Therapeutic Potential of Replication-Selective Oncolytic Adenoviruses on Cells from Familial and Sporadic Desmoid Tumors

Inge Peerlinck,[1] Saeid Amini-Nik,[2] Robin K. Phillips,[3] Richard Iggo,[4] Nicholas R. Lemoine,[1] Sabine Tejpar,[2] and Georges Vassaux[5,6,7]

Abstract

Purpose: Constitutive activation of the Wnt signaling pathway is a hallmark of many cancers and has been associated with familial and sporadic desmoid tumors. The aim of the present study is to assess the therapeutic potential of oncolytic adenoviruses selectively replicating in cells in which the Wnt signaling pathway is active on primary cells from desmoid tumors.

Experimental Design: Primary cells extracted from familial ($n = 3$) or sporadic ($n = 3$) desmoid tumors were cultured short term. Cancer cell survival and viral replication were measured *in vitro* upon infection with two different oncolytic adenoviruses targeting a constitutive activation of the Wnt signaling pathway. Adenoviral infectivity was also assessed.

Results: Although cells extracted from one sporadic desmoid tumor responded very well to the oncolytic action of the adenoviruses (<20% of viable cells upon infection at a multiplicity of infection of 10), cells from two tumor samples were totally resistant to the viral action. Cells from the remaining samples showed intermediate sensitivity to the oncolytic viruses. These effects were correlated to the level of infectivity of the cells. Finally, in responder cells, evidences of viral replication was observed.

Conclusions: Our experimental data suggest that the response of desmoid tumor cells to oncolytic adenovirus is neither correlated to the type of mutation activating the Wnt signaling pathway nor to the familial or sporadic nature of the tumor. In addition, they highlight the variability of infectivity of individual tumors and predict a great variability in the response to oncolytic adenoviruses.

Downloaded from http://aacrjournals.org/clincancerres/article-pdf/14/19/6187/1978940/6187.pdf by guest on 15 August 2024

Desmoid tumors are rare, benign, sometimes aggressive tumors resulting from unregulated proliferation of fibroblast-like cells (1, 2). Their natural history is one of slow growth with progressive infiltration of surrounding soft tissues leading in some cases to strangulation of nerves and blood vessels. Abdominal desmoid tumors are the most common and can be classified into sporadic and familial forms (2). In the latter case, inherited desmoid tumors are most frequently associated with familial adenomatous polyposis. At the molecular level, the development of desmoid tumors has been associated with a constitutive activation of the Wnt signaling pathway (3–7). Familial adenomatous polyposis–associated desmoid tumors are usually caused by germline *adenomatous polyposis coli* (*APC*) mutations followed by somatic inactivation of the wild-type *APC* allele (3–5), whereas sporadic desmoids are usually characterized by oncogenic mutations in the *β-catenin* gene, both identical molecular alterations to those found in the vast majority of colorectal cancers (3, 4).

The management of patients is difficult and these tumors are prone to local recurrence. Surgery is an obvious option but the development of 10% to 30% of sporadic abdominal wall desmoid tumors and 68% to 86% of familial adenomatous polyposis–associated intra-abdominal tumors has been associated with surgical trauma (8). As a result, there is currently no

Authors' Affiliations: [1]Institute of Cancer and the CR-UK Clinical Centre, Barts and The London, Queen Mary's School of Medicine and Dentistry, London, United Kingdom; [2]Center for Human Genetics, Laboratorium voor moleculaire diagnostiek, Herestraat 49, Leuven, Belgium; [3]Polyposis Registry, CR-UK Colorectal Cancer Unit, St Mark's Hospital, Harrow, United Kingdom; [4]Bute Medical School, University of St Andrews, Fife, United Kingdom; and [5]Institut National de la Sante et de la Recherche Medicale, CIC-04 Biothérapies Hépatiques, CHU Hôtel Dieu; [6]Universite de Nantes, Nantes Atlantique Université, EA4274; and [7]Institut des Maladies de l'Appareil Digestif, CHU Hôtel Dieu, Nantes, France

Received 2/15/08; revised 6/4/08; accepted 6/10/08.

Grant support: Cancer Research UK, the Medical Research Council, Institut National de la Sante et de la Recherche Medicale, la Ligue Nationale Contre le Cancer and by grant 0607 - 3D1615 - 66/AO Institut National de la Sante et de la Recherche Medicale from the French National Cancer Institute. S. Tejpar is a Senior Clinical Investigator of the Fund for Scientific Research-Flanders (Belgium; Fonds Wetenschappelijk Onderzoek-Vlaanderen). This project was funded by the Belgian Federation against Cancer, and the Fund for Scientific Research Flanders. The publication of this article was possible thanks to financial support brought by Association Française pour l'Etude du Foie and BMS laboratories.

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked *advertisement* in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Note: Supplementary data for this article are available at Clinical Cancer Research Online (http://clincancerres.aacrjournals.org/).

Requests for reprints: Georges Vassaux, Institut National de la Sante et de la Recherche Medicale CIC-04, EA4274ème étage HNB nord, CHU Hotel Dieu, 1 place Alexis Ricordeau, 44035 Nantes Cedex1, France. Phone: 33-240-087-508; Fax: 33-240-087-506; E-mail: georges.vassaux@nantes.inserm.fr.

©2008 American Association for Cancer Research.

doi:10.1158/1078-0432.CCR-08-0410

Translational Relevance

This study investigates the potential of replication-selective oncolytic adenoviruses in the treatment of desmoid tumors. The results show that infectivity of desmoid tumor cells is variable and is the key factor in determining whether oncolytic adenoviruses are likely to be efficient against this type of tumor. Therefore, this factor should be assessed before embarking into a clinical trial.

satisfactory treatment for these tumors, especially in the context of familial adenomatous polyposis–related desmoid tumors for which they represent a major cause of morbidity and mortality (1, 9). Therefore, there is a need for alternative or complementary therapies that could delay surgery if not eradicate the tumor. In this context, gene therapy through direct injection of gene delivery vectors in the tumor mass has already been suggested through preclinical studies involving nonviral and replication-deficient adenoviral vectors (10, 11).

Oncolytic adenoviruses are a class of adenoviruses genetically modified to selectively replicate in cancer cells (12, 13). This selectivity can be achieved through deletions in the viral genome (14–16) or replacement of the viral endogenous promoters by cancer-selective promoters (17–19). The resulting viruses have the unique property of tumor-dependent self-amplification. In addition, initial clinical trials have shown that these agents are very safe and well-tolerated (20). Recently, adenoviruses with Tcf binding sites in the early promoters were generated and these oncolytic adenoviruses showed up to 100,000-fold selectivity for cells with activated Wnt signaling (17, 21). As a constitutive activation of the Wnt signaling pathway is a common molecular defect in sporadic or familial desmoid tumors, the aim of the present study is to assess the efficacy of Wnt-selective oncolytic adenoviruses in these cells. In addition and as molecular imaging of gene transfer using the *Na/I symporter* (*NIS*) as a reporter gene could provide crucial information on the extent of gene transfer *in vivo* through positron emission tomography imaging (18, 22, 23), we have generated a Wnt-selective oncolytic adenoviruses encoding *hNIS*. The efficacy of these viruses was assessed *in vitro* on primary tumor cells extracted from familial (n = 3) or sporadic (n = 3) desmoid tumors.

Materials and Methods

Establishment of primary cultures of desmoid cells, cell lines. Desmoid tumors samples were obtained following surgical resection. The protocol was used in conjunction with ethical approval from the Harrow or Leuven Research Ethics Committee. The tumors were macerated in small pieces with a scalpel and digested overnight at 37°C in RPMI containing 20% fetal bovine serum (AutogenBioclear, Ltd.), 100 units/mL penicillin, 100 μg/mL streptomycin, and 0.2 μg/mL Butyl-p-hydroxybenzoate supplemented with 1 mg/mL of Collagenase D (Roche Diagnostic GmbH). The digest was then filtered through a 100-μm nylon cell strainer and centrifuged twice at 1,000 rpm. Cell pellets were washed twice with PBS, resuspended in RPMI 20% fetal bovine serum containing antibiotics (see above), and seeded. Primary cultures were maintained in a 5% CO_2 atmosphere at 37°C. Erythrocytes and cell debris were washed away with PBS 24 h later. Germline and somatic mutations were identified as follows: Desmoid 1, β-catenin substitution TTT for TCT results to a Ser to Phe change at codon 45; B-Cat substitution TTT for TCT results to a Ser to Phe change at codon 45. Desmoid 3, Mutations in APC or β-catenin not detected; Desmoid 4, APC: exon 15 c.3927_3931delAAAGA (p.Glu1309AspfsX4); Desmoid 5, APC: exon 13 c.1495C>T (p.Arg499X); Desmoid 5.2, germline exon 6 c.646 C > T (p.R216X); and somatic exon 15H, c.4385delA.

SKBR3, MCF7, HPAF, SUIT-2 and DLD-1 cells were cultured as previously described (11, 24, 25).

Generation and production of a Wnt-selective adenovirus encoding NIS. The plasmid vpKH1 encodes the genome of a Wnt-specific adenovirus in which TCF-4 binding sites are present in *E1A*, *E1B*, and *E4* of the viral genome (21). Insertion of the NIS cDNA in the gp19k of this adenovirus was done as previously described (18), using homologous recombination in yeast (26). Virus were produced and titrated as previously described (27).

Adenovirus nomenclature. AdWt, Wild-type adenovirus type 5. Ad-LacZ, Replication-deficient adenovirus type 5 encoding the *β-galactosidase* gene. Ad-hNIS, Replication-deficient adenovirus type 5 encoding the *NIS* coding sequence (23). AdKH1, Adenovirus selectively replicating in cells in which the Wnt signaling pathway is constitutively activated (21). AdIP2, Adenovirus selectively replicating in cells in which the Wnt signaling pathway is constitutively activated and encoding *NIS*.

Infections with adenoviruses. Cells were seeded at a cell density of 10^4 cells/cm^2. The following day, they were infected with adenoviruses at different multiplicity of infection (MOI) in serum-free medium for 30 to 45 min. Culture medium was then added to reach a serum concentration up to 20%.

Biochemical assays. Cell survival assays, measurement of green fluorescent protein–positive cells, and assessment of *in vitro* viral replication and E1A expression were done as previously described (18, 19, 28, 29), respectively.

Coxsackievirus and adenovirus receptor staining. Cells for staining were collected by trypsinisation, and washed. The pellet was resuspended and incubated with the anti–coxsackievirus and adenovirus receptor (CAR) primary monoclonal mouse antibody (30) 1:500 in fluorescence-activated cell sorting (FACS) buffer containing 5% normal goat serum (Dako Cytonation) for 90 min on ice. Cells were then washed thrice and incubated for 30 min at room temperature in the dark with secondary antibody goat anti-mouse FITC 1:30 in FACS buffer. The cells were washed thrice, and the final pellet was resuspended in 400 μL FACS buffer. Measurement of the number of CAR-positive cells was done by FACS on at least 5 10^5 cells.

Results

Effect of Wnt-selective oncolytic adenoviruses on desmoid tumor cells. To determine whether the insertion of the NIS cDNA affects the selectivity of the Wnt-selective virus, DLD-1 colon cancer cells carrying an *APC* mutation that results in constitutively high β-catenin signaling (31) and cell lines in which the Wnt signaling pathway is not activated in normal culture conditions (MCF7, SKBR3) were infected with AdIP2 and a wild-type adenovirus type 5 as positive control. Table 1 shows that the EC_{50} of AdIP2 and AdWt are in the same range in DLD-1 target cells, whereas AdWt is more than two log potent than AdIP2 on nontarget MCF7 or SKBR3 cells. These results show that AdIP2 can selectively kill cells in which the Wnt signaling pathway is constitutively activated.

To determine the effect of adenoviral infection on primary desmoid tumor cells, cells from sporadic (Fig. 1A) or familial adenomatous polyposis–related (Fig. 1B) desmoid tumors were infected at different MOI with AdKH1 or AdIP2. Different levels of sensitivity to oncolytic adenoviral treatment were

Downloaded from http://aacrjournals.org/clincancerres/article-pdf/14/19/6187/1978940/6187.pdf by guest on 15 August 2024

Table 1. Selectivity of the Wnt-selective adenovirus on human tumor cells *in vitro*

	MCF7	SKBR3	DLD-1
AdWt	8	0.63	1.33
AdIP2	>100	>100	4.77

NOTE: DLD-1 colon cancer cells carrying an APC mutation that results in constitutively high β-catenin signaling and cell lines in which the Wnt signaling pathway is not activated in normal culture conditions (MCF7, SKBR3) were infected with AdIP2 and a wild-type adenovirus type 5 as positive control at different multiplicity of an infection. Six days later, the number of viable cells was determined using a MTT assay. Dose-response curves were generated and concentrations killing 50% of cells (EC_{50} values) were determined using untreated cells as reference and are presented in plaque-forming unit.

observed with the following range of sensitivity: desmoid 2 (sporadic) > desmoid 5 (familial); desmoid 5.2 (familial) > desmoid 3 (sporadic) > desmoid 1 (sporadic); desmoid 4 (familial). Statistical analysis showed a highly significant difference ($P < 0.0001$) between uninfected cells and cell infected with AdKH1 and AdIP2 at MOI 100 for desmoids 2, 3, 5, and 5.2. These results showed that the sensitivity to oncolytic adenoviral treatment is not related to the type of mutation in the Wnt signaling pathway or the sporadic or familial nature of desmoid tumors.

Correlation between infectivity and sensitivity to adenoviral vectors. The infectivity of primary cells extracted from the different desmoid tumors was determined by infection with a replication-deficient adenovirus (MOI, 10) encoding the green fluorescent protein and measurement of green fluorescent protein–positive cells by FACS. Figure 2 shows that the range of infectivity is similar to that obtained for the sensitivity to adenoviral infection (Fig. 1). The CAR has been shown to act as a primary receptor to adenovirus and to play a critical role in viral entry in the cell (32). Surprisingly, CAR staining was negative in all desmoid cell samples (data not shown). This is in sharp contrast to highly positive (>95%) A549 cells used as positive control (data not shown) and known to express high levels of CAR (33). In an attempt to further show infection in the absence of CAR expression, E1A expression was monitored upon AdIP2 infection of Desmoid 3. Quantitative reverse transcription-PCR revealed that E1A expression was weak and hardly detectable 24 hours after infection but increased very significantly 4 days later (Supplementary Data), demonstrating that incubation of Desmoid 3 with AdIP2 lead to E1A expression resulting from cell infection, independently of the presence or CAR. Altogether, these results suggest that sensitivity to adenoviral agents and infectivity are tightly correlated and that a CAR-independent mechanism is involved in adenoviral infection of primary cells from desmoid tumors 2, 3, 5, and 5.2.

Replication of adenovectors in primary desmoid tumor cells sensitive to the viruses. To determine whether the reduced cell viability observed upon adenoviral infection of cells from desmoid 2, 3, 5, and 5.2 was associated with viral replication, DNA from cells infected with AdIP2 was collected 1 day or 4 days after infection. This DNA was subjected to quantitative PCR to titrate the amount of adenoviral DNA per culture well. Figure 3 shows that in all cases, viral amplification of the adenoviral genome was observed between day 1 and 4, suggesting replication of the oncolytic virus in these cells.

Additional toxic effect of the NIS transgene. In addition, at MOI 100, AdIP2, the *NIS*-positive virus is statistically more efficient ($P < 0.0001$ for the three tumors) than AdKH1 (*NIS*-negative) in cells from desmoids 2, 5, and 5.2 (Fig. 1). To determine whether the presence of *NIS* in the viral genome and its expression is toxic for desmoid cells, independently from the oncolytic action of the virus, primary cells from the desmoid tumors 2, 5, and 5.2 were infected at a MOI of 100 with a replication-deficient recombinant adenovirus encoding either the β-galactosidase gene (Ad-LacZ) or *NIS* (Ad-hNIS) under the control of the immediate-early cytomegalovirus promoter. Figure 4 shows that the toxicity of Ad-hNIS is not observed with Ad-LacZ, suggesting a toxicity of the *NIS* gene product in desmoid tumor cells. By contrast, this hNIS cytotoxicity is not observed with established cell lines such as HPAF or SUIT-2 cells (Fig. 4).

Downloaded from http://aacrjournals.org/clincancerres/article-pdf/14/19/6187/1978940/6187.pdf by guest on 15 August 2024

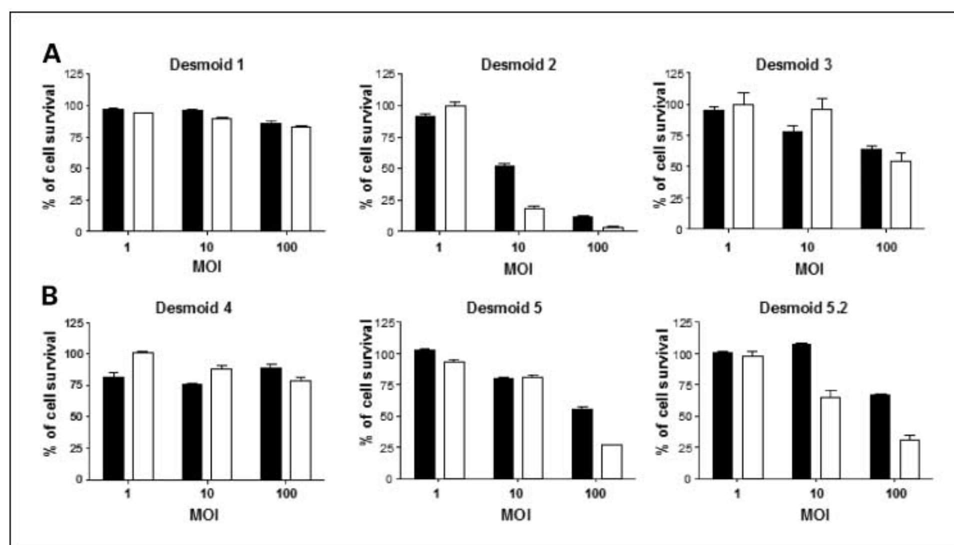

Fig. 1. Effect of Wnt-selective oncolytic adenoviruses on desmoid tumor cell survival. Primary cells from (*A*) sporadic or (*B*) familial desmoid tumors were infected at different MOIs with AdKH1 (*black bars*) or AdIP2 (*white bars*). Six days later, the number of surviving cells was assessed using an 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay. One hundred percent correspond to the number of cells in control, noninfected cells. Two-way ANOVA statistical analysis was done. Columns, mean of six experimental points; bars, SE. The data presented are representative of three independent experiments.

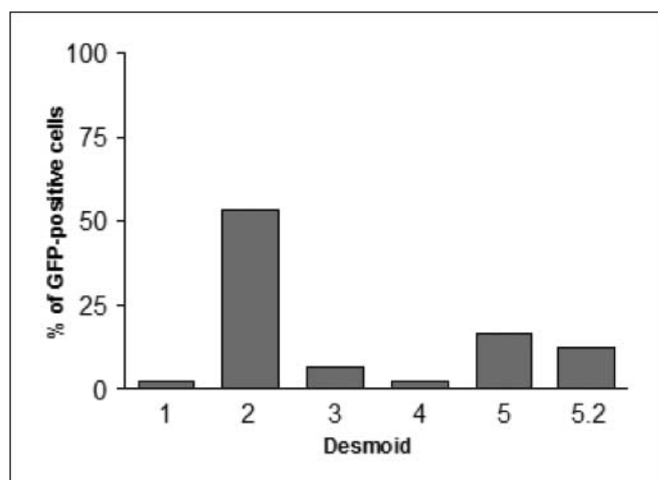

Fig. 2. Infectivity of primary desmoid tumor cells. Adherent cells were infected with a replication-deficient recombinant adenovirus encoding green fluorescent protein. Forty-eight hours later, the cells were trypsinized and the number of green fluorescent protein – positive cells was determined by FACS. The data presented corresponds to an acquisition of at least 50,000 events and are representative of 3 independent experiments. Data were analyzed using the χ^2 test. In all conditions, comparisons of the uninfected versus the infected cells showed P values of <0.0001.

Discussion

The Wnt signaling pathway is considered as the key molecular defect in sporadic or familial desmoid tumors (3 – 5), and therapeutic strategies targeting this pathway are expected to provide therapeutic benefits with minimal side effects in patients affected with this pathology. In this context, an oncolytic adenovirus, replicating selectively in cells in which the Wnt signaling pathway is constitutively activated is particularly relevant.

Replication-selective oncolytic adenoviruses represent a novel class of therapeutic agents. Preclinical and clinical studies have shown the safety and feasibility of the approach and their suitability for association with more classic cancer treatments such as chemotherapy has been shown (34 – 36). However, a clear limitation of adenoviral vectors is that only a minimal proportion of the injected dose reaches the tumors after systemic administration. As a result, intratumoral injections are advised. Considering the lack of metastasis and the size of the tumors observed in patients with desmoids (1), local injection of oncolytic adenovirus represents a practical approach that could even be implemented in conjunction with chemotherapy. Therefore, desmoid tumors are a relevant indication for adenoviral vectors.

Our data clearly show that primary cells from some desmoid tumors allow replication and are sensitive to the action of oncolytic adenoviruses. However, in two cases, the cells were completely refractory and the key difference between responder and nonresponders cells is the infectivity of the cells. Low or no CAR expression has already been reported in desmoids (37), and we confirm that CAR was absent from all the cellular samples tested, whether infectable with adenovirus or not. Taken together, these data suggest an alternative, CAR-independent mechanism of infection. Such mechanisms have been suggested (38) and may involve heparan sulfate proteoglycans (39) or coagulation factors (40, 41). Further studies will be required to address the mechanism of infection in these cells.

One of the particularity of desmoid tumors is their abundance in extracellular matrix that could prevent the diffusion of the virus in the tumor mass. In this context, pretreatment or coadministration of the oncolytic virus with enzymes capable of dissociating this matrix could enhance vector diffusion. A proof of principle has already been shown using hyaluronidase that was shown to improve adeno-associated virus-mediated gene transfer in the muscle (42),

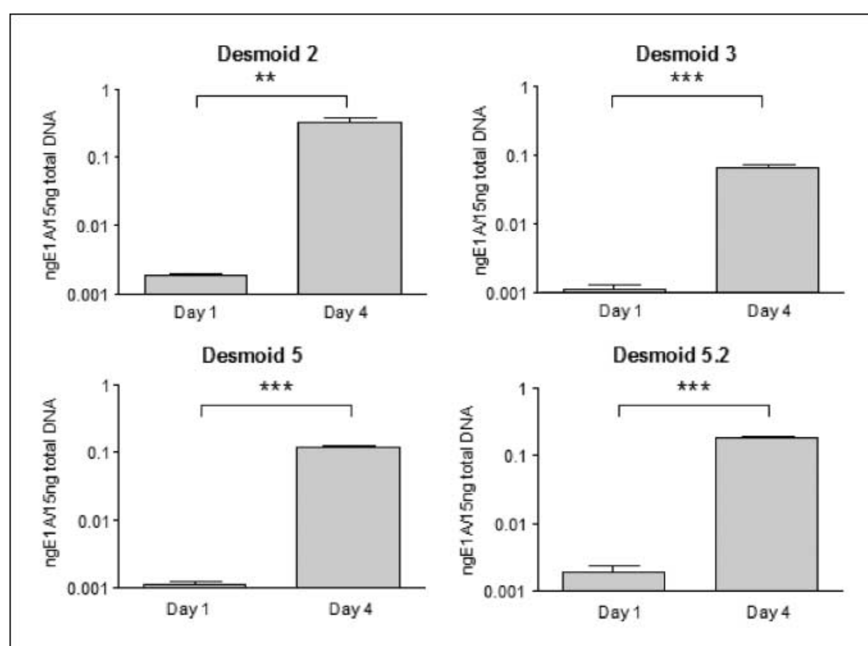

Fig. 3. Evidence of adenoviral replication in primary desmoid tumor cells infected with AdIP2. Cells were infected at low MOI (0.01) and total DNA was extracted on day 1 and 4 after infection. Adenoviral DNA was titrated by quantitative PCR. Statistical analysis was done using a two-tailed Student's t test. P values are 0.0052 and 0.0008 for desmoids 2 and 3, respectively, and <0.0001 for desmoids 5 and 5.2. Columns, mean of triplicate and are representative of three experiments; bars, SE.

Downloaded from http://aacrjournals.org/clincancerres/article-pdf/14/19/6187/1978940/6187.pdf by guest on 15 August 2024

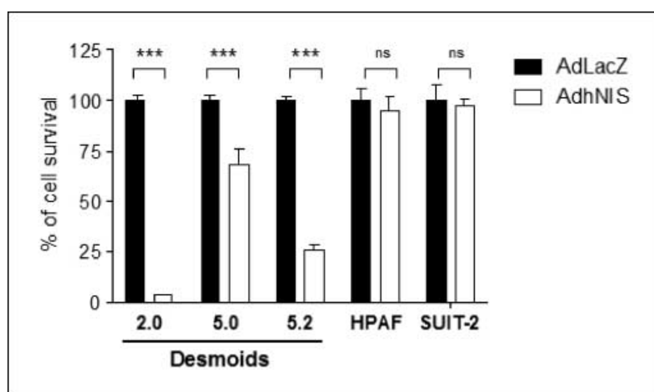

Fig. 4. Effect of replication incompetent adenoviruses encoding LacZ or NIS on desmoid tumor cell survival. Primary cells from desmoid tumors 2, 5, and 5.2 and cell lines HPAF and SUIt-2 were infected at MOI of 100 with replication incompetent adenoviruses encoding LacZ (*black bars*) or NIS (*white bars*). Six days later, the number of surviving cells was assessed using an MTT assay. Once hundred percent correspond to the number of cells in control, noninfected cells. Statistical analysis was done using a two-tailed Student's t test. P values are <0.0001 in all the conditions compared involving the desmoid tumors and nonsignificant (*ns*; $P > 0.05$) with the cell lines HPAF and SUIT-2. Columns, mean of four experimental points and are representative of three independent experiments; bars, SE.

and this type of approach could be applied to the context of adenovirus gene therapy and desmoid tumors.

The fate of gene therapy vectors encoding *NIS* can be visualized after administration into a subject using positron emission tomography (22, 23) or single-photon emission computed tomography (18). Both imaging methodologies are potentially applicable to humans and can provide unique information on the anatomic distribution of gene transfer. In addition, *NIS* can also be used as a therapeutic transgene through the administration of ^{131}I and the accumulation of radioactivity in tumor deposits transduced by the gene therapy vector (43, 44). In this report, we show for the first time a direct effect of NIS expression on the viability cells. This effect is unique to primary desmoid cells as many different types of tumor cell lines can be transduced with the *NIS* gene without apparent toxicity and therapeutic doses of ^{131}I (45–47) or high doses of nonradioactive iodide (48) are necessary to trigger cell death.

This report shows that gene therapy for desmoid tumor is feasible and the efficacy of the treatment is highly dependent on the infectivity of the cells. In the clinical setting, direct injection of the oncolytic adenovirus into desmoids under radiological guidance could be envisaged. This gene therapy approach would probably aim at debulking the tumor before attempting surgical resection, and in the case of a tumor susceptible to adenoviral infection, even a relatively modest effect could have an important clinical implication by making a previously unoperable intra-abdominal tumor amenable to surgery. Imaging of *NIS* gene transfer could also be done to provide additional information on the extent of gene transfer.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

We thank Dr Jhiang for providing the human NIS cDNA.

Downloaded from http://aacrjournals.org/clincancerres/article-pdf/14/19/6187/1978940/6187.pdf by guest on 15 August 2024

References

1. Sturt NJ, Clark SK. Current ideas in desmoid tumours. Fam Cancer 2006;5:275–85.

2. Sakorafas GH, Nissotakis C, Peros G. Abdominal desmoid tumors. Surg Oncol 2007;16:131–42.

3. Tejpar S, Michils G, Denys H, et al. Analysis of Wnt/β catenin signalling in desmoid tumors. Acta Gastroenterol Belg 2005;68:5–9.

4. Signoroni S, Frattini M, Negri T, et al. Cyclooxygenase-2 and platelet-derived growth factor receptors as potential targets in treating aggressive fibromatosis. Clin Cancer Res 2007;13:5034–40.

5. Sturt NJ, Gallagher MC, Bassett P, et al. Evidence for genetic predisposition to desmoid tumours in familial adenomatous polyposis independent of the germline APC mutation. Gut 2004;53:1832–6.

6. Wunder JS, Nielsen TO, Maki RG, O'Sullivan B, Alman BA. Opportunities for improving the therapeutic ratio for patients with sarcoma. Lancet Oncol 2007;8:513–24.

7. Kotiligam D, Lazar AJ, Pollock RE, Lev D. Desmoid tumor: a disease opportune for molecular insights. Histol Histopathol 2008;23:117–26.

8. Tolan S, Shanks JH, Loh MY, Taylor B, Wylie JP. Fibromatosis: benign by name but not necessarily by nature. Clin Oncol R Coll Radiol 2007;19:319–26.

9. Latchford AR, Sturt NJ, Neale K, Rogers PA, Phillips RK. A 10-year review of surgery for desmoid disease associated with familial adenomatous polyposis. Br J Surg 2006;93:1258–64.

10. Bright-Thomas RM, Agrawal A, Hargest R. Preclinical studies of gene transfer for the treatment of desmoid disease in familial adenomatous polyposis. Br J Surg 2002;89:1563–9.

11. Martinico SC, Jezzard S, Sturt NJ, et al. Assessment of endostatin gene therapy for familial adenomatous polyposis-related desmoid tumors. Cancer Res 2006;66:8233–40.

12. Young LS, Searle PF, Onion D, Mautner V. Viral gene therapy strategies: from basic science to clinical application. J Pathol 2006;208:299–318.

13. Alemany R. Cancer selective adenoviruses. Mol Aspects Med 2007;28:42–58.

14. Bischoff JR, Kirn DH, Williams A, et al. An adenovirus mutant that replicates selectively in p53-deficient human tumor cells. Science 1996;274:373–6.

15. Gomez-Manzano C, Alonso MM, Yung WK, et al. Δ-24 increases the expression and activity of topoisomerase I and enhances the antiglioma effect of irinotecan. Clin Cancer Res 2006;12:556–62.

16. Cascallo M, Gros A, Bayo N, Serrano T, Capella G, Alemany R. Deletion of VAI, VAII RNA. Genes in the design of oncolytic adenoviruses. Hum Gene Ther 2006;17:929–40.

17. Fuerer C, Iggo R. Adenoviruses with Tcf binding sites in multiple early promoters show enhanced selectivity for tumour cells with constitutive activation of the wnt signalling pathway. Gene Ther 2002;9:270–81.

18. Merron A, Peerlinck I, Martin-Duque P, et al. SPECT/CT imaging of oncolytic adenovirus propagation in tumours *in vivo* using the Na/I symporter as a reporter gene. Gene Ther 2007;14:1731–8.

19. Bilsland AE, Merron A, Vassaux G, Keith WN. Modulation of telomerase promoter tumor selectivity in the context of oncolytic adenoviruses. Cancer Res 2007;67:1299–307.

20. Hermiston T. A demand for next-generation oncolytic adenoviruses. Curr Opin Mol Ther 2006;8:322–30.

21. Homicsko K, Lukashev A, Iggo RD. RAD001 (everolimus) improves the efficacy of replicating adenoviruses that target colon cancer. Cancer Res 2005;65:6882–90.

22. Groot-Wassink T, Aboagye EO, Wang Y, Lemoine NR, Keith WN, Vassaux G. Noninvasive imaging of the transcriptional activities of human telomerase promoter fragments in mice. Cancer Res 2004;64:4906–11.

23. Groot-Wassink T, Aboagye EO, Wang Y, Lemoine NR, Reader AJ, Vassaux G. Quantitative imaging of Na/I symporter transgene expression using positron emission tomography in the living animal. Mol Ther 2004;9:436–42.

24. Vassaux G, Hurst HC, Lemoine NR. Insulation of a conditionally expressed transgene in an adenoviral vector. Gene Ther 1999;6:1192–97.

25. Groot-Wassink T, Aboagye EO, Glaser M, Lemoine NR, Vassaux G. Adenovirus biodistribution and noninvasive imaging of gene expression *in vivo* by positron emission tomography using human sodium/iodide symporter as reporter gene. Hum Gene Ther 2002;13:1723–35.

26. Gagnebin J, Brunori M, Otter M, Juillerat-Jeanneret L, Monnier P, Iggo R. A photosensitising adenovirus for photodynamic therapy. Gene Ther 1999;6:1742–50.

27. Martin-Duque P, Jezzard S, Kaftansis L, Vassaux G. Direct comparison of the insulating properties of two genetic elements in an adenoviral vector containing two different expression cassettes. Hum Gene Ther 2004;15:995–1002.

28. Critchley RJ, Jezzard S, Radford KJ, et al. Potential therapeutic applications of recombinant, invasive E. coli. Gene Ther 2004;11:1224–33.

29. Critchley-Thorne RJ, Stagg AJ, Vassaux G. Recombinant Escherichia coli expressing invasin targets the

Peyer's patches: the basis for a bacterial formulation for oral vaccination. Mol Ther 2006;14:183 – 91.

30. Wang Y, Thorne S, Hannock J, et al. A novel assay to assess primary human cancer infectibility by replication-selective oncolytic adenoviruses. Clin Cancer Res 2005;11:351 – 60.

31. Morin PJ, Sparks AB, Korinek V, et al. Activation of β-catenin-Tcf signaling in colon cancer by mutations in β-catenin or APC. Science 1997;275:1787 – 90.

32. Bergelson JM. Receptors mediating adenovirus attachment and internalization. Biochem Pharmacol 1999;57:975 – 9.

33. Vincent T, Pettersson RF, Crystal RG, Leopold PL. Cytokine-mediated down-regulation of coxsackievirus-adenovirus receptor in endothelial cells. J Virol 2004;78:8047 – 58.

34. Khuri FR, Nemunaitis J, Ganly I, et al. A controlled trial of intratumoral ONYX-015, a selectively-replicating adenovirus, in combination with cisplatin and 5-fluorouracil in patients with recurrent head and neck cancer. Nat Med 2000;6:879 – 85.

35. Alonso MM, Gomez-Manzano C, Jiang H, et al. Combination of the oncolytic adenovirus ICOVIR-5 with chemotherapy provides enhanced anti-glioma effect *in vivo*. Cancer Gene Ther 2007;14:756 – 61.

36. Cheong SC, Wang Y, Meng JH, et al. E1A-expressing adenoviral E3B mutants act synergistically with chemotherapeutics in immunocompetent tumor models. Cancer Gene Ther 2008;15:40 – 50.

37. Gu W, Ogose A, Kawashima H, et al. High-level expression of the coxsackievirus and adenovirus receptor messenger RNA in osteosarcoma, Ewing's sarcoma, and benign neurogenic tumors among musculoskeletal tumors. Clin Cancer Res 2004;10:3831 – 8.

38. Nicklin SA, Wu E, Nemerow GR, Baker AH. The influence of adenovirus fiber structure and function on vector development for gene therapy. Mol Ther 2005;12:384 – 93.

39. Dechecchi MC, Melotti P, Bonizzato A, Santacatterina M, Chilosi M, Cabrini G. Heparan sulfate glycosaminoglycans are receptors sufficient to mediate the initial binding of adenovirus types 2 and 5. J Virol 2001;75:8772 – 80.

40. Waddington SN, Parker AL, Havenga M, et al. Targeting of adenovirus serotype 5 (Ad5) and 5/47 pseudotyped vectors *in vivo*: fundamental involvement of coagulation factors and redundancy of CAR binding by Ad5. J Virol 2007;81:9568 – 71.

41. Waddington SN, McVey JH, Bhella D, et al. Adenovirus serotype 5 hexon mediates liver gene transfer. Cell 2008;132:397 – 409.

42. Favre D, Cherel Y, Provost N, et al. Hyaluronidase enhances recombinant adeno-associated virus (rAAV)-mediated gene transfer in the rat skeletal muscle. Gene Ther 2000;7:1417 – 20.

43. Boelaert K, Franklyn JA. Sodium iodide symporter: a novel strategy to target breast, prostate, and other cancers? Lancet 2003;361:796 – 7.

44. Groot-Wassink T, Barthel H, Lemoine NR, Vassaux G. Sodium iodide symporter: a new strategy to target cancer? Lancet 2003;361:1905 – 6.

45. Boland A, Ricard M, Opolon P, et al. Adenovirus-mediated transfer of the thyroid sodium/iodide symporter gene into tumors for a targeted radiotherapy. Cancer Res 2000;60:3484 – 92.

46. Cho JY, Shen DH, Yang W, et al. *In vivo* imaging and radioiodine therapy following sodium iodide symporter gene transfer in animal model of intracerebral gliomas. Gene Ther 2002;9:1139 – 45.

47. Spitzweg C, Baker CH, Bergert ER, O'Connor MK, Morris JC. Image-guided radioiodide therapy of medullary thyroid cancer after carcinoembryonic antigen promoter-targeted sodium iodide symporter gene expression. Hum Gene Ther 2007;18:916 – 24.

48. Zhang L, Sharma S, Zhu LX, et al. Nonradioactive iodide effectively induces apoptosis in genetically modified lung cancer cells. Cancer Res 2003;63:5065 – 72.

Downloaded from http://aacrjournals.org/clincancerres/article-pdf/14/19/6187/1978940/6187.pdf by guest on 15 August 2024