4 °C.
5. Resuspend the pellet with 10 ml of lysis buffer.
6. Freeze the lysate at -80 °C or in the dry ice/ethanol bath, then thaw it at 37 °C. Vortex for 1 min. Freeze and thaw the lysate 3 times.
7. Add MgCl₂ solution to the thawed lysate (make the final concentration of MgCl₂ in the lysate be 1 mM). Add the 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 nuclease or endonuclease treatment, dounce homogenize the lysates 20 times.
8. Centrifuge the sample at 4,800 x g for 20 min at 4 °C. Collect the supernatant.
9. Meanwhile, prepare the Iodixanol gradient solution:
 1. Prepare the 17% of the gradient solution by mixing 5 ml of 10x PBS, 0.05 ml of 1 M MgCl₂, 0.125 ml of 1 M KCl, 10 ml of 5 M NaCl, and 12.5 ml of density gradient medium. Adjust the total volume to 50 ml using H₂O.
 2. Prepare the 25% solution by mixing 5 ml of 10x PBS, 0.05 ml of 1 M MgCl₂, 0.125 ml of 1 M KCl, 20 ml of density gradient medium, and 0.2 ml of 0.5% (w/v) Phenol Red. Adjust the total volume to 50 ml using H₂O.
 3. Prepare the 40% solution by mixing 5 ml of 10x PBS, 0.05 ml of 1 M MgCl₂, 0.125 ml of 1 M KCl, and 33.3 ml of density gradient medium. Adjust the total volume to 50 ml using H₂O.
 4. Prepare the 60% solution by mixing 0.05 ml of 1 M MgCl₂, 0.125 ml of 1 M KCl, 50 ml of density gradient medium, and 0.1 ml of 0.5% (w/v) Phenol Red.
10. With a needle and syringe, load the Iodixanol gradient solution into the polypropylene tube in the order of 5 ml of 17%, 5 ml of 25%, 5 ml of 40% and 5 ml of 60%, starting from the bottom. Load all the lysate obtained from step 3.8 (14-16 ml) on top of the gradient. The gradient, listed from the bottom to top, is 60%, 40%, 25%, 17%, and the lysate layer. Fill the tube with lysis buffer and cover it with the cork.
11. Centrifuge at 185,000 x g for 90 min at 16 °C.
12. Harvest the viral fraction (40% layer) with a syringe. Insert the needle (21 gauge) into the intersection between the 40% and 60% fractions, only aspirating the 40% layer.
NOTE: Avoid aspirating ANY of the 25% layer.
13. Mix the viral fraction with sterilized polyoxyethylene-polyoxypropylene block copolymer PBS solution (10% polyoxyethylene-polyoxypropylene block copolymer stock 1:10,000 diluted in PBS) up to a total volume of 15 ml. Load the mixture into the filter tube (cut-off MW = 100 kD). Centrifuge at 2,000 x g for 30 min at 4 °C.
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 2,000 x g for 20 min at 4 °C. Repeat this step two more times. Collect the purified rAAV9 virus (the fraction above the filter).
15. Transfer the purified rAAV9 in the filter tube to 1.7-ml tubes. Aliquot the purified rAAV9 (100 - 400 µl/tube, depending on the volume and titer of the AAV) and store the virus at -80 °C.
NOTE: Avoid repeated freeze-thaws.

4. Measurement of the Titer of rAAV9

1. **Prepare standard DNA samples.**
 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; 35 cycles of 95 °C for 20 sec, 60 °C for 15 sec, and 72 °C for 10 sec; and the final extension at 72 °C for 10 min. However, the optimized primers and PCR conditions are plasmid-specific, as the inset sequence in the rAAV9 vector may affect the specificity and efficiency of PCR³¹.
 2. Perform the PCR reaction with the conditions shown in step 4.1.1. Purify the PCR product with a gel extraction kit.
 3. Measure the concentration of purified DNA using a spectrophotometer. Calculate the concentration in DNA molecular numbers based on the molecular weight/length of the PCR product.
 1. Calculate the molecular concentration using the following equation: molecular concentration (DNA molecules or fragments/ml) = $6.23 \times 10^{23} \text{ mol}^{-1} \times \text{Con.} \times 10^{-6} / \text{MW}$. Note: ($6.23 \times 10^{23} \text{ mol}^{-1}$ is Avagadro's Number; Con.: DNA concentration in µg/ml; MW.: molecular weight in g/mol). For instance, if the obtained concentration of the PCR product is 100 µg/ml and its length is 200 bp, the molecular weight of the double-stranded DNA is $2 \times 200 \times 310 = 124,000$ (the average molecular weight of each nucleotide in the single-stranded DNA is about 310 g/mol). The molecular concentration (DNA molecules/ml) = $6.23 \times 10^{23} \text{ mol}^{-1} \times 100 \text{ µg/ml} \times 10^{-6} / 124,000 \text{ g/mol} = 5.18 \times 10^{14}$ DNA molecules/ml.
 2. Perform a dilution series of the DNA fragment and prepare the standard samples, with concentrations of 10^{13} molecules/ml, 10^{12} molecules/ml, 10^{11} molecules/ml, 10^{10} molecules/ml, 10^9 molecules/ml, 10^8 molecules/ml, and 10^7 molecules/ml. Use 1 µl of solution for each standard sample for the quantitative PCR (qPCR, in step 4.6).
2. Mix 5 µl of purified rAAV9 solution with 5 µl of 10x DNase buffer, 1 µl of DNase (10,000 U/ml), and 39 µl of ddH₂O. The total volume should be 50 µl.

3. Incubate the vial at 37 °C for 30 min to remove residual unpackaged plasmid DNA.
4. Inactivate the DNase at 95 °C for 10 min. Cool down the solution, add 44 µl of H₂O, 5 µl of 10x DNase buffer, and 1 µl of Proteinase K stock (10 mg/ml).
5. Incubate the solution at 50 °C for 2 hr. Stop the reaction and inactivate the Proteinase K at 95 °C for 10 min.
6. Use 1 µl of the sample for the quantitative PCR (qPCR) assay. Calculate the titer.
 1. Run quantitative PCR (qPCR) with the primers designed in step 4.1.1 using the samples from step 4.1.4 (standard samples) and from step 4.5 (samples to be measured).
 1. For each reaction, mix 10 µl of 2x Green master mix (containing Taq polymerase, dNTP mix, buffer, MgCl₂, and Green dye), 0.5 µl of forward primer (5 µM), 0.5 µl of reverse primer (5 µM), 8 µl of H₂O, and 1 µl of the sample to be measured. Perform qPCR with the following conditions: hold the samples at 50 °C for 2 min and 95 °C for 10 min; perform 40 cycles at 95 °C for 15 sec and at 60 °C for 1 min; for the melt stage, incubate the samples at 95 °C for 30 sec and 60 °C for 15 sec. Generate the standard curve based on the C_T numbers of the standard samples (**Figure 3**).
 2. Calculate the molecular concentration/titer of the AAV sample against the standard curve. The rAAV9 has a single-strand DNA genome, so the molecular concentration will be 2-fold higher than the calculated value (2x power (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 µl in 100 µl total).

5. rAAV9 Injection in Neonatal Mice and Gene Expression Assays in the Heart

1. Prepare rAAV9 working solutions in polyoxyethylene-polyoxypropylene block copolymer PBS solution. Make the virus stock with the titers of $1-7 \times 10^{12}$ particles/ml.
NOTE: Deliver 50-70 µl of rAAV9 solution into each postnatal day 0.5-1.5 mouse 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.
NOTE: We used $1-1.5 \times 10^{11}$ particles/pup for overexpression and $2.5 - 5 \times 10^{11}$ particles/pup for knockdown in postnatal day 0.5-1.5 mice).
2. **Treat neonatal mice with rAAV9 at P0.5-P2.5 by subcutaneous injection.**
 1. Pre-fill a 29G1/2, 0.33 x 12.7 mm insulin syringe with the rAAV9 solution. Be careful to remove air bubbles.
 2. Hold the cryo-anesthetized pup in one hand with thumb and forefinger. Prior to injection, swipe the back skin of the pup with a swab stick saturated with 70% isopropyl alcohol to maintain the sterile condition. Insert the syringe needle into the anterior-dorsal subcutis of the animal at an angle of 5 to 10°. Inject 50-70 µl of the rAAV9 solution using the insulin syringe.
NOTE: rAAV9 can also be delivered to the mouse via intraperitoneal or intravenous injection^{26,27}. 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, the condition of the pups was monitored every day.
3. The level of gene expression in the heart can be monitored with qPCR, immunofluorescence, or western blot (representative results are shown in **Figures 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 the animals had 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 construction of rAAV9.cTNT::GFP or rAAV9.U6::shRNA plasmids are shown in **Figures 1 and 2**, respectively. As the examples, the rAAV9 vector was generated to overexpress the GFP gene in mouse hearts. The resulting plasmid contains the 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 C_T value. The Log₁₀ (concentration) values (y) and C_T numbers (x) exhibit a nice linear correlation ($R^2 = 0.9971$) and fit with the equation $y = -0.2832x + 14.616$ (**Figure 3A**). Titers of rAAV9 samples were calculated based on the linear equation (**Figure 3B**). With the method described in the protocol (step 4.6.2 and **Figure 3B**), a high titer of rAAV9 vectors (50-200 µL, $> 6 \times 10^{13}$ 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 (1×10^{11} particles/pup) of rAAV9.cTNT::Luciferase (AAV-Luc) or rAAV9.cTNT::GFP (AAV-GFP) by subcutaneous injection. Two weeks after injection, the 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 the rAAV9.cTNT vector.

To monitor the knockdown efficiency and tissue specificity of rAAV9.U6 vectors, P0.5 mice were treated with same amount (3×10^{11} 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 change is much lower.

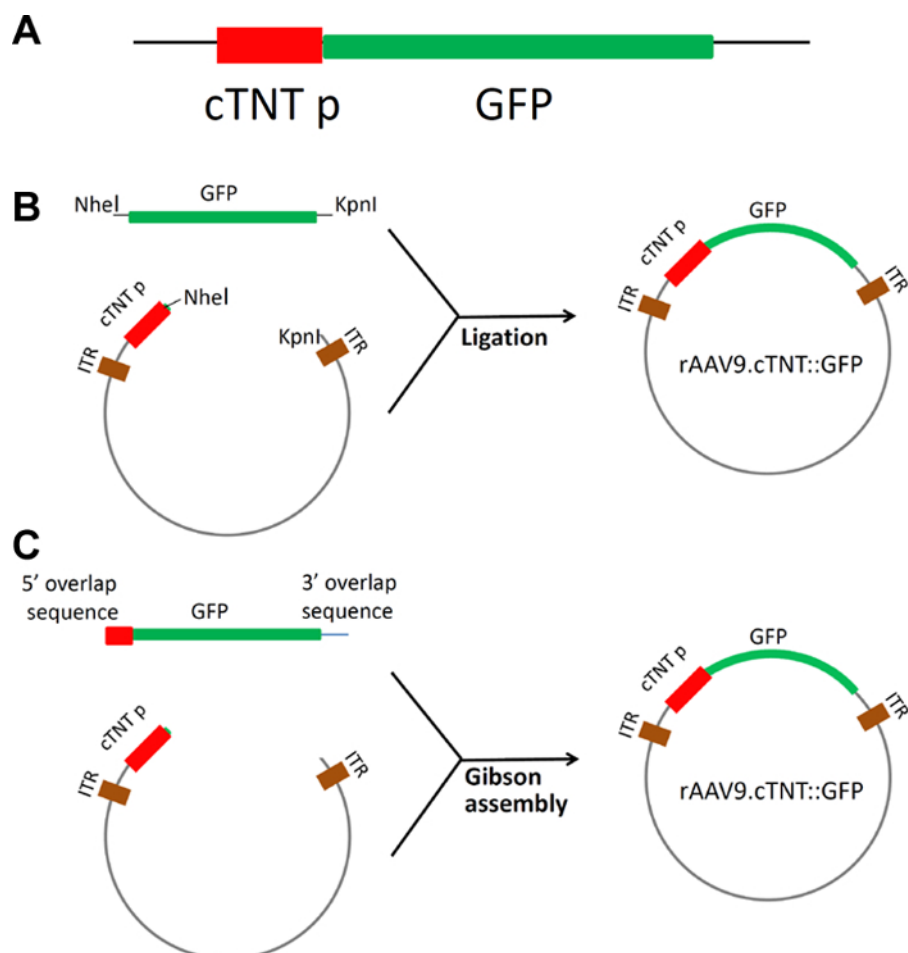
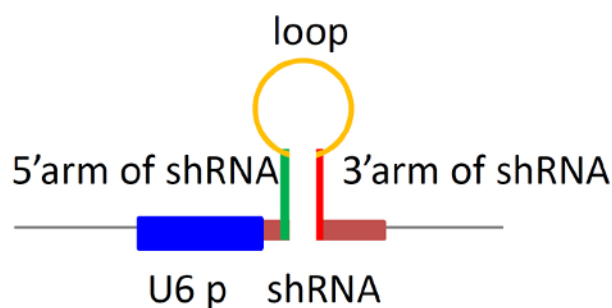
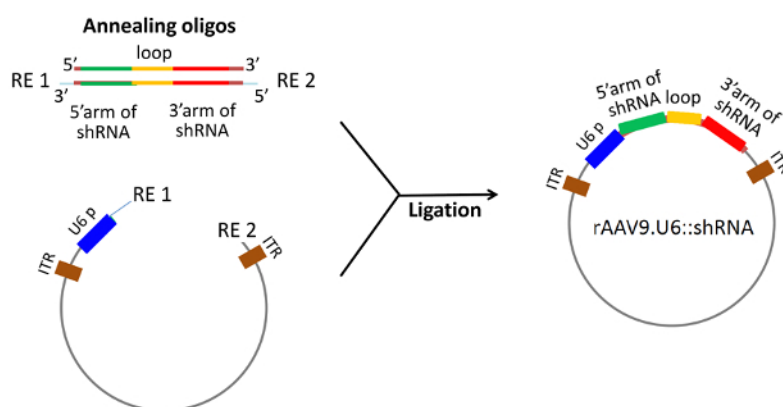


Figure 1: The Strategies to Construct the rAAV9.cTNT::GFP Plasmid. (A) The scheme of the cTNT::GFP cassette. (B) The rAAV9 plasmid has been modified to harbor the chicken *TNNT2* promoter (rAAV9.cTNT) followed by the two unique restriction sites (NheI and KpnI). The GFP open reading frame was cloned into the rAAV9.cTNT vector by restriction site-mediated ligation to generate the rAAV9.cTNT::GFP plasmid. (B) The rAAV9.cTNT::GFP plasmid can be constructed by Gibson assembly. [Please click here to view a larger version of this figure.](#)

A



B



C

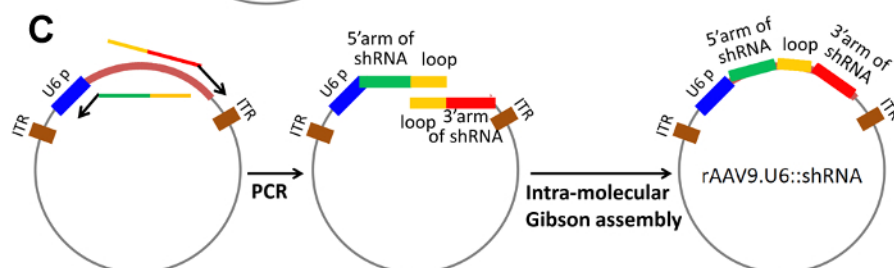
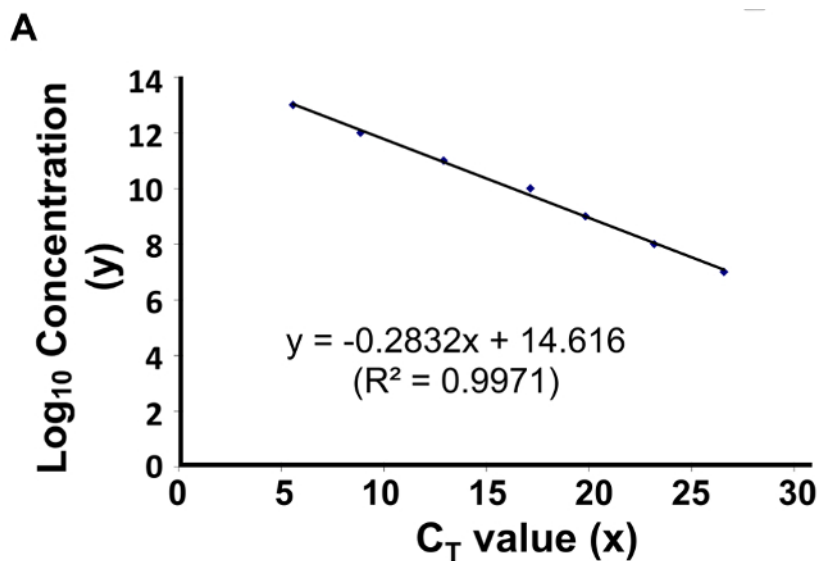


Figure 2: The Strategies to Construct the rAAV9.U6::shRNA Plasmid. (A) The scheme of the U6::shRNA cassette is shown. Expression of shRNA is driven by the U6 promoter (Blue). (B) rAAV9-U6-shRNA cassettes can be generated by annealing and ligating DNA oligos containing shRNA sequences into the restriction enzyme-digested rAAV9 vectors harboring the 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. [Please click here to view a larger version of this figure.](#)



B

	C _T value	Log10 (Concentration)	Concentration	Titer(particles/mL)
Sample	x	y	2XPower (10, y)	20X2XPower (10, y)
1	8.514024734	12.2048282	3.20522E+12	6.41045E+13
1	8.577964783	12.18672037	3.07433E+12	6.14866E+13
2	7.933270454	12.36929781	4.68088E+12	9.36177E+13
2	8.045316696	12.33756631	4.35107E+12	8.70214E+13

Figure 3: Calculation of the rAAV9 Titer. (A) The standard curve for rAAV9 titration was generated by linear aggression using the qPCR data. The manipulated variable y represents the Log₁₀ value of DNA molecular concentration of each standard sample, and the corresponding variable x represents the C_T value. (B) Titters of rAAV9 samples are calculated based on the linear equation of the standard curve. [Please click here to view a larger version of this figure.](#)

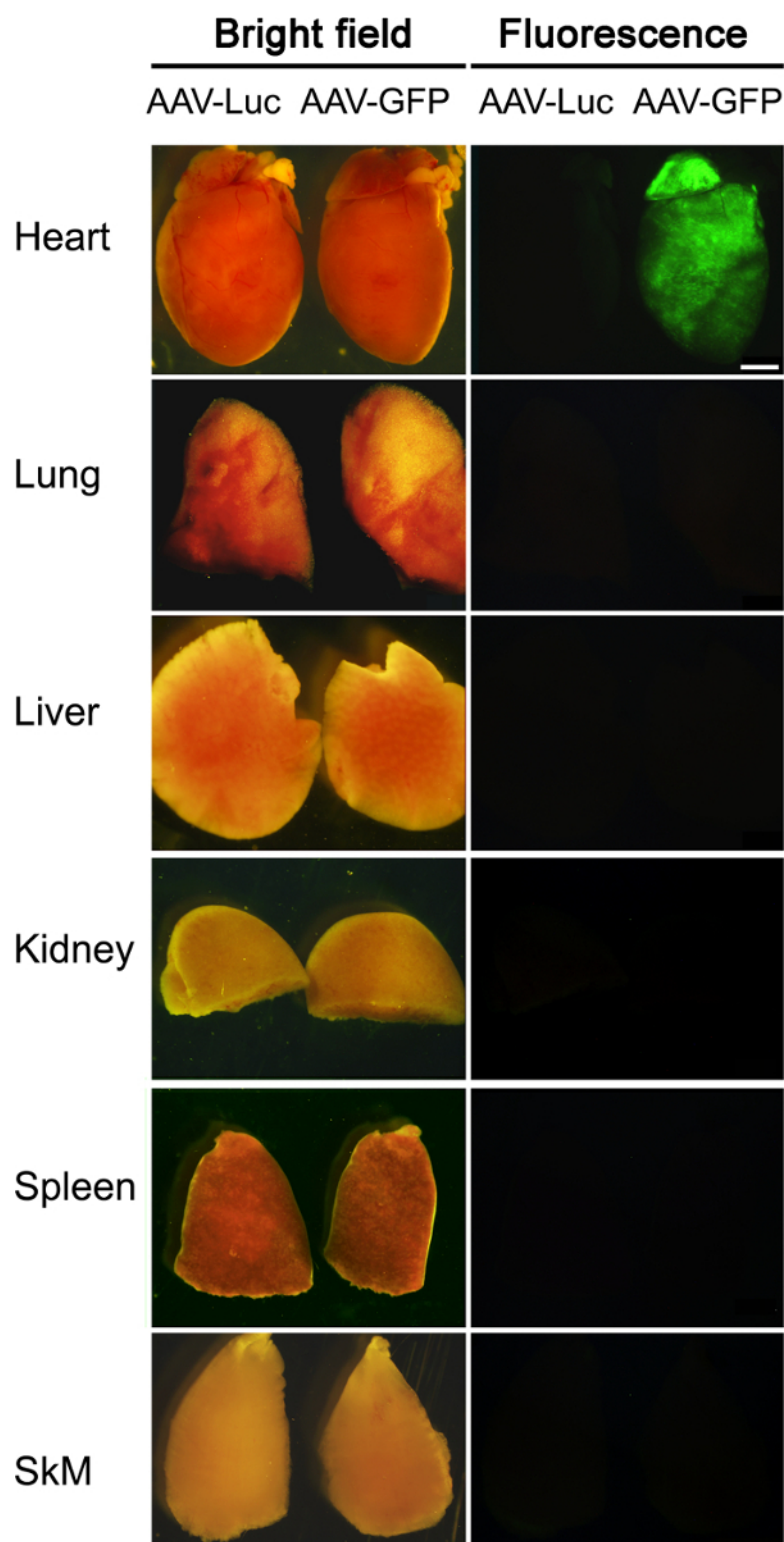


Figure 4: Expression Pattern of rAAV9.cTNT::GFP in Mice Tissues. P0.5 pups were treated with same amount (1×10^{11} particles/pup) of rAAV9.cTNT::Luciferase (AAV-Luc, negative control) or rAAV9.cTNT::GFP (AAV-GFP) by subcutaneous injection. Two weeks after injection, the tissue samples were harvested. Expression of GFP was monitored under a fluorescent dissection scope. Both bright field and fluorescence images are presented. The experiments have been repeated more than 3 times ($n > 3$). Scale bar = 2.0 mm. SkM, skeletal muscle. [Please click here to view a larger version of this figure.](#)

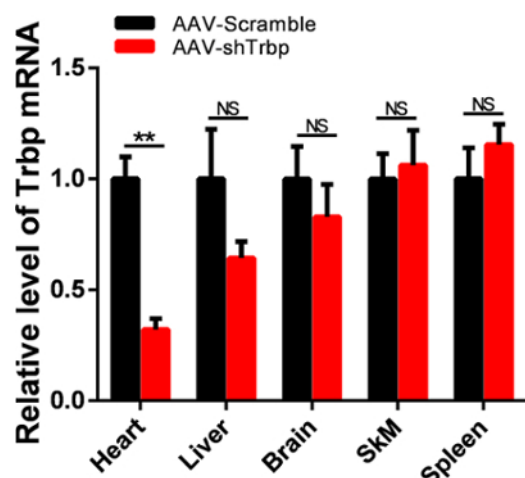


Figure 5: Knockdown Gene Expression with AAV-shRNA. P0.5 mice were treated with the same amount (3×10^{11} particles/pup) of rAAV9.U6::Scramble (AAV-Scramble) or rAAV9.U6::Trbp shRNA (AAV-shTrbp) by subcutaneous injection. Two weeks after injection, the mRNA levels of Trbp in various tissues were monitored by qPCR ($n = 3$). Data are presented as the Mean \pm SEM. The cut-off P value is 0.05. NS, $P > 0.05$, not significant. **, $P < 0.01$. SkM, skeletal muscle. [Please click here to view a larger version of this figure.](#)

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 using restriction digestion and agarose gel electrophoresis. It is impossible to obtain 100% intact plasmids, but the recombination ratio should be minimized as much 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 quickly. 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 site-mediated ligation or Gibson assembly can be used³⁰. For the 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 kb³³. Intein-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 specific advantages: high efficiency, high specificity, low genomic integration rate, minimal immunogenicity, and minimal pathogenicity. Thus, rAAV-based genome engineering is emerging as an ideal tool for *in vivo* gene manipulation.

Previous studies have shown that the rAAV9 system enables the efficient expression of delivered genes *in vivo*. With the cTNT (chicken TnnT2) promoter, heart-specific gene expression was obtained (**Figure 4**)^{25,26}. 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 rAAV^{35,36}. 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 heart³⁵. 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 system, 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., the 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 provides the reader with the specific techniques for capitalizing upon the rAAV9 technology in cardiovascular investigations.

Disclosures

The authors have nothing to disclose.

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