

Article

Efficient intravenous tumor targeting using the $\alpha\beta6$ integrin selective precision virotherapy Ad5_{NULL}-A20.

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Abstract:

Background: We previously developed a refined, tumor selective adenovirus, Ad5_{NULL}-A20, harboring tropism ablating mutations in each major capsid protein, to ablate all native means of infection. We incorporated a 20mer peptide (A20) in the fiber knob for selective infection via $\alpha\beta6$ integrin, a marker of aggressive epithelial cancers.

Methods: To ascertain the selectivity of Ad5_{NULL}-A20 for $\alpha\beta6$ positive tumor cell lines of pancreatic and breast cancer origin, we performed reporter gene and cell viability assays. Biodistribution of viral vectors in mice harboring xenografts with low, medium, and high $\alpha\beta6$ levels was quantified by qPCR for viral genomes 48 hours post intravenous administration.

Results: Ad5_{NULL}-A20 vector transduced cells in an $\alpha\beta6$ selective manner, whilst cell killing mediated by oncolytic Ad5_{NULL}-A20 was $\alpha\beta6$ selective. Biodistribution analysis following intravenous administration into mice bearing breast cancer xenografts demonstrated that Ad5_{NULL}-A20 resulted in significantly reduced liver accumulation coupled with increased tumor accumulation compared to Ad5 in all three models, with tumor: liver ratios improved as a function of $\alpha\beta6$ expression.

Conclusions: Ad5_{NULL}-A20 based virotherapies efficiently target $\alpha\beta6$ integrin positive tumors following intravenous administration, validating the potential of Ad5_{NULL}-A20 for systemic applications, enabling tumor selective overexpression of virally encoded therapeutic transgenes.

Keywords: Adenovirus; Oncolytic; Virotherapy; Targeting; $\alpha\beta6$ integrin; Systemic delivery

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1. Introduction

Cancer virotherapies are an emerging in the clinical setting, with oncolytic viral therapy has been an approved immunotherapy since talimogene laherparepvec (T-VEC, Imlygic®) was approved by the Food and Drug Administration (FDA) and European Medicines Agency (EMA) for melanoma treatment in 2015 [1]. Moreover, an accumulating body of evidence indicates that the immunogenic nature of oncolytic virus-induced cell death provides a suitable environment to sensitize resistant tumors to immunotherapies [2]. Various oncolytic viruses (OVs), such as HF10 (Canerpaturev – C-REV) and CVA21 (CAVATAK), are now actively being developed in phase II as monotherapies, or in combination with immune checkpoint inhibitors against melanoma [3].

OVs have shown efficacy when delivered by direct intratumoral injection. However, systemic delivery of OV has proven more challenging. For OVs to treat a range of primary and metastatic tumors they will need to be efficiently delivered via intravenous administration [4]. This will require development of new OVs designed to overcome the problems facing systemic administration.

Adenovirus (Ad) have proven popular choices for oncolytic applications. Their double stranded DNA genome is ideally suited to genetic manipulation, and they can be grown to high, clinically useful titers. Adenovirus 5 (Ad5) is the most commonly used platform for cancer and other gene therapy applications [5], however, this serotype has several features that may hamper its use clinically as an oncolytic agent.

In vitro Ad5 enters host cells via an initial interaction between viral fiber protein and its primary receptor, coxsackie and adenovirus receptor (CAR) [6]. Subsequently Ad5 internalizes via $\alpha\beta 3/5$ integrins mediated by the viral penton base protein [7]. CAR is ubiquitously expressed within tight junctions on polarized epithelial cells but often downregulated in cancers [8] making it a poor target for cancer therapies. Ad5 is a common respiratory virus, with seroprevalence rates close to 100 % in certain populations [9], neutralizing antibodies (nAbs) can rapidly inactivate therapeutic vectors. In addition there is extensive off-target sequestration to the liver upon systemic administration via bridging of the viral hexon protein to heparan sulphate proteoglycans (HSPGs) [10] via human coagulation factor 10 (FX) [11].

We previously ablated the native tropisms of Ad5 by the introduction of a panel of point mutations in the main capsid components [12]. This generated a triple de-targeted Ad5-based vector containing a combination of tropism-modifications in hexon hypervariable region 7 (HVR7 mutation) [13], fiber knob AB loop (KO1 mutation) [14] and penton integrin-binding motif Arg-Gly-Asp (RGD \rightarrow RGE mutation) [7]. The vector was made cancer-selective by genetic incorporation of an $\alpha\beta 6$ integrin-binding peptide (A20, NAVPNLRGDLQVLAQKVART) within the viral fiber knob HI loop [15]. A20 peptide was originally derived from foot-and-mouth disease virus (FMDV) capsid protein VP1 and has a very high affinity to its native receptor, $\alpha\beta 6$ integrin [16]. $\alpha\beta 6$ integrin represents an exciting candidate for targeted delivery of cancer therapeutics, since it is absent in the normal epithelia, but plays a key role in TGF- β mediated epithelial to mesenchymal transformation (EMT) and metastasis [17, 18]. Expression of $\alpha\beta 6$ integrin has been shown to correlate with poor clinical prognosis [19, 20], and several advanced therapies are under development that are targeted to this tumor associated antigen [21-23]. This new vector, Ad5^{NULL}-A20, was able to selectively and efficiently infect $\alpha\beta 6$ integrin positive cell lines and primary ovarian tumor cells. Furthermore, our *in vivo* biodistribution analysis demonstrated significantly reduced sequestration in "off target" organs compared to the unmodified parental vector, Ad5. In our *in vivo* efficacy studies, intraperitoneal administration of oncolytic Ad5^{NULL}-A20 resulted in selective and efficient infection of peritoneal tumor metastases in a mouse model of advanced ovarian cancer, resulting in dramatically improved survival rates compared to mice treated with vector controls or with untreated mice [12].

In this study we have evaluated the potential for Ad5^{NULL}-A20 to transduce and kill $\alpha\beta 6$ integrin positive cancer cells of pancreatic and breast origin. We also sought to establish whether the Ad5^{NULL}-A20 platform could selectively infect $\alpha\beta 6$ integrin positive tumors following intravascular delivery in an *in vivo* mouse model of breast cancer.

2. Materials and Methods

Viruses

All replication-deficient and oncolytic vectors are based on a wild type Ad5 genome captured in a bacterial artificial chromosome (BAC). Subsequent modifications were introduced into the BACs by homologous recombineering [24]. Replication-deficient vectors carry a complete *E1/E3* gene deletion. Oncolytic vectors have a 24-base pair deletion *dl922-947* ($\Delta 24$) [25] in the *E1A* gene to restrict viral replication to pRB-defective cells and a T1 mutation [26] in the *E3/19K* gene to enhance oncolytic efficacy. The A20 peptide sequence (NAVPNLRGDLQVLAQKVART) from FMDV was inserted into the fiber knob HI loop. Control virus was produced in HEK293 cells, the Ad5^{NULL}-A20 was produced in HEK293- $\beta 6$ cells. Virus was purified and characterized according to standard protocols [15]

Cell lines

Pancreatic cell lines used in this study, as well as the triple negative breast cancer cell line BT-20 were kindly gifted by collaborators. BT-474, MDA-MB-231 and MDA-MB-231 were purchased from American Type Culture Collection (ATCC). All cell lines were cultured to ATCC guidelines.

In vitro assays

To quantify cell surface receptors cells were detached with trypsin/EDTA resuspended and incubated on ice for 1 hour with the respective primary mouse mAb; anti-CAR (RmcB, Millipore) and anti- $\alpha v\beta 6$ (10D5, Millipore). Bound antibodies were detected with secondary goat anti-mouse IgG conjugated to Alexa 647 (A21237, LifeTechnologies) for 1 hour. Cells were analyzed on a BD Accuri C6 (BD Biosciences) flow cytometer. The results were analyzed using the BD Accuri software.

Cell transduction efficiency was assessed in luciferase reporter assays, 20,000 cells were seeded into each well of a 96 well plate and incubated overnight at 37°C. Cells were infected with 5,000 viral particles per cell (vp/cell) in triplicate for 3 hours in serum free media. 48 hours post infection the cells were lysed and analysed using the Luciferase Assay system (Promega) following the manufacturers protocol to determine relative light units (RLU). Protein concentration for each well was determined using the BCA assay (Pierce) following the manufacturers protocol. RLU values for each sample were normalised against total protein for each sample (RLU/mg).

Cytotoxicity of oncolytic virus was determined using the CellTiter 96 AQueous One Solution Cell Proliferation assay (Promega) according to the manufacturer's recommended protocol. 20,000 cells were seeded into each well of a 96 well plate and incubated overnight. Cells were infected with 5,000 vp/cell for 3 hours in serum free media. Viable cells were determined at 24, 48, 72, 96 and 144 hours after infection, by adding 20 μ l CellTiter 96 AQueous One Solution reagent per well. Absorbance was measured at 490nm after a 2-hour incubation in a humidified 5% CO₂ atmosphere. % viable cells were calculated related to untreated cells. Results are mean, n=3, error bars represent standard deviation.

In vivo studies

Two PDX models [27] of breast cancer, available in-house, which had low (PDX2665) or med/high (PDX3204) levels of $\alpha v\beta 6$ integrin expression, as well as a BT-20 ($\alpha v\beta 6^{\text{HIGH}}$) xenograft model (implanted with Matrigel to support growth), were implanted subcutaneously in NSG mice. When tumors reached a palpable size, mice were injected intravenously with 1×10^{11} vp of replication deficient Ad5 or Ad5_{NULL}-A20. 72 hours post injection, organs were harvested, and qPCR for viral genomes was performed on DNA isolated from the liver and tumors. Viral and total genomic DNA was obtained using DNeasy Blood & Tissue DNA extraction kit. DNA was subjected to fluorogenic quantitative PCR using Fast SYBR Green Master Mix system in triplicate, using primers for the hexon: Forward: 5'-CGCGGTGCGGCTGGTG-3' and Reverse: 5'-TGGCG-CATCCCATCTCC-3'. Total adenoviral genomes were calculated using a standard curve of 10^1 – 10^7 viral genomes.

Statistical analyses

All figures and statistical analyses were done in GraphPad Prism 6.03. Vector transduction efficiency and *in vivo* biodistribution was analysed by two-tailed unpaired t-tests. *, p < 0.05; **, p < 0.01; ***, p < 0.001; ****, p < 0.0001.

3. Results

To assess the potential of Ad5^{NULL}-A20 as an agent to treat pancreatic and breast cancer we determined the expression levels of $\alpha\beta6$ integrin and CAR on a panel of cell lines.

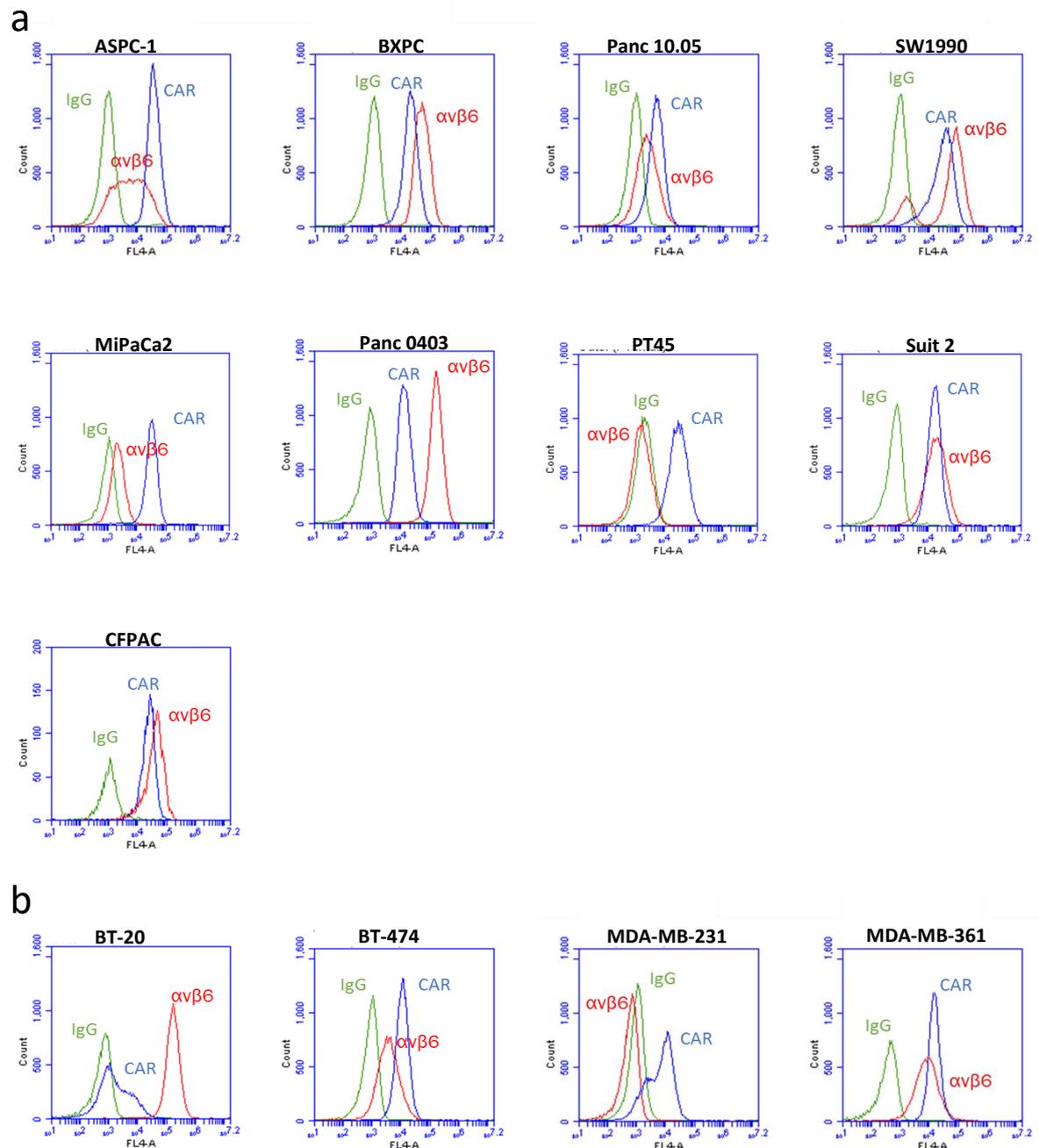
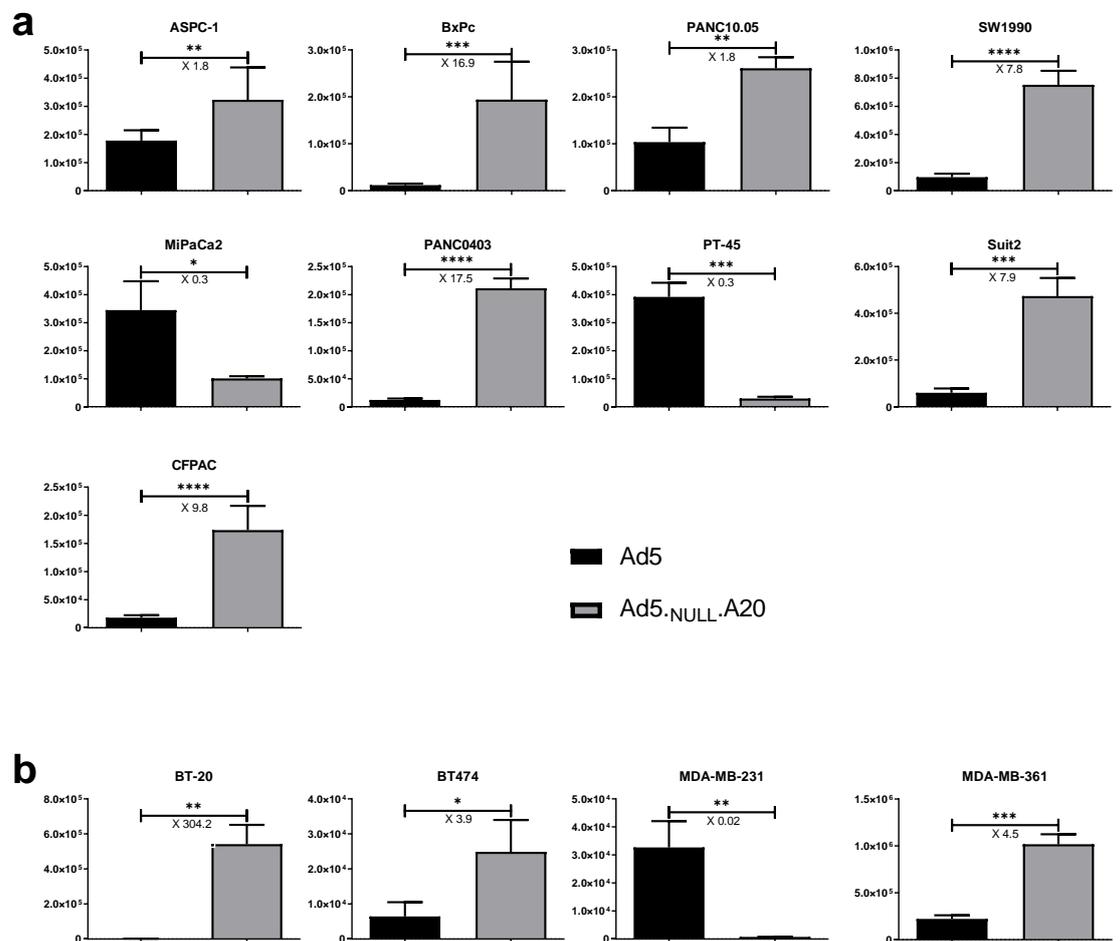


Figure 1. Protein expression levels of $\alpha\beta6$ and CAR were measured by flow cytometry in (a) pancreatic and (b) breast cancer cell lines.

In the nine pancreatic cancer cell lines tested, seven were positive for $\alpha\beta6$ integrin expression, including BxPc, PANC0403, Suit2, CFPAC, SW1990, PANC10.05 and ASPC-1. Two lines, MiPaCa2 and PT-45 (Figure 1a) were extremely low or negative for $\alpha\beta6$ expression, respectively. The highest expression levels were seen in PANC0403. CAR was detected in all nine cell lines. We screened four breast cancer cell lines (Figure 1b), and identified 3 cell lines (BT-20, MDA-MB-361, BT474) which expressed $\alpha\beta6$ integrin and one (MDA-MB-231) which did not express $\alpha\beta6$. Of interest the cell line BT20 was

$\alpha\text{v}\beta\text{6}^{\text{high}}/\text{CAR}^{\text{null}}$ whilst MDA-MB-231 cells were of the opposite phenotype, $\alpha\text{v}\beta\text{6}^{\text{null}}/\text{CAR}^{\text{high}}$ (Figure 1b).

The transduction efficiency of replication-deficient Ad5 and Ad5_{NULL}-A20 vectors ex-



pressing a luciferase transgene was then assessed in these cell lines (Figure 2).

Figure 2. Transduction of pancreatic and breast cancer cell lines with Ad5 and Ad5_{NULL}-A20.

Nine pancreatic cell lines (a) and four breast cancer cell lines (b) were transduced with 5,000 vp/cell of either Ad5 (black bars) or Ad5_{NULL}-A20 (grey bars) vectors expressing luciferase. Luciferase expression was quantified 48 hours post infection and normalized to total cellular protein. Error bars represent standard deviation of n=4.

In all cases, transduction correlated well with the expression levels of $\alpha\text{v}\beta\text{6}$ integrin /CAR. Cell lines expressing $\alpha\text{v}\beta\text{6}$ integrin were efficiently and selectively transduced using the Ad5_{NULL}-A20 vector. Conversely cells negative for $\alpha\text{v}\beta\text{6}$ were poorly transduced by the Ad5_{NULL}-A20 vector. The majority of cell lines tested expressed CAR and these could be transduced by Ad5, where cells expressed $\alpha\text{v}\beta\text{6}$ integrin and CAR transduction was greater for Ad5_{NULL}-A20. Suit2 and MDA-MB-361 cell lines expressed high levels of both $\alpha\text{v}\beta\text{6}$ and CAR but transduction of Ad5_{NULL}-A20 was 7.9 and 4.6 times greater, respectively. The greatest difference in transduction between Ad5 and Ad5_{NULL}-A20 was seen in $\alpha\text{v}\beta\text{6}^{\text{high}}/\text{CAR}^{\text{null}}$ BT-20 cells which showed an increase in transduction of over 300-fold.

Cell killing by oncolytic virus, as gauged by MTS cell viability assay, also correlated well with the expression levels of $\alpha\text{v}\beta\text{6}$ integrin /CAR (Figure 3).

Ad5_{NULL}-A20 was able to effectively kill $\alpha\text{v}\beta\text{6}^{\text{high}}/\text{CAR}^{\text{null}}$ BT-20 cells which were resistant to Ad5, due to the lack of expression of the Ad5 receptor, CAR. This was reversed

in $\alpha\beta6^{\text{null}}/\text{CAR}^{\text{high}}$ MDA-MB-361 cell line with only Ad5 showing cell killing. Cells expressing high levels of $\alpha\beta6$ (BxPc, PANC0403, Suit2) were killed more efficiently by Ad5_{NULL}-A20 than Ad5.

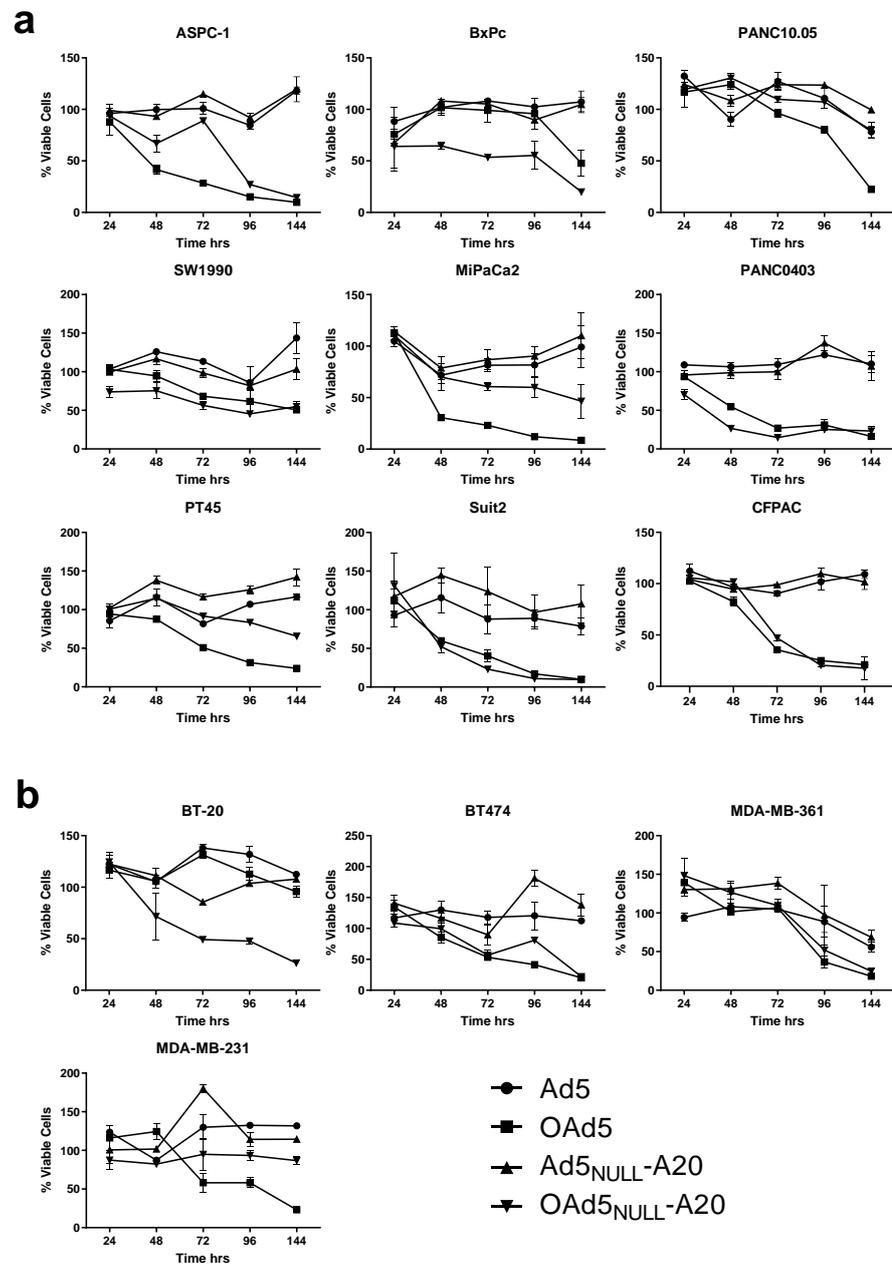


Figure 3. Oncolytic activity of Ad5 and Ad5_{NULL}-A20 in pancreatic and breast cancer cell lines. Pancreatic cell lines (a) and breast cancer cell lines (b) were transduced with 5,000 vp/cell of either oncolytic Ad5 (black squares), oncolytic Ad5_{NULL}-A20 (triangle upside down), replication deficient Ad5 vector (black circle) or replication deficient Ad5_{NULL}-A20 vector. Cell viability was quantified 48 hours post infection using MTS assay. Error bars represent standard deviation of n=4.

Given the favourable, tumor selective targeting observed *in vitro*, we performed *in vivo* studies to evaluate whether intravenous administration of replication-deficient Ad5_{NULL}-A20 resulted in targeting to permissive tumors *in vivo* in NSG mice. We elected to use replication-deficient vectors to get an accurate reflection of viral biodistribution, since the use of oncolytic vectors would result in the replication of virus within the xenograft and would therefore skew the data towards increased accumulation in the tumor. Since PDX platforms have more translational relevance, we selected two PDX models of

breast cancer from a panel available in-house, which were found to have low (PDX2665) or med/high (PDX3204) levels of $\alpha v\beta 6$ integrin based on mRNA expression relative to A549 cells (Figure 4a), as well as a BT-20 ($\alpha v\beta 6^{\text{high}}$).

72 hours post viral injection, organs were harvested, and qPCR for viral genomes was performed on DNA isolated from the liver and tumors. Our data demonstrate that in all three models tested, Ad5_{NULL}-A20 showed increased tumor accumulation compared to Ad5 (Figure 4b).

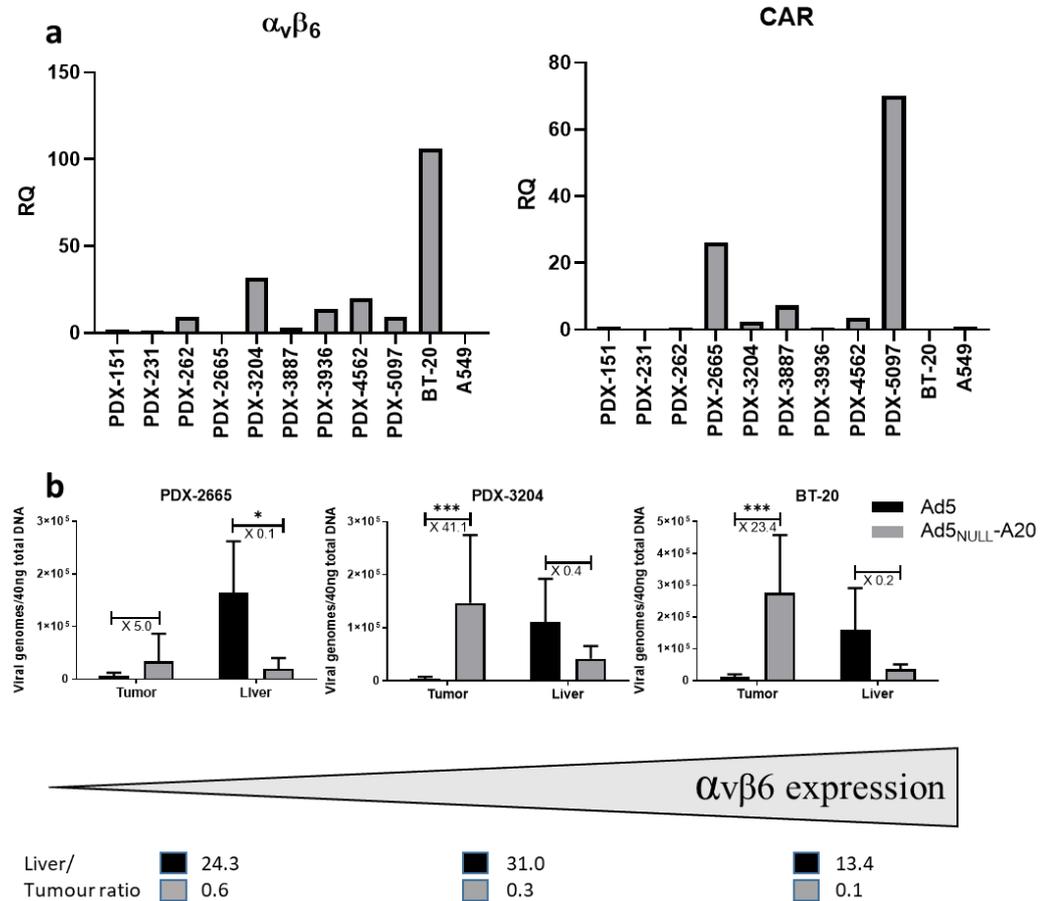


Figure 4. Biodistribution of Ad5 and Ad5_{NULL}-A20 in an in vivo breast cancer model. A panel of PDX breast cancer lines (a) were analysed by RT-qPCR to determine levels of $\alpha v\beta 6$ and CAR, gene expression relative to A549 cell line. PDX and BT-20 tumors were established in NSG mice (b), when tumors reached a palpable size, mice were injected intravenously with 1×10^{11} vp of Ad5 (black bars) or Ad5_{NULL}-A20 (grey bars). 72 hours post injection, organs were harvested, and qPCR for viral genomes was performed. Liver/tumor ratios are included below the graphs.

We found 5-fold (low $\alpha v\beta 6$ model, PDX2665), 41-fold (for med $\alpha v\beta 6$ model, PDX3204) and 23-fold (for high $\alpha v\beta 6$ model, BT-20) higher amounts of viral DNA in the tumors of mice injected with Ad5_{NULL}-A20 compared to mice injected with Ad5. We also noted decreased hepatic accumulation, leading to dramatically improved liver/tumor ratio. An improvement of over 100-fold was seen in both the PDX3204 and BT20 models compared to Ad5.

4. Discussion

We previously generated a triple-detargeted Ad5 based virotherapy (Ad5_{NULL}) that could be specifically retargeted to $\alpha v\beta 6$ integrin expressing cells by incorporation of the A20 peptide, and demonstrated this to be an effective treatment in an *in vivo* model of peritoneal ovarian cancer [12]. Here, we have progressed development of Ad5_{NULL}-A20 to evaluate its potential in other cancers with high unmet clinical need where $\alpha v\beta 6$ integrin

has previously been reported to be commonly expressed. Analysis of a large number of pancreatic ductal adenocarcinoma (PDAC, 383 primary tumors, 7 lymph node, and 8 distant metastases) and 34 pancreatic intraepithelial neoplasia (PanIN) specimens revealed a high prevalence of $\alpha v\beta 6$ -integrin expression in PDAC primaries (88%) and in almost all metastases, as well as in PanIN (57%) [28]. While an analysis of 2000 breast cancer patient samples [19] showed high expression of $\alpha v\beta 6$ integrin in 15% to 16% of invasive ductal carcinoma and a significant association between high expression of $\alpha v\beta 6$ integrin and poor survival. Pancreatic and breast cancers were therefore considered good targets for Ad5^{NULL}-A20 virotherapy. We showed $\alpha v\beta 6$ was expressed in 7 of 9 pancreatic cancer cell lines and 3 of 4 breast cancer cell lines tested. Furthermore, Ad5^{NULL}-A20 was able to selectively infect and kill pancreatic and breast cancer cell lines in an $\alpha v\beta 6$ dependent manner. Cell lines with high $\alpha v\beta 6$ integrin showed enhanced oncolytic cell killing compared to Ad5.

While intratumoral injection of oncolytic vectors has been effective in cancer treatments [29] development of oncolytic vectors that can be given systemically are required for treatment of non-accessible tumors. Various strategies have been employed to improve systemic of delivery of Ads including shielding of the virus [30] and swapping of hypervariable loops with non FX binding serotypes to reduce liver transduction [31]. Here, we demonstrate that Ad5^{NULL}-A20 can effectively target $\alpha v\beta 6$ positive tumors established in NSG mice following intravenous injection. Even the low $\alpha v\beta 6$ expressing PDX 2665 showed increased tumor accumulation compared to Ad5, presumably due to the increased bioavailability of this viral vector since its modification reduces off target depletion in sinks such as the liver and spleen, thus maximizing the likelihood of passive, as well as active accumulation within the tumor microenvironment. We saw a 40x increase in tumor accumulation in the med $\alpha v\beta 6$ PDX 3204 model compared to Ad5, coupled with a substantial decrease in liver accumulation. This manifested in an improvement in liver/tumor ratio of over 100-fold compared to Ad5. The high $\alpha v\beta 6$ BT-20 model showed the highest accumulation of Ad5^{NULL}-A20 as expected. However, accumulation of Ad5 was higher than the PDX models despite the lack of CAR in BT-20 cells. The accumulation of Ad5^{NULL}-A20 was still over 20x higher than Ad5 and liver/tumor ratio improved over 100x.

5. Conclusions

Ad5^{NULL}-A20 represents an exciting platform with significant potential to treat $\alpha v\beta 6$ integrin expressing tumors by both intraperitoneal [12] and, as demonstrated here, systemic approaches. This heavily engineered virotherapy platform has the potential to be further armed with therapeutic transgenes, offering the enticing possibility that the platform can be adapted to enable the overexpression of potent, virally mediated immunological transgenes within the tumor microenvironment following systemic administration. The Ad5^{NULL}-A20 platform therefore has significant potential for efficacy and onward clinical translation.

6. Patents

Cardiff University has patented the Ad5^{NULL} platform and the Ad5^{NULL}-A20 targeted virotherapy (WO201958914A1)

Author Contributions: Conceptualization JAD, JDC and ALP; methodology JAD, GM, HKU-K, GS, LP, RWEC, JDC and ALP; production of viruses described JAD, HKU-K; investigation JAD, GM, HKU-K, GS, LP, ALP; data curation and analysis JAD and GM; writing – original draft preparation JAD and ALP; writing – review and editing JAD, GM, HKU-K, GS, LP, RWEC, JDC and ALP; Supervision ALP. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: All animal experiments were approved by the Animal Ethics Committee, Cardiff University.

Data Availability Statement: Due to confidentiality agreements with research collaborators, supporting data can only be made available to bona fide researchers subject to a non-disclosure agreement. Details of the data and how to request access can be made via the corresponding author.

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