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## Prevention of Cardiac Dysfunction in Acute Coxsackievirus B3 Cardiomyopathy by Inducible Expression of a Soluble Coxsackievirus-Adenovirus Receptor

Sandra Pinkert, MSc; Dirk Westermann, MD; Xiaomin Wang, BSc; Karin Klingel, MD; Andrea Dörner, PhD; Konstantinos Savvatis, MD; Tobias Gröbl, MSc; Stefanie Krohn, MSc; Carsten Tschöpe, MD; Heinz Zeichhardt, PhD; Katja Kotsch, PhD; Kerstin Weitmann, MSc; Wolfgang Hoffmann, MD; Heinz-Peter Schultheiss, MD; O. Brad Spiller, PhD; Wolfgang Poller, MD; Henry Fechner, DVM

**Background**—Group B coxsackieviruses (CVBs) are the prototypical agents of acute myocarditis and chronic dilated cardiomyopathy, but an effective targeted therapy is still not available. Here, we analyze the therapeutic potential of a soluble (s) virus receptor molecule against CVB3 myocarditis using a gene therapy approach.

**Methods and Results**—We generated an inducible adenoviral vector (AdG12) for strict drug-dependent delivery of sCAR-Fc, a fusion protein composed of the coxsackievirus-adenovirus receptor (CAR) extracellular domains and the carboxyl terminus of human IgG1-Fc. Decoy receptor expression was strictly doxycycline dependent, with no expression in the absence of an inducer. CVB3 infection of HeLa cells was efficiently blocked by supernatant from AdG12-transduced cells, but only in the presence of doxycycline. After liver-specific transfer, AdG12 (plus doxycycline) significantly improved cardiac contractility and diastolic relaxation compared with a control vector in CVB3-infected mice if sCAR-Fc was induced before infection (left ventricular pressure  $59 \pm 3.8$  versus  $45.4 \pm 2.7$  mm Hg, median 59 versus 45.8 mm Hg,  $P < 0.01$ ;  $dp/dt_{max}$   $3645.1 \pm 443.6$  versus  $2057.9 \pm 490.2$  mm Hg/s, median 3526.6 versus 2072 mm Hg/s,  $P < 0.01$ ; and  $dp/dt_{min}$   $-2125.5 \pm 330.5$  versus  $-1310.2 \pm 330.3$  mm Hg/s, median  $-2083.7$  versus  $-1295.9$  mm Hg/s,  $P < 0.01$ ) and improved contractility if induced concomitantly with infection (left ventricular pressure  $76.4 \pm 19.2$  versus  $56.8 \pm 10.3$  mm Hg, median 74.8 versus 54.4 mm Hg,  $P < 0.05$ ;  $dp/dt_{max}$   $5214.2 \pm 1786.2$  versus  $3011.6 \pm 918.3$  mm Hg/s, median 5182.1 versus 3106.6 mm Hg/s,  $P < 0.05$ ), respectively. Importantly, hemodynamics of animals treated with AdG12 (plus doxycycline) were similar to uninfected controls. Preinfection induction of sCAR-Fc completely blocked and concomitant induction strongly reduced cardiac CVB3 infection, myocardial injury, and inflammation.

**Conclusion**—AdG12-mediated sCAR-Fc delivery prevents cardiac dysfunction in CVB3 myocarditis under prophylactic and therapeutic conditions. (*Circulation*. 2009;120:2358-2366.)

**Key Words:** receptors ■ viruses ■ myocarditis ■ gene therapy ■ coxsackieviruses

Coxsackievirus B3 (CVB3), a member of the enterovirus group of *Picornaviridae*, is one of the most commonly identified infectious agents associated with acute and chronic myocarditis<sup>1</sup>; it can also mediate infectious pancreatitis and meningitis. Acute enteroviral myocarditis may not lead to initial mortality, but there is strong evidence to show that it often leads to the insidious development of dilated cardiomyopathy.<sup>1</sup> Currently, enteroviral myocarditis is treated nonspecifically by palliative care, because no effective antiviral

therapy is available. CVB load, replication, and persistence are directly associated with cardiac injury and progression of the disease.<sup>2,3</sup> A direct cytopathic effect of CVB in vitro and the induction of cardiac injury in immunodeficient mice in vivo support the significance of direct virus-mediated cardiac injury in disease pathogenesis.<sup>4</sup> Specific targeting of CVB in viral myocarditis, therefore, will not only abrogate virus-mediated direct cardiac damage but will diminish immune response-mediated damage by blocking viral spread to uninfected tissue.

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## Clinical Perspective on p 2366

The coxsackievirus-adenovirus receptor (CAR) mediates cellular attachment for adenovirus subtypes A and C through F and is essential to permit infection of all 6 serotypes of CVB.<sup>5</sup> CAR is a member of the immunoglobulin superfamily that consists of 2 extracellular immunoglobulin-like domains (D1 and D2), a transmembrane domain, and an intracellular tail of variable length.<sup>6</sup> The N-terminal D1 domain has been shown to bind both adenovirus fiber knob protein and the canyon structure of CVB capsids.<sup>7,8</sup> Soluble decoy viral receptors have been found to efficiently inhibit infection by rhinoviruses, measles viruses, and adenoviruses.<sup>9–11</sup> Soluble CAR (sCAR) proteins inhibit CVB infection of susceptible target cells in vitro and in vivo.<sup>12,13</sup> The interaction of CVB3 with sCAR leads to formation of altered particles that are characterized by loss of VP4 from the virion shell and subsequent irreversible loss of infectivity.<sup>14,15</sup> However, severe side effects, with increased cardiac inflammation and heart injury, have been observed after treatment of CVB3-infected mice with CAR4/7, a native sCAR variant with an intact CVB3-binding D1 domain, half of the D2 domain, and a 23-amino acid-long C-terminus.<sup>16</sup>

Previous investigations have shown that dimeric sCAR, expressed as an immunoglobulin Fc-region fusion protein, has reduced systemic clearance and increased virus-neutralizing capacity relative to monomeric sCAR and does not induce undesirable side effects.<sup>14</sup> Therefore, the aim of the present study was to create an in vivo delivery system that would express sCAR-Fc in the liver for systemic release under the tight control of an inducible promoter. An adenoviral vector (AdV) was constructed that only expressed sCAR-Fc in the presence of doxycycline (Dox). It was our primary hypothesis that delivery of sCAR-Fc via a recombinant adenovirus expression vector to CVB3-infected animals would inhibit myocardial CVB3 infection and improve cardiac function relative to CVB3-infected animals treated with a vector control. We used hemodynamic indices as the best measure of cardiac function and histological measurements to monitor cardiomyopathy after CVB3 infection.

## Methods

### Coxsackievirus B3

In vitro and in vivo experiments used the genetically characterized, cardiocidal Nancy strain of CVB3.<sup>17</sup> Methods detailing virus propagation and titration of CVB3 in HeLa cells, as well as storage at  $-80^{\circ}\text{C}$ , before infection of cells or animals have been published previously.<sup>13</sup>

### Development of AdVs

sCAR-Fc was generated by fusion of the extracellular domain of human CAR with the carboxy terminus of the human IgG1 Fc coding region and inserted into an adenoviral shuttle plasmid that contained improved elements of the Tet-On gene expression system in different configurations. AdVs were generated as described previously.<sup>18</sup> Details of cloning strategies and adenoviral generation are provided in the online-only Data Supplement.

### Cell Cultures, Northern Blot, Western Blot, Virus Plaque Assays, and IgG ELISA

HeLa (human cervical carcinoma) cells and HEK293 (human embryonic kidney) cells were cultured in Dulbecco's modified Eagle's

medium (Gibco BRL, Karlsruhe, Germany) supplemented with 10% FCS and 1% penicillin/streptomycin. Northern and Western blot analysis and virus plaque assays were performed as described previously.<sup>18</sup> Human IgG ELISA (Bethyl Laboratories Inc, Montgomery, Tex) for detection of the Fc tail of sCAR-Fc was performed according to the supplier's instructions. Details are provided in the online-only Data Supplement.

### Murine CVB3 Myocarditis

AdG12 was injected into the jugular vein of 6- to 8-week-old BALB/c mice. Two days after AdV injection, mice were infected with  $5 \times 10^4$  plaque-forming units (pfu) of CVB3 intraperitoneally. Doxycycline (200  $\mu\text{g}/\text{mL}$ ) was administered orally to the mice via drinking water 2 days before CVB3 infection (prophylactic approach) or concomitantly with or 1 day after CVB3 infection (therapeutic approach). The water was replaced daily by fresh water that contained doxycycline. Seven days after CVB3 infection, the hemodynamic parameters of the mice were analyzed as described previously,<sup>19</sup> then blood was taken and organs were harvested for histopathological analysis. CVB3 positive-strand genomic RNA in tissues was detected by in situ hybridization with single-stranded <sup>35</sup>S-labeled RNA probes as described previously<sup>20</sup> or standard plaque assay for CVB3 as described previously.<sup>19</sup> All animals investigated in the present study were inbred male mice with identical genomes. For this reason, no special randomization algorithm was used. The investigation was performed in accordance with the principles of laboratory animal care and the German law on animal protection.

### Statistical Analysis

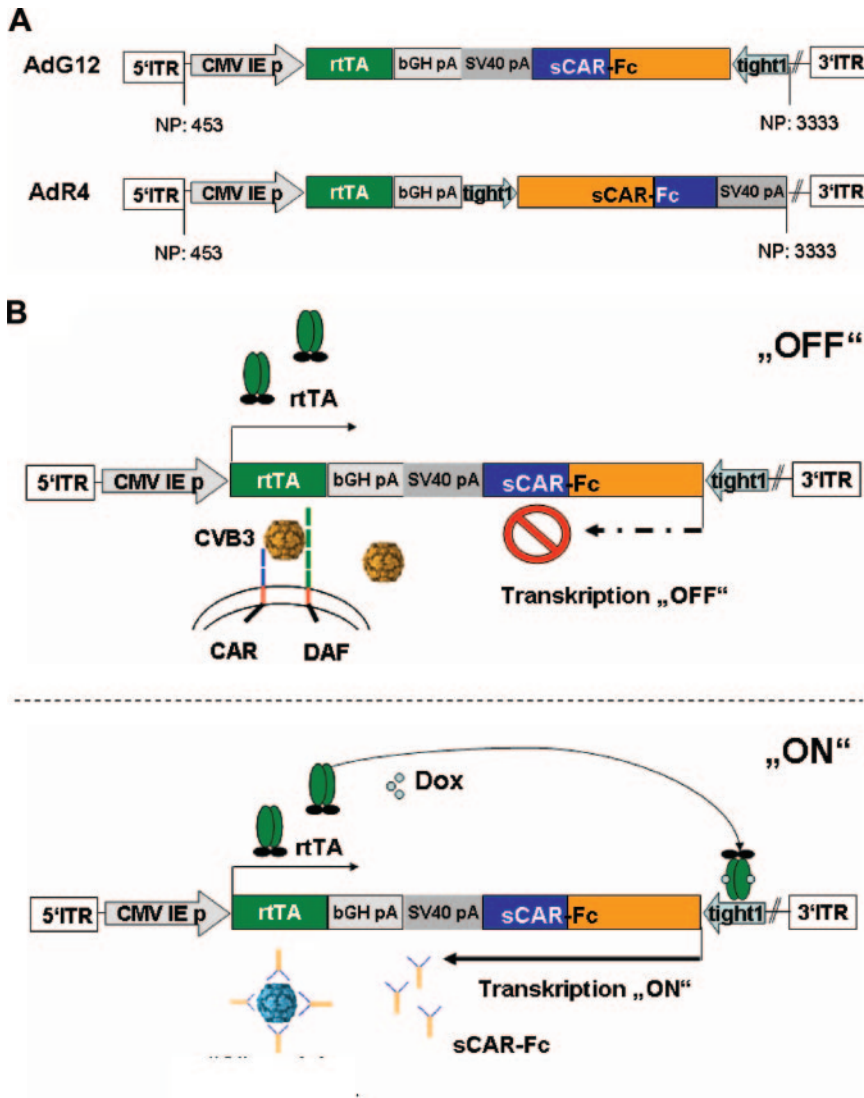
Statistical analysis of the in vivo measurements was performed with SAS version 9.1 (SAS Institute Inc, Cary, NC). Nonnormally distributed parameters (left ventricular pressure [LVP],  $dP/dt_{\text{max}}$ ,  $dP/dt_{\text{min}}$ , and virus load in the heart) are described as mean, SD, median, and 25th and 75th percentiles. Prespecified 2-group comparisons [sham (–Dox) versus sham (+Dox), AdG12 (–Dox) versus AdG12 (+Dox)] of the medians of nonnormally distributed data were performed by Mann–Whitney *U* test. The option “exact” for small sample sizes was selected (procedure: npar1way). Fisher's exact test was used for analysis of differences between myocarditis scores. Differences were considered significant at  $P < 0.05$ .

## Results

### Doxycycline-Dependent Regulation of sCAR-Fc Therapy

To achieve doxycycline-dependent sCAR-Fc expression, 2 AdVs were constructed. Each AdV contained 2 expression cassettes, 1 for constitutive expression of the second-generation reverse tetracycline transactivator rTA-M2,<sup>21</sup> the other for expression of sCAR-Fc from the improved second-generation tetracycline response promoter tight1.<sup>22</sup> The expression cassettes were inserted either in tandem orientation (AdR4) or in opposite orientations (AdG12) into the E1 region of an E1-deleted, E3-deleted adenovirus 5 backbone (Figures 1A and 1B). To analyze doxycycline-dependent regulation of AdV-mediated sCAR-Fc expression, HeLa cells were transduced with AdR4 or AdG12 and cultured in the presence or absence of doxycycline. Northern blot analysis found sCAR-Fc mRNA expression to be strictly doxycycline dependent, whereas rTA-M2 expression was constitutively high (Figure 2A). However, as detected by phosphorimaging of Northern blots (Figure 2A), doxycycline-induced sCAR-Fc mRNA expression was up to 6-fold higher in AdG12- than in AdR4-transduced cells. Therefore, AdG12 was selected for further in vitro and in vivo studies.

sCAR-Fc protein was only detectable in AdG12-transduced cells and in the cell culture supernatant in the presence of



**Figure 1.** Structure of sCAR-Fc-expressing AdVs and mechanism of sCAR-Fc-mediated CVB3 inhibition. **A**, Schematic of doxycycline-regulated sCAR-Fc-expressing AdVs AdG12 and AdR4. Two expression cassettes, 1 for expression of the doxycycline-dependent transactivator rTA-M2 and the other for doxycycline-inducible expression of sCAR-Fc, were inserted into the E1 region between nucleotide positions 453 and 3333 of an E1-deleted, E3-deleted adenovirus 5 backbone. AdR4 contains the 2 expression cassettes in a tandem direction, whereas in AdG12, the cassettes were inserted in opposite orientations. **B**, Mechanism of doxycycline-dependent adenoviral expression of sCAR-Fc and sCAR-Fc-mediated inhibition of CVB3 infection. In the absence of doxycycline, rTA-M2 is unable to transactivate the tight1 promoter; therefore, sCAR-Fc is not expressed, and CVB3 infection cannot be inhibited (top). In the presence of doxycycline, rTA-M2 transactivates the tight1 promoter, and sCAR-Fc is expressed and neutralizes CVB3 infection (bottom). CMV IE p indicates immediate-early CMV promoter; rTA, reverse tetracycline-controlled transactivator rTA-M2; tight1, doxycycline-dependent response promoter; sCAR-Fc, fusion protein of the soluble extracellular domain of human CAR and the human IgG1 Fc region; SV40 pA and bGH pA, polyadenylation signal of SV40 and bovine growth hormone; 5' ITR, nucleotide positions 1 to 453 of adenovirus type 5 containing the left inverted terminal repeat of adenovirus 5 and the packaging signal  $\Psi$ ; and 3' ITR, right inverted terminal repeat of adenovirus 5.

doxycycline (Figure 2B, left). As expected, Western blot analysis (under nonreducing conditions) confirmed that sCAR-Fc was expressed as a dimeric protein (Figure 2B, right). Furthermore, rapid doxycycline-dependent on/off switching of sCAR-Fc expression from AdG12 could be confirmed (Figure 1 in the online-only Data Supplement).

#### Inhibition of CVB3 Infection by AdG12 In Vitro

Next, we studied sCAR-Fc-mediated inhibition of CVB3 in vitro as a function of AdG12 dose, doxycycline concentration, and the dose of CVB3. Transduction of HeLa cells with 5 multiplicities of infection (MOI) of AdG12 and induction with doxycycline 500 ng/mL for 48 hours were sufficient to prevent CVB3 infection in sCAR-Fc-expressing cells completely. Under these transducing conditions, sCAR-Fc expression levels reached a maximum with 29.4  $\mu$ g/mL in the cell culture supernatant. sCAR-Fc expressed from AdG12 efficiently blocked CVB3 doses of up to 2.5 MOI (Figures IIA through IID in the online-only Data Supplement). Therefore, sCAR-Fc expressed by AdG12-transduced cells efficiently inhibited CVB3 infection of these cells, and secreted

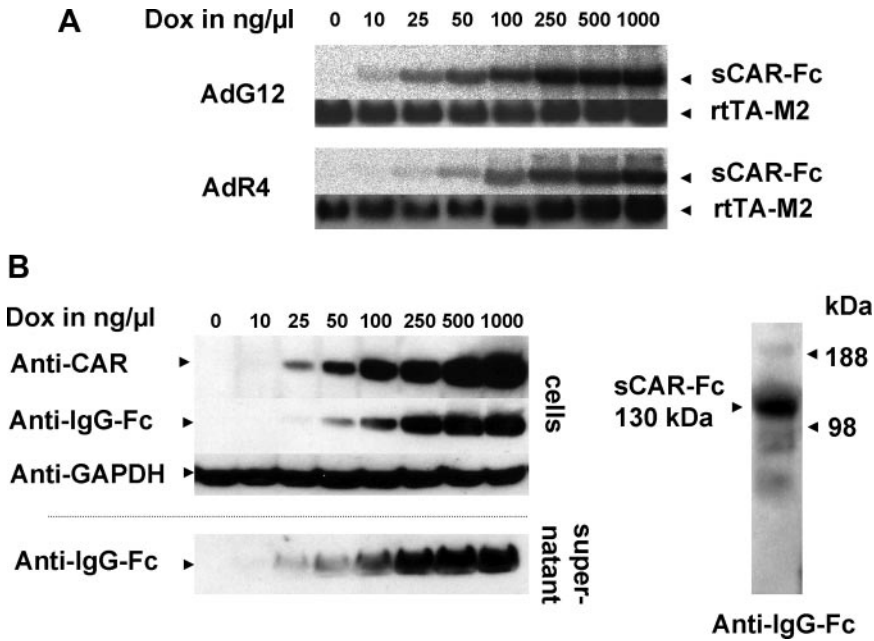
sCAR-Fc levels were directly related to initial AdG12 MOI and doxycycline concentration.

To assess the potential of AdG12 to suppress ongoing infections, which represents the typical situation encountered in the clinical setting, HeLa cells were transduced with AdG12, and sCAR-Fc expression was induced with doxycycline at different times relative to CVB3 infection. Expression of sCAR-Fc 48 and 24 hours before CVB3 infection resulted in complete inhibition of CVB3 infection in the transduced cells. The inhibitory efficiency of sCAR-Fc was gradually reduced the later the sCAR-Fc expression was induced. However, even if sCAR-Fc expression was induced 24 hours after infection, CVB3 progeny virus number was still reduced approximately 10<sup>6</sup>-fold compared with controls without sCAR-Fc (Figure 3), which demonstrates the high efficacy of sCAR-Fc in ongoing CVB3 infections.

#### Preinfection sCAR-Fc Gene Therapy Prevents Cardiac Dysfunction and Inflammation

Encouraged by the in vitro data, we tested the ability of AdG12-transduced mice to inhibit CVB3-mediated myocar-

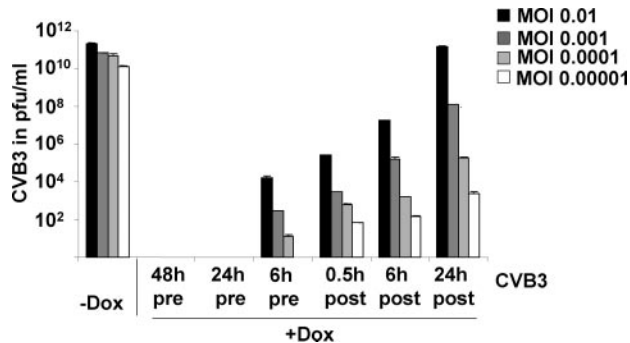




**Figure 2.** Doxycycline (Dox)-dependent expression of sCAR-Fc by AdG12. A, Expression of sCAR-Fc mRNA. HeLa cells were transduced with AdG12 and AdR4, each at an MOI of 2, and then cultured in the presence and absence of doxycycline. Northern blot analysis performed 48 hours after transduction showed a doxycycline dose-dependent increase of sCAR-Fc mRNA expression for both vectors, whereas rtTA-M2 expression remained constant. sCAR-Fc transcription could not be detected in the absence of doxycycline. B, Expression of sCAR-Fc protein. HeLa cells were transduced with AdG12, and sCAR-Fc expression was induced as described in (A) above. sCAR-Fc was detected by Western blot analysis (reducing conditions) in both cells and cell culture supernatant with antibodies directed against human CAR and the human IgG-Fc domain. Immunoreactivity against GAPDH was used as a loading control (left). Right, Dimeric sCAR-Fc detected by Western blotting under nonreducing conditions in cell culture supernatant.

ditis. Mice were transduced with AdG12, and sCAR-Fc expression was induced and maintained via constant oral doxycycline administration. The AdG12 dose was reduced to  $1 \times 10^{10}$  virus particles per mouse because initial experiments with  $3 \times 10^{10}$  particles of AdG12 (Figure IIIA in the online-only Data Supplement) resulted in sCAR-Fc serum levels that easily exceeded therapeutic levels, previously identified to be  $< 100$  ng/mL.<sup>11</sup> Two days after vector transduction, animals were infected with  $5 \times 10^4$  pfu of CVB3 (Figure 4A). At the point of CVB3 infection, circulating sCAR-Fc concentrations were  $228.5 \pm 174$  ng/mL, and 7 days later, when mice were euthanized, sCAR-Fc concentrations were  $99.63 \pm 22.7$  ng/mL. No sCAR-Fc was measured in the AdG12-transduced mice that did not receive doxycycline, which were identical to animals that did not receive AdG12. CVB3-infected mice that did not receive AdG12 or were transduced with AdG12 in the

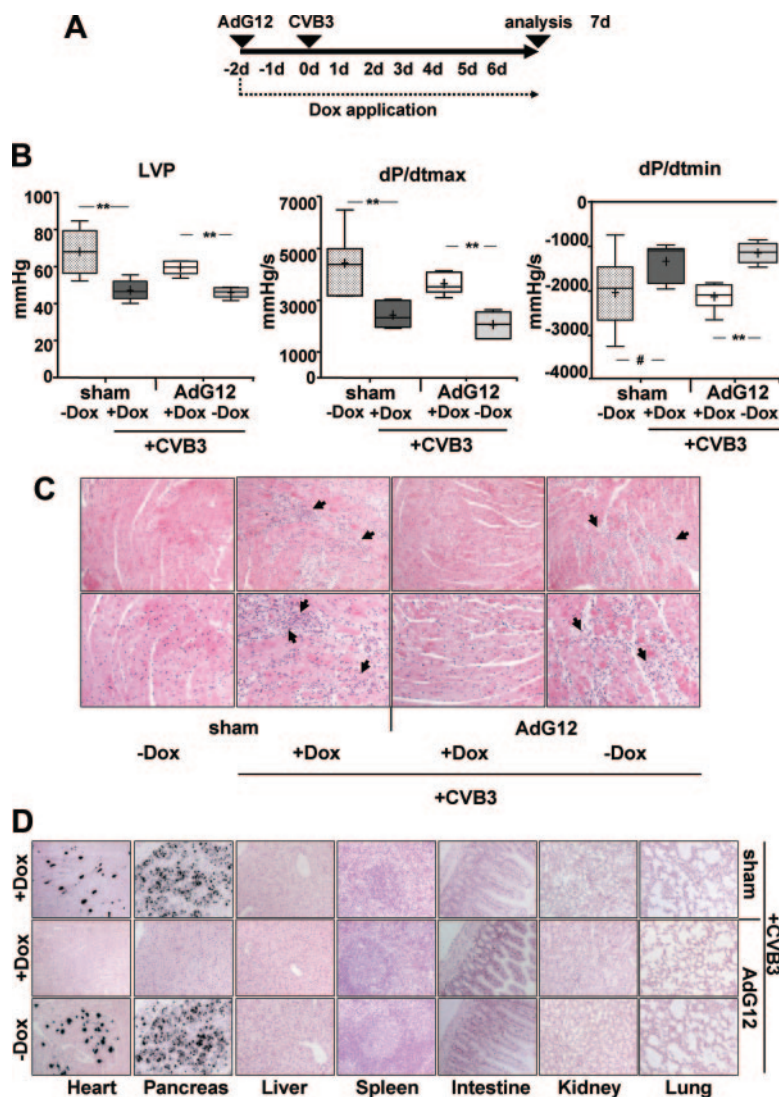
absence of doxycycline administration showed a continuous loss in body weight, which resulted in an average 30% decrease by day 7 after infection. By comparison, CVB3-infected mice that received AdG12 and doxycycline only lost roughly 5% of their body weight (Figure IVA in the online-only Data Supplement). Hemodynamics were measured by tip catheter on day 7 after CVB3 infection. AdG12 (+Dox)-treated CVB3-infected mice had significantly improved cardiac contractility and diastolic relaxation compared with CVB3-infected animals transduced with AdG12 in the absence of doxycycline (LVP  $59 \pm 3.8$  versus  $45.4 \pm 2.7$  mm Hg, median 59 versus 45.8 mm Hg,  $P < 0.01$ ;  $dp/dt_{max}$   $3645.1 \pm 443.6$  versus  $2057.9 \pm 490.2$  mm Hg/s, median 3526.6 versus 2072 mm Hg/s,  $P < 0.01$ ;  $dp/dt_{min}$   $-2125.5 \pm 330.5$  versus  $-1310.2 \pm 330.3$  mm Hg/s, median  $-2083.7$  versus  $-1295.9$  mm Hg/s,  $P < 0.01$ ). Importantly, hemodynamics of CVB3-infected animals treated with AdG12 (+Dox) were similar to noninfected control animals (Figure 4B). For statistical details, see Tables IA and IB in the online-only Data Supplement. Myocardial histological grading revealed extensive areas of damage, with myocyte necrosis and infiltration of mononuclear cells in CVB3-infected control mice and in CVB3-infected AdG12 (-Dox) mice (myocarditis score of 3 to 4 in both groups). Cell damage and inflammation were completely absent in the AdG12 (+Dox) group (myocarditis score = 0) and showed histology comparable to that of hearts of noninfected control mice (Figure 4C).



**Figure 3.** Inhibition of ongoing CVB3 infection by sCAR-Fc. HeLa cells were transduced with AdG12 at an MOI of 5. Forty-eight hours later, cell culture supernatant was harvested, preincubated with CVB3 (MOI 0.01 to 0.00001) for 30 minutes at 4°C, deposited to the AdG12-transduced cells for 30 minutes, and then replaced with fresh medium. CVB3 replication was analyzed by plaque assays after 48 hours of culture. For induction of sCAR-Fc expression, doxycycline (Dox; 1 μg/mL) was added to the medium at the time points indicated, from 48 hours before to 24 hours after CVB3 infection.

**Preinfection sCAR-Fc Gene Therapy Inhibits CVB3-Mediated Cardiomyopathy and Pancreatitis**

To document whether the absence of pathological changes of the heart correlated with cardiac CVB3 infection, we performed radioactive in situ hybridization experiments to visualize the presence of positive-strand CVB3 RNA at the cellular level with a high sensitivity. Animals in the AdG12 (+Dox) CVB3-infected group did not show any CVB3-infected cells in the heart and no (Figure 4D) or minimal (results not shown) levels of CVB3 RNA in the pancreas,



**Figure 4.** Effects of AdG12-mediated preinfection sCAR-Fc expression on murine CVB3 myocarditis. **A**, Application scheme and timeline of sample preparation. Eleven mice were transduced with  $1 \times 10^{10}$  particles of AdG12, and sCAR-Fc expression was induced and maintained through doxycycline (Dox) in 5 of the 11 animals. Twelve control mice were sham operated, and 6 of them were treated with doxycycline. AdG12 (+Dox), AdG12 (-Dox), and sham-operated (+Dox) animals were infected with  $5 \times 10^4$  pfu of CVB3 2 days later and analyzed 7 days after CVB3 infection. Sample sizes: Sham (-Dox),  $n=6$ ; sham (+Dox),  $n=6$ ; AdG12 (+Dox),  $n=5$ ; AdG12 (-Dox),  $n=6$ . **B**, Effect of sCAR-Fc and CVB3 infection on cardiac function. Left ventricular function in CVB3-infected animals was severely disturbed, with impaired contractility (LVP,  $dp/dt_{max}$ ) compared with sham-operated controls without CVB3 infection. The AdG12 (+Dox) group had significantly improved systolic and diastolic left ventricular function compared with the AdG12 (-Dox) group.  $**P<0.01$ ,  $\#P=0.065$ . Values are medians; (+) indicates the mean. **C**, AdG12 reduces CVB3-mediated cardiomyopathy. Top, 100-fold magnification. Bottom, 200-fold magnification. Heart sections were stained with hematoxylin and eosin. The AdG12 (+Dox) group exhibited complete preservation of myocardial integrity, whereas in AdG12 (-Dox) and sham-operated (+Dox) control animals, extensive areas with myocyte necrosis and inflammation were prominent. Arrows represent extensive areas of inflammation. **D**, Virus entry into and replication in the heart and pancreas are blocked by sCAR-Fc. The distribution of viral RNA was visualized by in situ hybridization with a  $^{35}S$ -labeled RNA probe specific to CVB3. In CVB3-infected sham-operated (+Dox) control mice, cardiomyocytes were infected as indicated by the black precipitate, which represents the virus RNA. CVB3 infection was also detected in pancreas, whereas spleen, lung, gut, kidney, and liver were not infected. No virus-positive cells could be detected in AdG12 (+Dox) mice in any of the organs investigated, whereas in AdG12 (-Dox), a similar organ distribution of CVB3 infection as in CVB3-infected sham-operated (+Dox) control mice was observed.

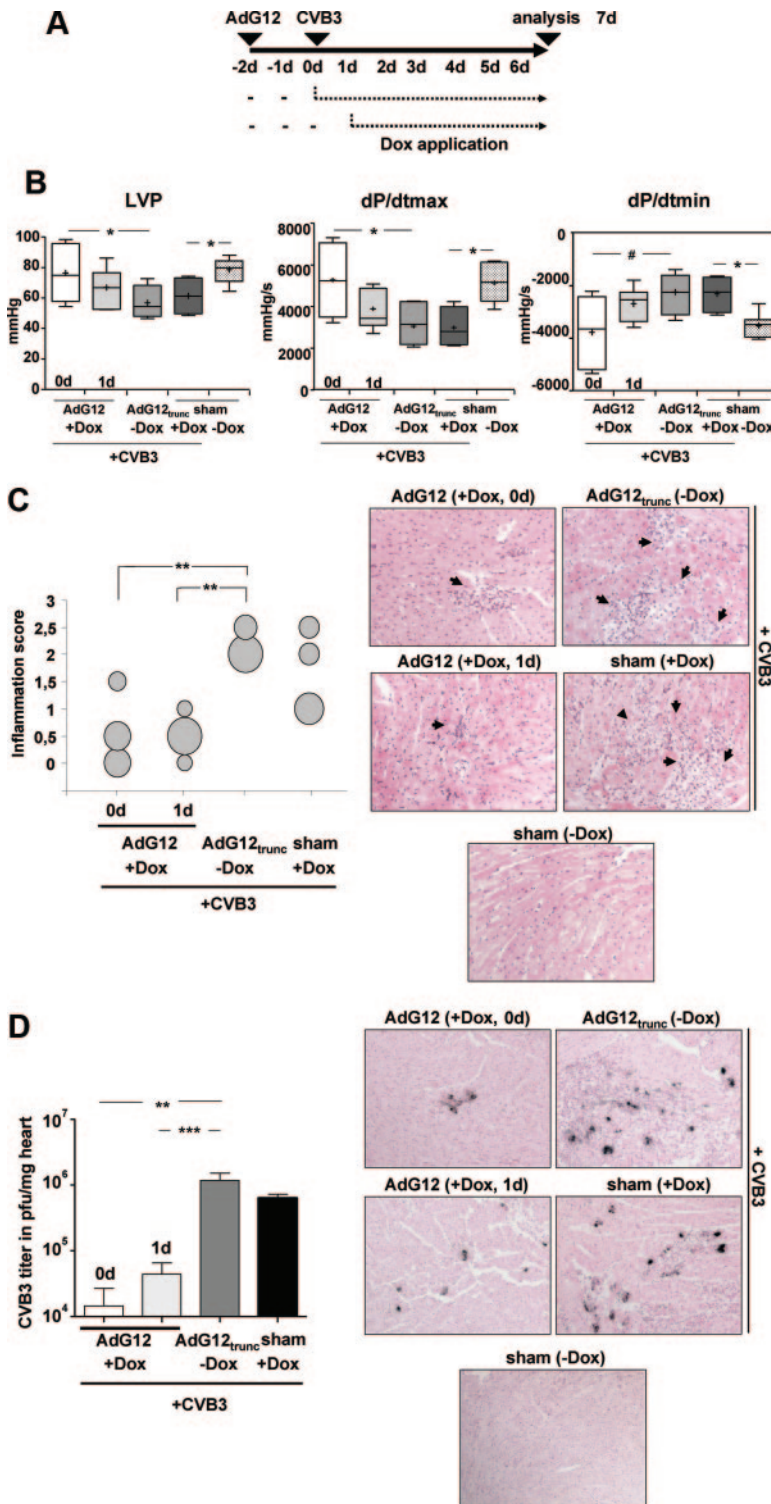
which is the primary site of CVB replication and the most susceptible organ for CVB infection in mice. In contrast, CVB3-infected and AdG12 (-Dox) CVB3-infected mice showed high prevalence of CVB3 RNA in the heart and pancreas. In other organs (spleen, liver, kidney, intestine, and lung), CVB3 RNA was undetectable in AdG12 (+Dox) and in the control groups by in situ hybridization (Figure 4D). Thus, sCAR-Fc efficiently protected mice from virus entry and subsequent replication in the heart and other organs.

### Therapeutic sCAR-Fc Gene Therapy Improves Cardiac Contractility and Reduces Cardiomyopathy

We next analyzed the efficacy of sCAR-Fc gene therapy in a therapeutic approach. Mice were transduced with AdG12, and doxycycline-mediated induction of sCAR-Fc was delayed either to be concomitant with CVB3 infection (2 days after transduction) or to occur 1 day after CVB3 infection (day 3 after transduction; Figure 5A). By use of this experimental approach, low levels of sCAR-Fc (28.4 ng/mL) were just detectable at 16 hours after induction (ie, either 16 hours or 40 hours after CVB infection for the 2 groups, respectively; Figure IIIB in the online-only Data Supplement). Body

weights for the concomitant-induction group were reduced by an average of 4%, whereas body weights for the 1-day delayed-induction group decreased by an average of 14% and that of untreated CVB3-infected controls decreased by an average of 18% by day 7 after infection (Figure IVB in the online-only Data Supplement). Compared with CVB3-infected animals transduced with the control vector AdG12<sub>unc</sub>, which did not express sCAR-Fc, induction of sCAR-Fc concomitant with CVB3 infection led to significantly improved cardiac contractility (LVP  $76.4 \pm 19.2$  versus  $56.8 \pm 10.3$  mm Hg, median  $74.8$  versus  $54.4$  mm Hg,  $P<0.05$ ;  $dp/dt_{max}$   $5214.2 \pm 1786.2$  versus  $3011.6 \pm 918.3$  mm Hg/s, median  $5182.1$  versus  $3106.6$  mm Hg/s,  $P<0.05$ ), with values that surprisingly were in the range of uninfected control animals. The diastolic relaxation in the CVB3-infected group with concomitant sCAR-Fc expression showed no significant improvement relative to control vector-transduced animals but revealed a clear trend toward improvement ( $dp/dt_{min}$   $-3756.6 \pm 1418$  versus  $-2212 \pm 745.7$  mm Hg/s, median  $-3624.3$  versus  $-2217.43$  mm Hg/s,  $P=0.073$ ). However, animals with induced sCAR-Fc expression 1 day after CVB3 infection did not show improved hemodynamics (Figure 5B). For statistical details, see Tables IIA and IIB in the online-only





**Figure 5.** AdG12-mediated therapeutic sCAR-Fc expression in murine CVB3 myocarditis. **A**, Application scheme and timeline of sample preparation. Twelve mice were transduced with  $1 \times 10^{10}$  particles of AdG12 and infected with CVB3 2 days later. sCAR-Fc expression was induced through doxycycline (Dox) in 5 animals concomitantly with (AdG12 +Dox, 0d) and in 7 animals 1 day after (AdG12 +Dox, 1d) CVB3 infection, respectively. Seven mice were transduced with  $1 \times 10^{10}$  particles of the control Adv (AdG12<sub>trunc</sub> -Dox), which has overall sequence identity to AdG12 but does not express sCAR-Fc, and infected with CVB3 2 days after transduction. Eleven mice were sham operated, and 4 of them were treated with doxycycline and infected with CVB3 (sham +Dox). Sample size: AdG12 (+Dox, 0d), n=5; AdG12 (+Dox, 1d), n=7; AdG12<sub>trunc</sub> (-Dox), n=7; sham (+Dox), n=4; sham (-Dox), n=7. **B**, Effect of sCAR-Fc and CVB3 infection on cardiac function. Left ventricular function in CVB3-infected untreated animals was severely disturbed, with impaired contractility (LVP, dP/dt<sub>max</sub>) and relaxation (dP/dt<sub>min</sub>) compared with sham-operated controls without CVB3 infection. The AdG12 (+Dox, 0d) group had significantly improved systolic left ventricular function compared with the control vector AdG12<sub>trunc</sub> (-Dox)-transduced group. \* $P < 0.05$ , # $P = 0.073$ . Values are medians; (+) indicates the mean. **C**, AdG12 mediates reduced cardiomyopathy. Left, Myocarditis score of CVB3-infected and sCAR-Fc-treated groups. Shown are frequencies of myocarditis score weighted with number of animals. Myocardial pathological grading revealed significantly reduced myocarditis score in both the concomitant and postinfection sCAR-Fc treatment groups. \*\* $P < 0.01$ . Right, Heart sections were stained with hematoxylin and eosin. The AdG12 (+Dox, 0d) and (+Dox, 1d) groups exhibited complete preservation of myocardial integrity, whereas in AdG12<sub>trunc</sub> (-Dox) and sham (+Dox) control animals, extensive areas with myocyte necrosis and inflammation were prominent. Arrows represent areas of inflammation. Original magnification  $\times 200$ . **D**, AdG12 reduces parenchymal viral load. Left, Cardiac tissue samples were homogenized, and viral titers were assessed by plaque assay. Values shown are mean  $\pm$  SEM. \*\* $P < 0.01$ ; \*\*\* $P < 0.001$ . Right, Distribution of viral RNA was visualized by in situ hybridization with a <sup>35</sup>S-labeled RNA probe specific to CVB3. Black precipitates represent CVB3-RNA.

Data Supplement. Myocardial pathological grading revealed reduced myocarditis scores in both the concomitant and postinfection sCAR-Fc treatment groups (Figure 5C) and significantly decreased infectious CVB3 titers in the heart compared with CVB3-infected control animals (Figure 5D). For statistical details, see Tables IIC and IID in the online-only Data Supplement. However, all animals in these groups with sCAR-Fc expression after CVB3 infection showed high pathological scoring and inflammatory damage to the pancreas (pancreatitis

score 3 to 4; not shown), which indicates that only prophylaxis was capable of saving the pancreas from destruction.

### Discussion

In the present study, we report inhibition of CVB3 infection by a sCAR-Fc fusion protein expressed from the newly developed doxycycline-regulated adenovector AdG12. sCAR-Fc expressed from AdG12 inhibited CVB3 infection of susceptible target cells in vitro and inhibited CVB3

infection of the myocardium *in vivo*. As a consequence, sCAR-Fc prevented heart injury and cardiac inflammation and prevented the development of systolic and diastolic cardiac dysfunction in CVB3-infected animals.

Previous reports demonstrated inhibition of CVB3 myocarditis through application of purified recombinant sCAR-Fc<sup>13</sup> or through delivery of sCAR-Fc from plasmids.<sup>11</sup> However, plasmid-based transgene expression *in vivo* is inefficient owing to low-level and transient protein expression, which severely limits its use in acute CVB3 infections with high virus load.<sup>11</sup> Furthermore, methods that are used to enhance plasmid uptake, eg, electroporation, appear to be inapplicable for therapeutic use in humans. Generation of purified recombinant proteins is time consuming and expensive, and *ex vivo* production of the proteins in bacterial or mammalian cells runs the risk of copurifying proinflammatory substances (ie, lipopolysaccharide) or altering the glycosylation of proteins that accelerate their systemic clearance. Moreover, repeated readministration frequently is necessary to maintain therapeutic protein levels for both the plasmid-based and the recombinant protein approach.

Therefore, we focused on the development of a gene therapy approach that used an AdV as a carrier to deliver sCAR-Fc. This viral vector type enables fast, strong, persistent expression of therapeutic genes *in vivo*. Intravenous AdG12 application resulted in a typical expression profile of sCAR-Fc after its doxycycline-mediated induction with the highest sCAR-Fc serum levels at days 4 and 5 after induction. Most importantly, sCAR-Fc was already detectable in the serum 16 hours after induction with doxycycline, and serum levels rapidly increased to >100 ng/mL within 1 day after transduction. These levels exceeded serum sCAR-Fc levels measured after plasmid-based gene transfer, and moreover, they exceeded the sCAR-Fc serum concentration that has been shown to be required to protect animals from CVB3-induced myocarditis.<sup>11</sup> In addition, if the AdG12 dose of  $1 \times 10^{10}$  particles used for mice is adapted to human weight, it would be within the range of AdV doses previously used in clinical trials, which suggests that therapeutically relevant sCAR-Fc serum levels could be produced in humans after AdG12 treatment.

CVB3 infection is known to evoke severe left ventricular systolic and diastolic failure in humans during acute infection<sup>23</sup> and in the present well-established experimental model.<sup>24</sup> Here, we confirm cardiac dysfunction in CVB3-infected mice as reduced left ventricular contractility and relaxation.

The present study demonstrates for the first time that CVB3-induced cardiac failure can be prevented by sCAR-Fc, because the hemodynamic parameters (LVP,  $dP/dt_{max}$ , and  $dP/dt_{min}$ ) of sCAR-Fc-expressing AdG12 (+Dox)-treated mice were significantly better than those of untreated CVB3-infected mice, almost reaching the values measured in uninfected control animals. The effect was visible when sCAR-Fc was expressed prophylactically, but much more importantly, LVP and  $dP/dt_{max}$  were also improved if sCAR-Fc was induced concomitantly with CVB3 infection, which demonstrates a strong potential for therapeutic efficacy of the sCAR-Fc gene therapy approach after CVB3 infection. Although sCAR-Fc induction corresponding to approximately

40 hours after CVB3 infection did not improve heart function or pancreatitis, histological cardiomyopathy grading and myocardial virus load were decreased significantly, which likely would lessen the risk of development of dilated cardiomyopathy. In agreement with previous reports,<sup>11,25</sup> prophylactic sCAR-Fc delivery abrogated pancreatic and cardiac inflammation and necrosis and resulted in negligible virus load as assessed by *in situ* visualization of CVB3 genome presence and parenchymal virus titer. The present study improves on previous methods of delivering sCAR-Fc by showing higher and more prolonged circulating levels of decoy receptor, without the variability of plasmid delivery or expense and potential copurification of contaminants associated with the production of purified recombinant proteins.

The decreased efficacy of sCAR-Fc gene therapy when administered after CVB3 infection likely reflects the inability of sCAR-Fc to penetrate sufficiently into the parenchyma of the heart and pancreas once initial virus infection has been established and the virus predominantly spreads between adjacent cells or perhaps is unable to fully neutralize the initially high levels of CVB3 in the serum that are seen early in infection.<sup>26</sup> The present results were similar to those previously reported that examined administration of purified recombinant sCAR-Fc<sup>13</sup> to CVB3-infected mice, but the present results advance these studies by showing a significant decrease in cardiac inflammation, virus load, and cardiac function if treatment begins within the first 24 hours of CVB infection.

The present *in vitro* data demonstrate that sCAR-Fc could neutralize up to  $10^4$  CVB3 particles (results not shown) and reduce CVB3 replication by up to 11 orders of magnitude. In addition to virus-neutralization capacity, we cannot rule out other antiinflammatory effects of sCAR-Fc. Other decoy receptor Fc fusion proteins (eg, CD55-Fc) and purified pooled immunoglobulins have been shown to decrease myocardial lesion area, inflammation, viral replication, and viral progeny synthesis in CVB3 infection *in vivo*; however, these were not as effective as sCAR-Fc.<sup>13,25,27</sup> CAR has also been reported to bind human IgG and IgM, which suggests a further role for CAR in immune system interactions.<sup>28</sup> Future studies examining the ability of sCAR-Fc to modulate cardiomyopathy in mouse models by other nonenteroviral pathogens will be needed to address this possibility.

Extension of the efficacy of sCAR-Fc beyond 24 hours after CVB infection may be achieved by combining viral neutralization with potent antiinflammatory therapies (for example, targeting proinflammatory cytokines, which have also been shown to be potent in inhibiting CVB3-induced myocarditis<sup>29,30</sup>). Another potential approach would be to combine sCAR-Fc with RNA interference that specifically targets intracellular CVB3 during replication. In this context, we have shown that small hairpin RNAs directed against CVB3 RNA-dependent RNA polymerase were capable of increasing systolic and diastolic function in CVB3-infected animals.<sup>19</sup>

The safety of viral vectors plays an important role in gene therapy applications. AdG12 treatment did not induce side effects in CVB3-infected or uninfected animals. Furthermore, because AdG12 is a first-generation AdV, its presence in the



body is self-limited to several weeks.<sup>31</sup> Moreover, the doxycycline-dependent control of sCAR-Fc expression in AdG12 enables on/off switching and confers the ability to shut off transgene expression at any point after delivery, thereby further increasing its safety. It is a hallmark of AdG12 that there is no leaky sCAR-Fc expression in the absence of the inducer drug, doxycycline. This was achieved through the use of improved key components of the Tet-On gene expression system, the second-generation transactivator (rtTA-M2) and a new response promoter (tight1). Each was shown to be able to reduce background activity of the Tet-On system,<sup>21,22</sup> but in contrast to the results presented here, the use of rtTA-M2 with the original tetracycline-response promoter, TRE, still resulted in leaky expression of the Tet-On system in the context of AdVs.<sup>32,33</sup> The resistance of tight1 to nonspecific transactivation may be responsible for the lack of leakiness of AdG12. Moreover, the use of improved components of the Tet-On system enables side-by-side insertion of cytomegalovirus-promoter-driven rtTA-M2 and tight1-promoter-driven sCAR-Fc expression cassettes into the adenoviral E1 region, thereby simplifying the construction of doxycycline-regulated AdVs.

Host immune responses often prevent readministration of an AdV of the same serotype.<sup>34</sup> This may limit the potential clinical utility of our proof-of-concept approach in cases in which repeated AdV administration would be necessary, eg, to extend the treatment period. However, administration of AdVs derived from different serotypes,<sup>35</sup> or the use of significantly less immunogenic vectors that are derived from adeno-associated virus, is an available tactic to overcome this limitation.

In conclusion, here we show therapeutic efficacy in treating CVB3 myocarditis with sCAR-Fc delivered from a pharmacologically regulated AdV. The treatment was highly efficient, without clinically observable side effects, and led to improved hemodynamics and heart function in CVB3-infected animals. For the purpose of the present study, the chosen sample sizes were appropriate to document statistical significance; however, if the prognostic relevance of this treatment, including survival changes, is to be investigated in the future, considerably larger study groups must be used. The combination of the sCAR-Fc approach with gene therapy methods represents a promising new approach for treatment of cardiac CVB3 infections.

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### Disclosures

Dr Fechner and S. Pinkert have a patent pending on AdG12 and AdR4, their doxycycline-regulated expression cassettes, and their use for expression of soluble receptor proteins for antiviral therapy. The remaining authors report no conflicts.

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### CLINICAL PERSPECTIVE

Group B coxsackieviruses (CVBs) are the prototypical agents of acute myocarditis in humans, but an effective targeted therapy is not yet available. Acute enteroviral myocarditis may not lead to initial mortality but often results in the insidious development of chronic dilated cardiomyopathy and terminal heart failure. Here, we analyze the therapeutic potential of a soluble (s) virus receptor molecule against CVB3 myocarditis, delivered by use of a gene therapy approach. We generated an inducible adenoviral vector (AdG12) for strictly drug (doxycycline)-dependent delivery of sCAR-Fc, a fusion protein composed of the coxsackievirus-adenovirus receptor (CAR) extracellular domain and the carboxyl terminus of human IgG1-Fc. After intravenous injection, AdG12 significantly improved systolic and diastolic function in CVB3-infected mice if sCAR-Fc expression was pharmacologically induced in a prophylactic or therapeutic setting. Importantly, the hemodynamics of animals treated with AdG12 were similar to those of healthy control animals. With respect to the underlying pathomechanism, sCAR-Fc completely blocked (prophylactic) or strongly reduced (therapeutic) cardiac CVB3 infection and the resultant myocardial injury and inflammation. The strength of the cardioprotective effect and the additional safety feature mediated by the strict drug dependency of the sCAR-Fc expression make this strategy a promising approach for treatment of this life-threatening cardiac disease. It may also serve as a paradigm for analogous treatments of other severe viral infections by systemic delivery of “virus-trap” proteins, generated either by vectors as described here or by direct intravenous infusion of the encoded recombinant protein.

## SUPPLEMENTAL MATERIAL

### Supplemental Methods

#### Construction of Adenoviral Shuttle Plasmids

For construction of sCAR-Fc fusion protein, total cellular RNA was extracted from HeLa cells using TRIzol<sup>®</sup> Reagent (Invitrogen GmbH, Karlsruhe, Germany) following the manufacturer's instructions. RNA was reverse transcribed by the use of Superscript RTase (Invitrogen, Carlsbad, USA, CA). The extra cellular domain of human CAR was then amplified by PCR using *NheI* linked hCARs (5' - cta gct agc tcg gca gcc agc atg gcg – 3') and *NotI* linked human CAR specific primer B618 (5' - ggc ggc cgc ttt att tga agg agg g – 3'). The resulting fragment was inserted via *NheI/NotI* into the plasmid pTorsten<sup>1</sup>, upstream and in frame with the carboxy terminus of human IgG1 Fc coding region, leading to generation of sCAR-Fc fusion protein containing plasmid pTorsten-sCAR-Fc.

For generation of a Dox-regulated sCAR-Fc expressing AdV, an expression cassette (TRE-tight1-MCS-SV40pA) containing an improved Dox responsive tight1 promoter<sup>2</sup>, a multiple cloning site (MCS) and a SV40 polyA signal was amplified with the primer pair P1-*AatIII-Spels* (5' - aac tga gac gtc taa cta gtc tca ggt tta ctc cct atc agt gat aga ga – 3') and P2-*XhoI-XbaI* (5' - ccg ctc gag gca gtc tag agc gag gaa gct aga ggc agt g – 3') from pTRE-tight (Clontech, Palo Alto, CA, USA) and then cloned into pCR<sup>®</sup>4Blunt-TOPO (Invitrogen). The expression cassette was cut out with *SpeI* and *XhoI* and subcloned into the adenoviral shuttle plasmid pZS2-CMV-rtTA<sup>3</sup>, in two opposite directions, via a singular *XbaI* site located downstream of the second-generation reverse tetracycline (tet)-controlled transactivator rtTA-M2<sup>4</sup>. The plasmids generated were termed pAdTREtight-od-M2-G (opposite direction to that of the rtTA-M2 expression cassette) and pAdTREtight-sd-M2-R (same direction). sCAR-



Fc was then amplified using the primer pair sCARFc-*Kpn*Is (5'- cgg ggt acc cag cat ggc gct cct gct g – 3') and sCARFc-*Mlu*Is (5' - cga cgc gtc gcc att tag gtg acc act aat – 3') in a 30-cycle PCR with *Pwo* polymerase (Roche, Mannheim, Germany) from pTorsten-sCAR-Fc and cloned into pAdTREtight-od-M2-G and pAdTREtight-sd-M2-R via *Kpn*I/*Mlu*I downstream to the TRE-tight1 promoter, resulting in the plasmids pAdG12-sCAR-Fc and pAdR4-sCAR-Fc. pAdG12-sCAR-Fc<sub>trunc</sub> was constructed as pAdG12-sCAR-Fc. Different to pAdG12-sCAR-Fc in pAdG12-sCAR-Fc<sub>trunc</sub> a frameshift mutation at nucleotide position 9 (deletion of a cytosine) was inserted in sCAR-Fc leading to premature translation stop at amino acid 13. Therefore, the vector do not expresses sCAR-Fc.

The correctness of all plasmids was confirmed by sequencing on an ABI 310 genetic analyzer (Applied Biosystems, Foster City, CA, USA).

### Development of Adenoviral Vectors

The adenoviral shuttle plasmids pAdG12-sCAR-Fc, pAdR4-sCAR-Fc and pAdG12-sCAR-Fc<sub>trunc</sub> were linearized with *Xba*I and ligated to the 5' long arm of *Xba*I-digested E1-E3- adenovirus 5 mutant RR5. Transfection into HEK293 cells and propagation were done as described <sup>5</sup> generating the adenoviral vectors termed AdG12, AdR4 and AdG12<sub>trunc</sub>. All adenoviral constructs were tested for RCA contamination by PCR as described before <sup>6</sup> and the viral titres were determined using standard plaque assays on HEK293 cells.

### Northern Blot

RNA was isolated using TRIzol<sup>®</sup> Reagent (Invitrogen GmbH) following the manufacturer's instructions. 10 µg of total RNA were separated on a 1 % formaldehyde agarose gel and transferred to a Hybond N nylon membrane (Amersham Biosciences, Buckinghamshire, UK). After prehybridization, the membranes were hybridized with a [<sup>32</sup>P]dCTP-labeled single stranded *antisense* probe in ExpressHyb Solution (Clontech) following the manufacturer's instructions. The probe was labelled in a PCR-like reaction as described previously <sup>7</sup> by use of primer B618 and a DNA fragment comprising the extra

cellular domain of human CAR as template. Hybridized filters were exposed to Kodak Biomax MS film (Integra Biosciences, Fernwald, Germany). The hybridization signal intensity was determined by phosphoimaging in a Fuji Film BAS-1500 imager (Fuji Photo Film, Dusseldorf, Germany).

### **Western Blot**

For detection of sCAR-Fc protein, cells were transduced with viral vectors expressing sCAR-Fc or truncated sCAR-Fc and cultured with or without Dox. Supernatants were removed and collected, while cells were lysed with lysis buffer [20 mM Tris, pH 8, 10 mM NaCl, 0.5% (v/v) Triton X 100, 5 mM EDTA, 3 mM MgCl<sub>2</sub>]. After heating the cell-lysate and supernatants at 95° C for 5 min, protein was separated on NuPAGE 4-12% Bis-Tris gels (Invitrogen) under denaturing and reducing conditions and transferred onto a PVDF membrane (Bio-RAD Lab. Hercules, CA, USA). For detection of sCAR-Fc, the immunoreactivity membrane was incubated with anti-CAR monoclonal antibody RmcB (Upstate Biotechnology, Lake Placid, NY, USA) in a dilution of 1:200 or anti-GAPDH polyclonal antibody 1:7.500 (Chemicon International, Hofheim, Germany) for 1 h in 5 % dry milk/TBST. After washing, membranes were incubated with secondary goat-anti-mouse (primary antibody: RmcB) antibodies or swine-anti-rabbit antibodies (primary antibody: anti-GAPDH) conjugated with peroxidase (DAKO GmbH, Hamburg, Germany) at a dilution of 1:10.000. To detect the IgG1-Fc domain of sCAR-Fc, the membrane was stripped with 1.5 % glycine, 1 % SDS, 0.001 volume Tween 20 [pH 2] for 1 h at 55°C and reincubated with horseradish peroxidase conjugated sheep anti-human IgG antibody 1:500 (Amersham Bioscience) in TBST/5 % dry milk for 1 h. Detection by chemiluminescence was achieved using the ECL system (Amersham Bioscience).

### **Detection of sCAR-Fc Expression *In Vivo* by Use of the IgG specific Enzyme-linked Immunosorbent Assay**

Blood samples were taken from vector transduced animals by puncture of the *vena facialis*. The serum was separated by centrifugation at 4.000 rpm for 8 min and stored at -80°C. The serum sCAR-Fc protein levels were determined by a human IgG ELISA kit (*Bethyl Laboratories Inc.*, Montgomery, TX, USA).

### **Virus Plaque Assay**

The amount of infectious CVB3 in HeLa cells was determined on monolayers of HeLa cells by agar overlay plaque assay, as described elsewhere <sup>8</sup>. For *in vivo* analysis midventricular portions of the heart from CVB3 infected mice were homogenized in serum-free DMEM, and subsequently analyzed by plaque assay. Results to be shown were gained by two independent experiments, each performed in duplicate.

### **Histopathological Analysis**

The apical parts of the hearts were fixed in 4% formalin, embedded in paraffin, and 5- $\mu$ m sections were cut and stained with hematoxylin and eosin (H&E) to assess myocardial injury and inflammation. To quantify myocardial damage comprising cardiac cell necrosis, inflammation, and scarring, we applied a myocarditis score of 0 to 4 as described <sup>9</sup> (score: 0, no inflammatory infiltrates; 1, small foci of inflammatory cells between myocytes; 2, larger foci >100 inflammatory cells; 3,  $\leq$ 10% of the cross-section involved; 4, 10 to 30% of the cross-section involved).

### **Haemodynamic Measurements**

Left ventricular (LV) function was analyzed using pressure volume loops. As described recently <sup>10</sup>, the animals were anesthetized, intubated, and artificially ventilated. A 1.2 F pressure-volume catheter (*Scisense Inc.*, Ontario, Canada) was positioned in the LV for registration of LV pressure–volume (PV) loops in an open-chest model. Systolic function



was quantified by LV end-systolic pressure (LVP) (mmHg) and dP/dt max (mmHg/s). Diastolic function was quantified by analyzing dP/dt min (mmHg/s).

### ***In situ* Hybridization**

CVB3 positive-strand RNA in tissues was detected using single-stranded <sup>35</sup>S-labeled RNA probes which were synthesized from the dual-promoter plasmid pCVB3-R1. Control RNA probes were obtained from the vector pSPT18 <sup>11</sup>. Pre-treatment, hybridization, and washing procedures of dewaxed 5- $\mu$ m paraffin tissue sections were performed as described previously <sup>11</sup>. Slide preparations were subjected to autoradiography, exposed for 3 weeks at 4°C, and finally counterstained with HE.

## Supplemental Tables

### Supplementary Table I

#### A. Prophylactical approach – p-values for haemodynamic parameter comparisons

	Outcome parameters		
	LVP	dP/dtmax	dP/dtmin
AdG12 (-Dox) vs. AdG12 (+Dox)	p=0.0043	p=0.0043	p=0.0087
sham (+Dox) vs. sham (-Dox)	p=0.0043	p=0.0022	p=0.0649

#### B. Statistical data of haemodynamics of the prophylactical approach

group	N	LVP [mmHg]					dP/dtmax [mmHg/s]					dP/dtmin [mmHg/s]				
		Q1	median	Q3	mean	STD	Q1	median	Q3	mean	STD	Q1	median	Q3	mean	STD
AdG12 (-Dox)	6	43.68	45.77	47.90	45.39	2.73	1512.70	2071.95	2549.10	2057.90	490.24	-1464.40	-1295.90	-1025.00	-1310.23	330.30
AdG12 (+Dox)	5	58.24	59.03	62.01	58.99	3.75	3388.00	3526.60	4072.70	3645.10	443.56	-2210.70	-2083.70	-1878.39	-2125.52	330.52
sham (-Dox)	6	57.19	67.49	77.09	67.51	12.84	3168.90	4383.20	4992.40	4429.32	1287.57	-2656.50	-1941.32	-1477.80	-2117.39	713.47
sham (+Dox)	6	43.15	45.84	50.27	46.60	5.54	1956.50	2333.25	2995.50	2428.50	490.44	-1825.50	-1094.70	-1049.50	-1330.49	437.41

N=number of animals; Q1: 25th percentile; Q3: 75th percentile; STD= standard deviation

## Supplementary Table II

## A. Therapeutical approach – p-values for haemodynamic parameter comparisons

	Outcome parameters		
	LVP	dP/dtmax	dP/dtmin
AdG12 (+Dox, 0d) vs. AdG12 <sub>trunc</sub> (-Dox)	p=0.048	p=0.0303	p=0.0732
AdG12 (+Dox, 1d) vs. AdG12 <sub>trunc</sub> (-Dox)	p=0.1649	p=0.1282	p=0.1649
sham (+Dox) vs. sham (-Dox)	p=0.0424	p=0.0121	p=0.0242

## B. Statistical data of haemodynamics of the therapeutical approach

group	N	LVP [mmHg]					dP/dtmax [mmHg/s]					dP/dtmin [mmHg/s]				
		Q1	median	Q3	mean	STD	Q1	median	Q3	mean	STD	Q1	median	Q3	mean	STD
AdG12 (+Dox, 0d)	5	61.29	74.83	93.03	76.38	19.18	3722.60	5182.13	6748.63	5214.19	1786.16	-5046.33	-3624.33	-2596.33	-3756.62	1418.03
AdG12 (+Dox, 1d)	7	52.63	66.72	76.54	66.86	12.35	3062.30	3384.87	4819.50	3842.24	982.22	-3343.58	-2502.33	-2223.80	-2659.38	662.87
AdG12 <sub>trunc</sub> (-Dox)	7	47.92	54.39	68.18	56.82	10.32	2145.97	3106.57	4180.87	3011.62	918.34	-3087.37	-2217.43	-1555.10	-2212.04	745.68
sham (+Dox)	4	50.59	61.30	72.10	61.35	12.63	2180.02	2760.45	3711.60	2945.81	964.82	-2877.27	-2214.78	-1682.47	-2279.87	716.20
sham (-Dox)	7	70.94	79.89	84.35	78.66	8.27	4210.90	5101.47	6054.23	5076.71	854.92	-3949.27	-3455.37	-3272.75	-3505.97	471.88

N=number of animals; Q1: 25th percentile; Q3: 75th percentile; STD= standard deviation



**C. Therapeutical approach – p-values for CVB3 load in the heart comparisons**

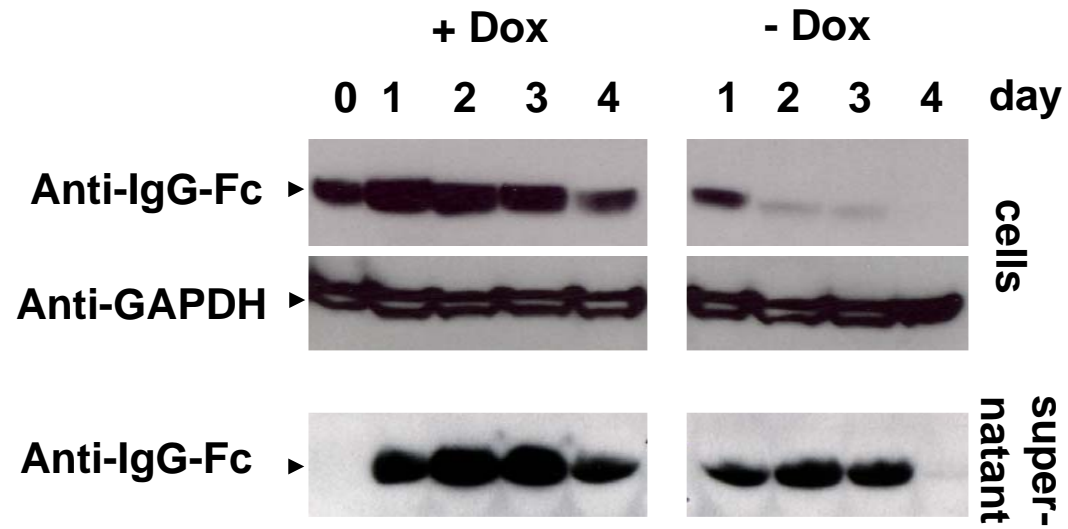
	<b>CVB3 titer</b>
AdG12 (+Dox, 0d) vs. AdG12 <sub>trunc</sub> (-Dox)	p=0.0025
AdG12 (+Dox, 1d) vs. AdG12 <sub>trunc</sub> (-Dox)	p=0.0006

**D. Statistical data of plaque assays of the therapeutical approach**

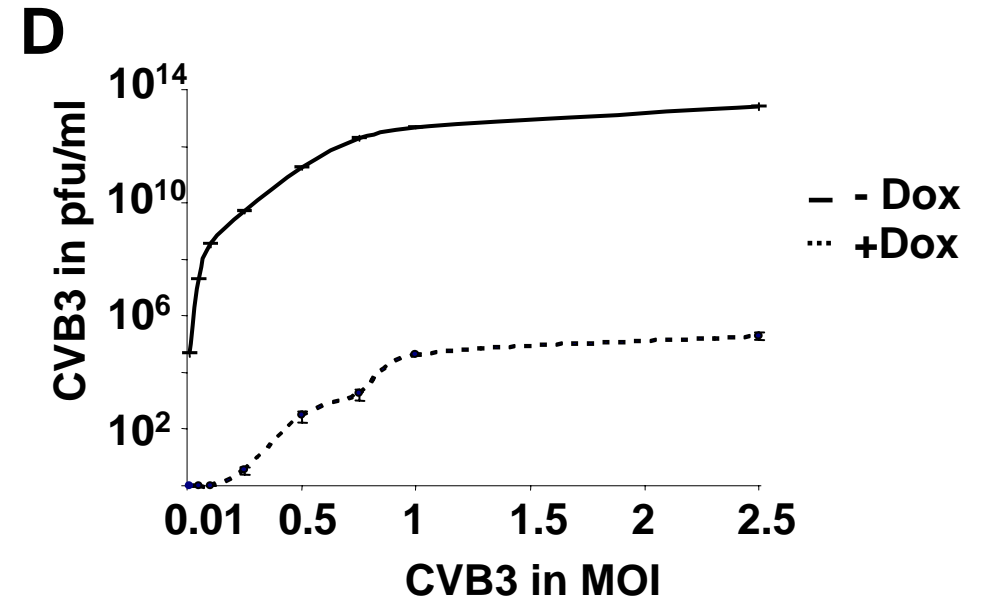
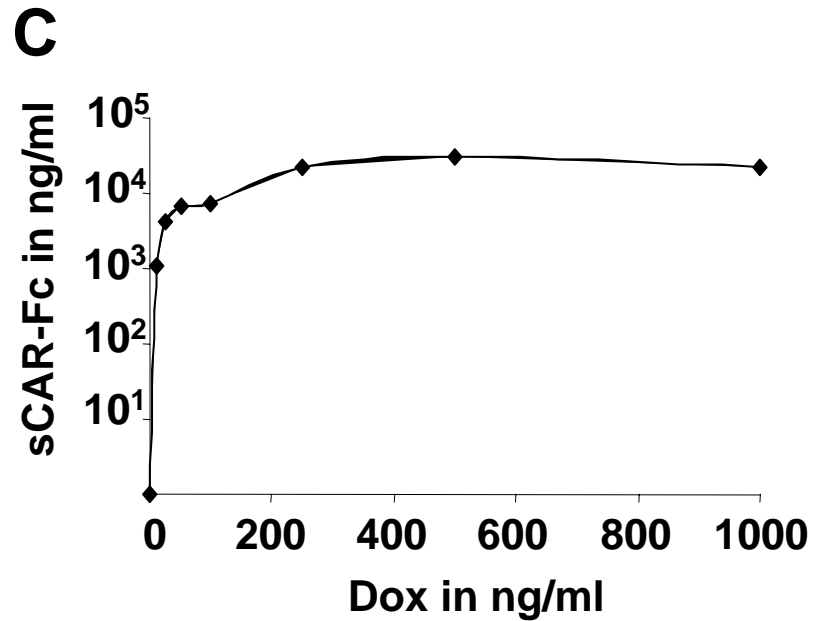
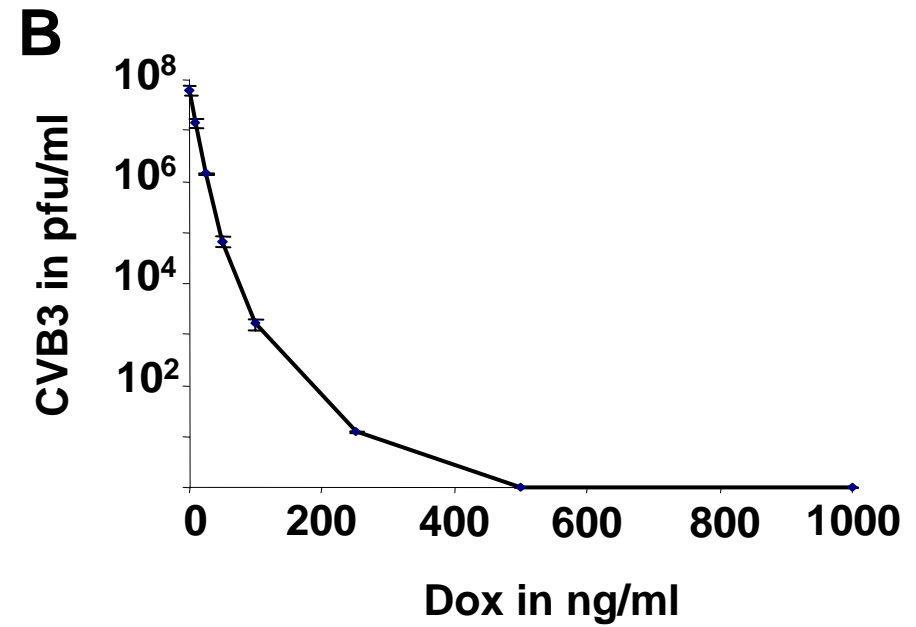
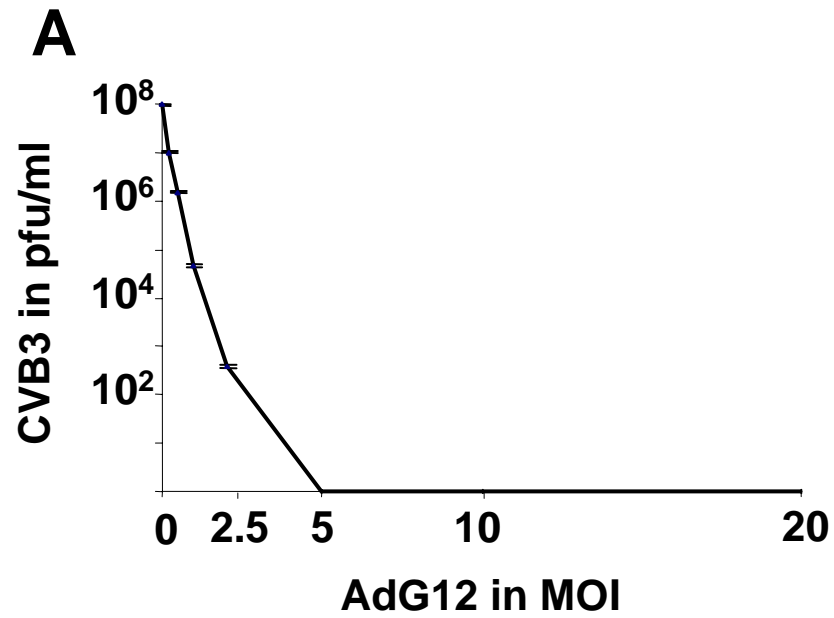
<b>group</b>	<b>N</b>	<b>CVB3 titer in PFU/mg heart</b>				
		<b>Q1</b>	<b>median</b>	<b>Q3</b>	<b>mean</b>	<b>STD</b>
AdG12 (+Dox, 0d)	5	5.70	294.00	9090.00	14544.34	27549.81
AdG12 (+Dox, 1d)	7	5020.33	5438.05	109155.80	43906.66	56748.30
AdG12 <sub>trunc</sub> (-Dox)	7	494395.00	648083.30	2421327.00	1175006.59	910721.67
sham (+Dox)	4	506405.20	574586.35	762618.65	634511.93	180380.50

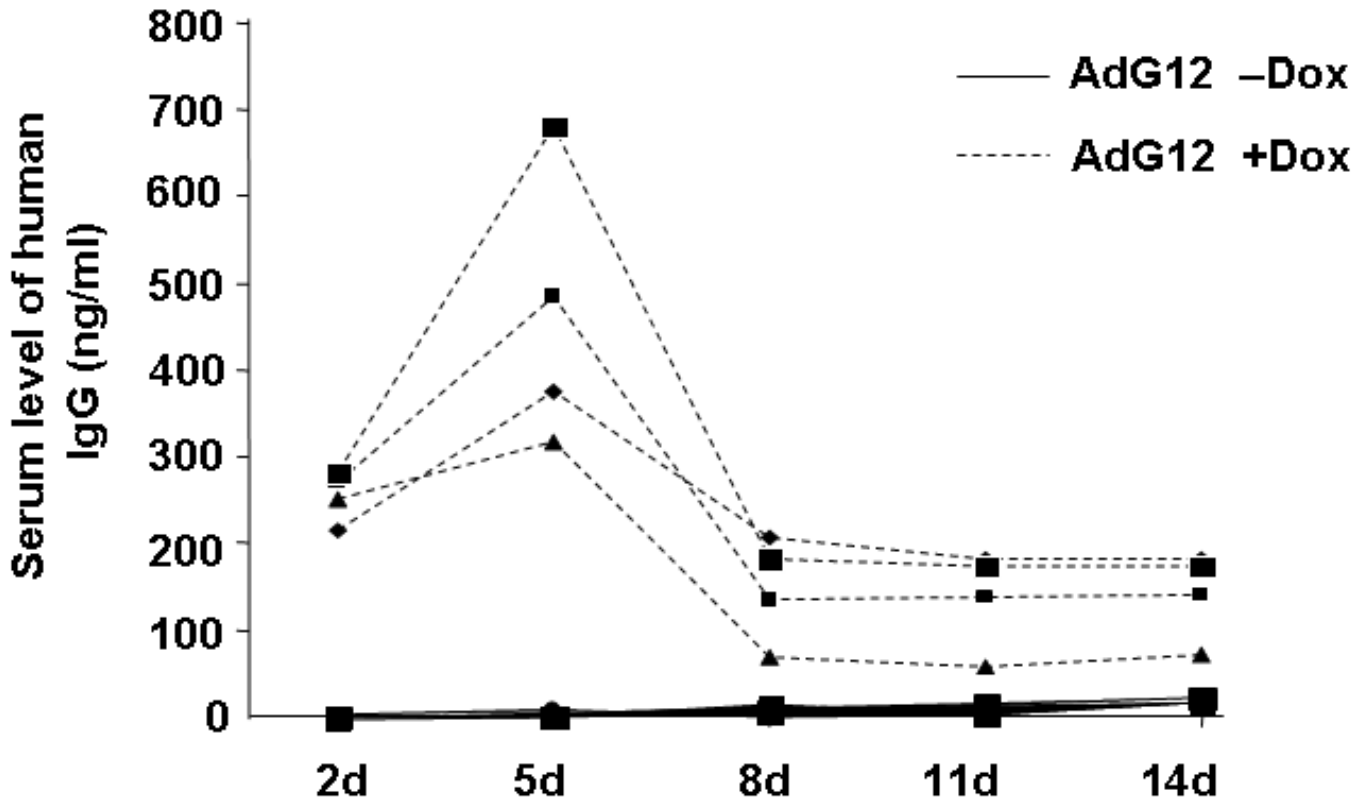
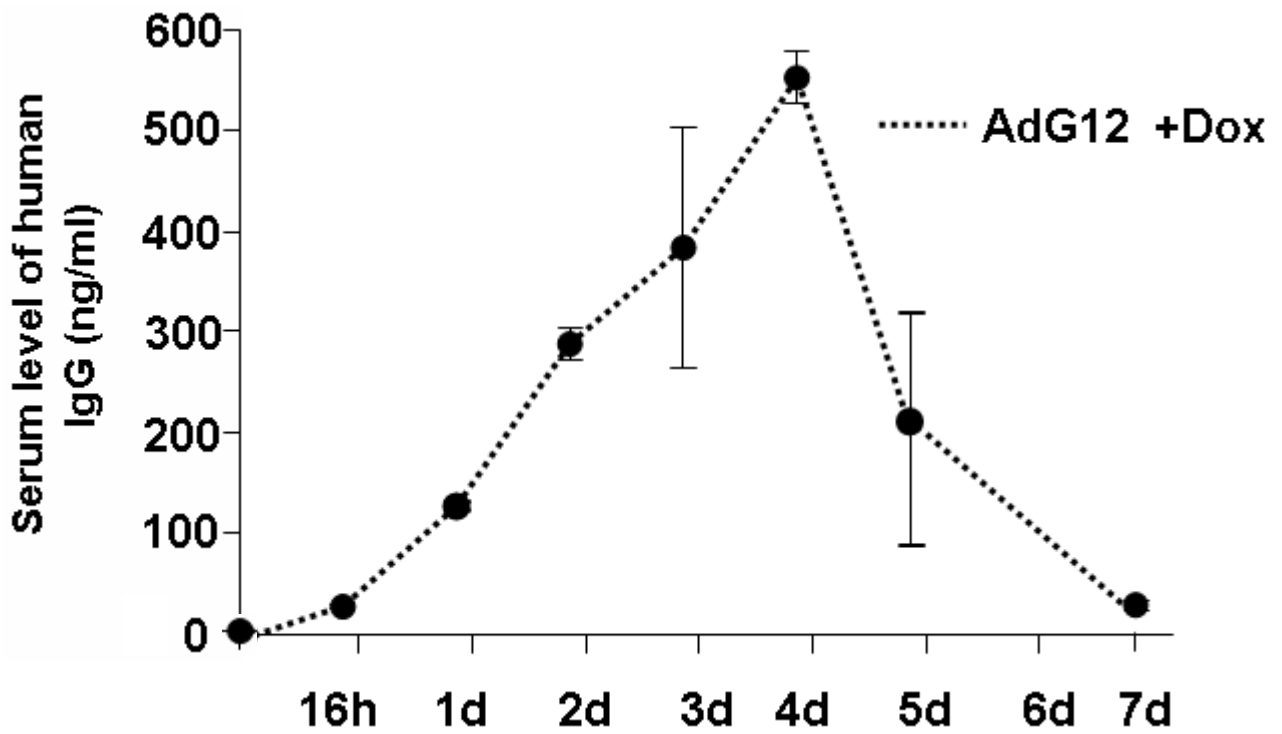
N=number of animals; Q1: 25th percentile; Q3: 75th percentile; STD= standard deviation

## Supplementary Figure I

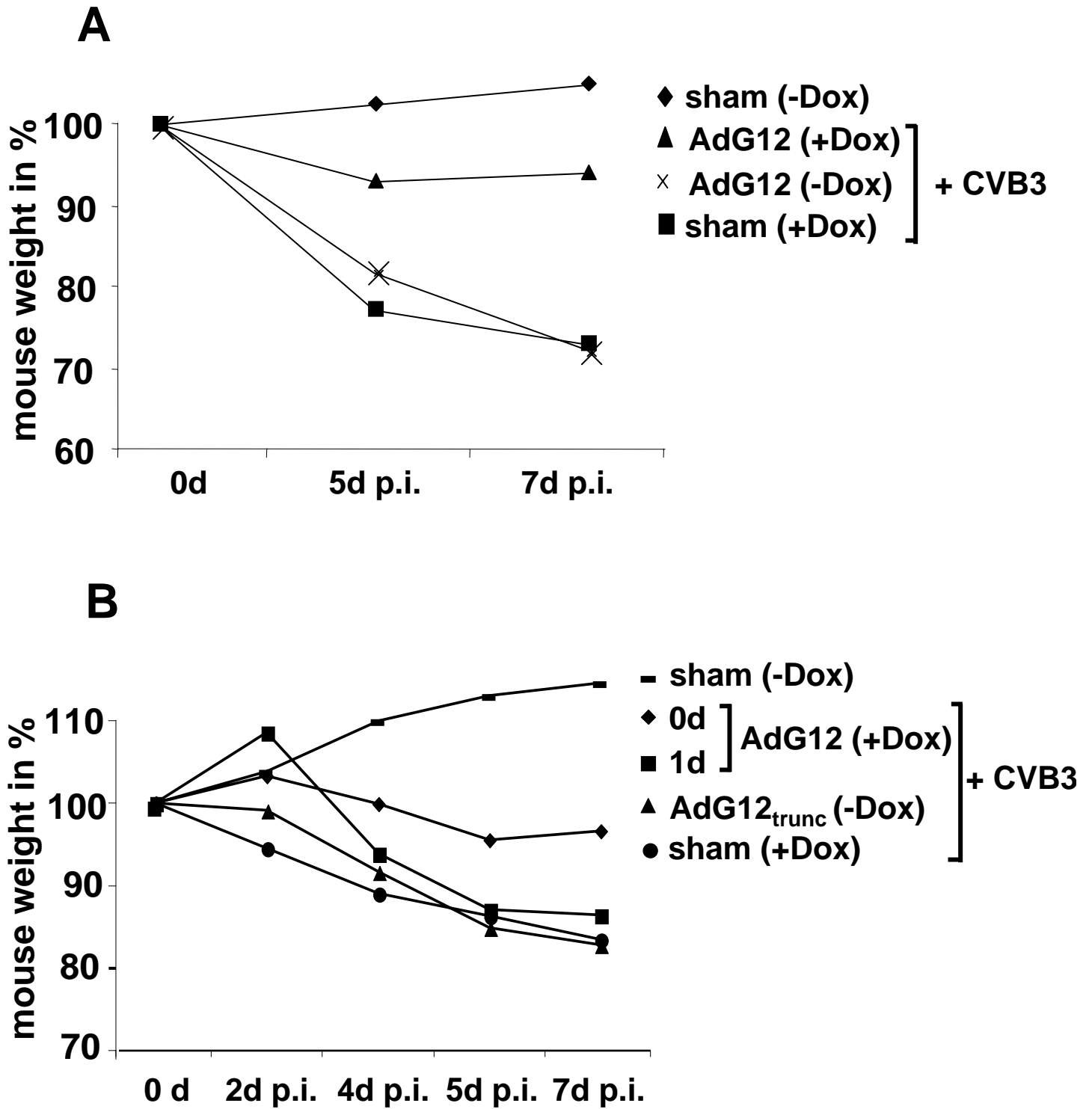


## Supplementary Figure II



**A****Supplementary Figure III****B**

## Supplementary Figure IV





**Supplementary Figure I. On/off switching of sCAR-Fc expression.**

HeLa cells were transduced with AdG12 at a MOI of 2 and incubated with Dox (1 µg/ml). After 24 h (day 0) medium was replaced by fresh medium and cells were cultured for an additional 4 days with Dox (*left panel*) or without Dox (*right panel*). During this time, medium was replaced daily with fresh medium. sCAR-Fc was detected in both cells and medium by Western analysis using an anti-IgG-Fc antibody. GAPDH immunoreactivity was used as loading control. sCAR-Fc completely disappeared in the cells and nearly completely disappeared in the supernatant on day four after withdrawal of Dox in comparison to the samples taken before.

**Supplementary Figure II. Inhibition of CVB3 replication in permissive HeLa cells through sCAR-Fc.**

**(A)** Inhibition of CVB3 replication as a function of AdG12 dose. HeLa cells were transduced with AdG12 (MOI 0 to 20) and cultured with Dox (1 µg/ml). Forty-eight hours later cell culture supernatant was harvested, pre-incubated with an MOI of 0.1 of CVB3 for 30 min at 4°C, deposited to the AdG12 transduced cells for 30 min and then replaced with fresh medium. CVB3 replication was analysed by plaque assays after 24 h of culture.

**(B)** Influence of Dox dose on sCAR-Fc mediated inhibition of CVB3 replication. HeLa cells were transduced with AdG12 at a MOI of 5 and then cultured with Dox in different concentrations (0 - 1 µg/ml) for 48 h. CVB3 neutralization assays were performed as described under (A) above.

**(C)** Measurement of Dox-dependent expression of sCAR-Fc in cell culture supernatant. HeLa cells were transduced and sCAR-Fc expression induced as described under (B) above. sCAR-Fc expression levels were measured in the cell culture supernatant by IgG ELISA.

**(D)** Inhibition of CVB3 replication by AdG12 as a function of CVB3 doses escalation. HeLa cells were transduced with AdG12 at a MOI of 5 and incubated in the absence or presence of Dox (1 µg/ml) for 48 h. CVB3 neutralization assays were carried out as described under (A) above.

**Supplementary Figure III. Systemic sCAR-Fc Gene Transfer Supports Inducible sCAR-Fc Delivery *in vivo***

**(A)** Kinetics of individual sCAR-Fc serum level after transduction of mice with AdG12. Balb/c mice (n=7) were injected intravenously with  $3 \times 10^{10}$  particles of AdG12. sCAR-Fc expression was induced and maintained in four animals by addition of 200  $\mu\text{g/ml}$  Dox to the drinking water. The other three AdG12-transduced animals did not contain the drug. sCAR-Fc serum concentrations in AdG12 (+Dox) transduced animals roughly doubled from day 2 (254 $\pm$ 29 ng/ml) to day 5 (464 $\pm$ 159 ng/ml), then decreased at day 8 (147 $\pm$ 60 ng/ml), but expression did not decrease further when measured at day 14 (141 $\pm$ 51 ng/ml). In the absence of Dox, sCAR-Fc serum levels were indistinguishable from levels in untransduced control mice. Histopathological examination of liver and heart samples did not show any signs of tissue damage and inflammation at various time points (not shown).

**(B)** Kinetics of sCAR-Fc expression after delayed induction of sCAR-Fc. Balb/c mice (n=6) were injected intravenously with  $10^{10}$  particles of AdG12. Measurement of sCAR-Fc expression in the serum revealed absence of sCAR-Fc in the serum two days after AdG12 transduction. Dox (200  $\mu\text{g/ml}$ ) was then added to the drinking water to induce sCAR-Fc. sCAR-Fc serum levels reached 28.4 ng/ml 16 h after Dox treatment, increased to 552.7 ng/ml at day 4 after induction and drop to 28.8 ng/ml at day 7 after induction.

**Supplementary Figure IV. sCAR-Fc prevents body weight loss in CVB3 infected animals. (A)** Animals were treated as described in Figure 4A. **(B)** Animals were treated as described in Figure 5A. The values shown in A and B are mean values. No mortality was observed in any of the groups.

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