Hepatocellular carcinoma (HCC) carries a dismal prognosis, with advanced disease being resistant to both radiotherapy and conventional cytotoxic drugs, whilst anti-angiogenic drugs are marginally efficacious. Oncolytic viruses (OVs) offer the promise of selective cancer therapy through direct and immune-mediated mechanisms. The premise of OVs lies in their preferential genomic replication, protein expression and productive infection of malignant cells. Numerous OVs are being tested in preclinical models of HCC, with good evidence of direct and immune-mediated anti-tumour efficacy. Efforts to enhance the performance of these agents have concentrated on engineering OV cellular specificity, immune evasion, enhancing anti-tumour potency and improving delivery. The lead agent in HCC clinical trials, JX-594, a recombinant Wyeth strain vaccinia virus, has demonstrated evidence for significant benefit and earned orphan drug status. Thus, JX-594 appears to be transcending the barrier between novel laboratory science and credible clinical therapy. Relatively few other OVs have entered clinical testing, a hurdle that must be overcome if significant progress is to be made in this field. This review summarizes the preclinical and clinical experience of OV therapy in the difficult-to-treat area of HCC.
stimulation of an anti-cancer immune response, as reviewed by Melcher et al. (2011). To date, hundreds of patients with HCC have been treated using OVs in phase 1 and 2 clinical trials. The emerging data are encouraging in terms of both the relatively favourable side-effect profiles and early signs of efficacy. The current lead agent, JX-594, also known as Pexa-Vec (pexastimogene devacirepvec) was granted orphan drug status in HCC by the US Food and Drug Administration in 2013 and by the European Medicines Agency in 2009 (MarketWired, 2013). Orphan drug designation signifies approval for drugs that seek to treat rare diseases for which there may be few adequate therapies, and comes with incentives that include marketing exclusivity, grant-funding for clinical trials and tax credits for clinical research expenses. Whilst these incentives assert the dominance of JX-594 in the field, they have not perturbed the translational development of other OVs for HCC therapy. In addition to JX-594, three other OVs have been or are currently being tested in HCC-directed therapies, and comes with incentives that include marketing exclusivity, grant-funding for clinical trials and tax credits for clinical research expenses. Whilst these incentives assert the dominance of JX-594 in the field, they have not perturbed the translational development of other OVs for HCC therapy. In addition to JX-594, three other OVs have been or are currently being tested in HCC-directed clinical trials, including two based on type 5 adenoviruses, dl1520 (ONYX-015; Habib et al., 2002) and H101 (Oncorine, NCT01869088), as well as a vesicular stomatitis virus (VSV) encoding the human IFN-β gene (VSV-hIFN-β, NCT01628640).

This review summarizes the preclinical and clinical progress of oncolytic virotherapy in HCC, focussing on the molecular methods employed to improve virus-targeting to malignant hepatocytes, the use of virus-encoded therapeutic genes, and methods to improve viral survival. We also summarize the completed and ongoing clinical trials, routes of clinical viral delivery, and published clinical safety and efficacy data.

**Engineering OVs for HCC therapy**

Although the first wave of OV clinical trials took place in the 1950s and 1960s, it was not until the 1990s that engineered OVs blossomed, alongside advances in DNA manipulation and molecular biology techniques.

**Targeting malignant hepatocytes**

The specificity of any given drug determines its side-effect profile and greatly influences its efficacy. JX-594, dl1520, H101 and VSV-hIFN-β have all been engineered for pan-cancer specificity, targeting hallmark cancer characteristics, such as TP53 deletion and upregulated thymidine kinase (TK) expression. Other engineered pan-cancer-specific OVs have also shown efficacy in preclinical HCC models, including OVs whose genome expression is driven by survivin, an inhibitor of the apoptosis protein family that is overexpressed in the majority of HCC cases (survivin promoter-regulated oncolytic adenovirus vector carrying TP53 gene, AdSurp-P53), and human telomerase reverse transcriptase (hTERT), expressed in up to 90% of hepatoma cells (Ye et al., 2003). Expression of hTERT is significantly enhanced by the insertion of an insulator element upstream of the HCC-specific promoter, to shield from further increased by the insertion of an insulator element upstream of the HCC-specific promoter, to shield from destruction of healthy cells (Ohguchi et al., 1998; Foka et al., 2010). Viral gene expression in these systems can be further increased by the insertion of an insulator element upstream of the HCC-specific promoter, to shield from viral silencers, while retaining specific gene expression in hepatoma cells (Ye et al., 2003).

A further approach to specifically target malignant hepatocytes is to exploit the differential expression of micro-RNA (miRNA) transcripts; recently, a 30 miRNA signature consisting of 10 downregulated and 20 upregulated miRNAs was established for distinguishing HCC from non-cancerous liver tissues (Wei et al., 2013). Sequences complementary to miRNA transcripts that are specifically downregulated in HCC, e.g. mir-122 and mir-199, have been inserted into the 3' untranslated regions of OVs, including oncolytic type 5 adenovirus and HSV (Cawood et al., 2009; Fu et al., 2012; Khalid Elamin Elhag, 2012). The resulting selective viral RNA degradation in normal hepatocytes led to decreased hepatotoxicity, whilst retaining anti-HCC potency in animal models.

These methods are not without their problems, as shown in Table 1, and the protein or miRNA-binding site to be engineered into the OV genome must be chosen wisely.

**Enhancing anti-cancer efficacy**

Numerous therapeutic anti-cancer genes have been engineered into OVs in a bid to enhance efficacy. In particular, replication-competent adenovirus genes have been extensively modified and tested in preclinical models of HCC, as illustrated in Fig. 1. The engineered therapeutic genes fall under one of two broad categories: those that modify the tumour microenvironment, including stimulation of anti-HCC immune responses, and those acting directly on HCC cells to induce apoptosis and reduce cell growth and survival. In addition to the examples shown in Fig. 1, both oncolytic measles and Newcastle disease viruses have been engineered to express enzymes that convert the prodrug 5-fluorocytosine into the active chemotherapeutic 5-fluorouracil, enabling OV-mediated targeted chemotherapy, significantly enhancing OV efficacy (Lv et al., 2013; Lampe et al., 2013). The majority of approaches to arming OVs can equally be applied in the treatment of any solid malignancy. Exceptions include recombinant human
### Table 1. HCC-specific OVs; mechanisms of targeting

<table>
<thead>
<tr>
<th>Targeting principle</th>
<th>Example</th>
<th>Description</th>
<th>Issues</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver-specific viral promoter</td>
<td>Transthyretin-promoter-driven adenovirus</td>
<td>Transthyretin is a thyroid hormone transport protein, secreted into serum by hepatocytes</td>
<td>Requires additional cancer specificity</td>
<td>Hsieh et al. (2009)</td>
</tr>
<tr>
<td>HCC-specific viral promoter</td>
<td>AFP-promoter-driven adenovirus</td>
<td>AFP is produced in high levels from foetal liver and yolk sac, but not normally in adults</td>
<td>AFP is frequently only expressed in a sparse population of HCC cells; it can also be expressed from non-malignant hepatocytes in chronic hepatitis and cirrhosis</td>
<td>Zhang et al. (2012); Ohguchi et al. (1998); Johnson (2001)</td>
</tr>
<tr>
<td>Enzyme-activated viral protein</td>
<td>MMP-activated MVF</td>
<td>MMP substrate site inserted into MVF</td>
<td>Efficacy is dependent on tumour MMP expression; it could have broader cancer specificity</td>
<td>Mühlebach et al. (2010)</td>
</tr>
<tr>
<td>miRNA-mediated control of virus gene expression in normal liver cells</td>
<td>mir-122-regulated adenovirus</td>
<td>mir-122-binding sites inserted into 3' untranslated region of adenovirus type 5 E1A-luciferase transcription cassette</td>
<td>mir-122 expression is preserved in HCV-induced HCC, potentially rendering mir-122-regulated adenovirus ineffective in this subset of patients</td>
<td>Cawood et al. (2009); Varnholt et al. (2008)</td>
</tr>
</tbody>
</table>

AFP, α-Fetoprotein; MMP, membrane metalloproteinase; MVF, measles virus fusion.
adaptive immune responses observed (Kanto et al., 2004; Averill et al., 2007). OVs are capable of driving successful T-cell anti-cancer therapy, as shown in melanoma models utilizing oncolytic WT reovirus and VSV-GFP (Prestwich et al., 2008b; Wongthida et al., 2011). In HCC preclinical models, the oncolytic vaccinia virus GLV-1h68, encoding several biomarker genes only (see Table 2), has been shown to promote the intense infiltration of DCs into both HBV-positive and hepatitis virus-negative xenografts, whilst VSV-GFP promoted the infiltration of DCs into HCC...
tumours in an orthotopic immunocompetent animal model (Gentschev et al., 2011; Shinozaki et al., 2005). Although not a prerequisite for successful T-cell therapy, the OV-mediated expression of engineered immunostimulatory genes has the potential to greatly improve efficacy. Several approaches to enhance DC maturation/activation have been tested in preclinical HCC models, and include arming viruses with granulocyte macrophage colony-stimulating factor (GM-CSF) or CpG-rich sequences, the latter of which have been shown to increase IFN-γ and DC activation in draining lymph nodes, resulting in improved therapy against hepatoma lung metastases in comparison with the WT virus (Raykov et al., 2008). Other groups have shown enhanced DC and CD4+ T-cell tumour infiltration using vaccinia viruses encoding CCL5 or a secretory bispecific T-cell engager consisting of two single-chain variable fragments specific for CD3 and the tumour-cell surface antigen EphA2 (Li et al., 2011; Yu et al., 2014).

Immune cell recruitment and activation also plays a prominent role in the OV-induced disruption of tumour-associated vasculature. Indeed, inflammation-mediated disruption of vasculature is a well-documented phenomenon (Bryant et al., 2005; Lee & Slutsky, 2010). VSV infection of subcutaneous tumours resulted in transcriptional activation of the neutrophil chemottractants CXCL1 and CXCL5, inducing tumour infiltration by neutrophils, vascular shutdown and the apoptosis of uninfected tumour cells (Breitbach et al., 2007). The depletion of neutrophils prior to VSV infection abrogated these effects. In addition to the role played by OV-induced inflammation, JX-594 has been shown to directly infect and kill tumour-associated vascular endothelial cells in mice following intravenous (IV) delivery (Breitbach et al., 2013). These findings have been confirmed in human HCC trials, demonstrating disruption of tumour perfusion following JX-594 therapy (Liu et al., 2008; Heo et al., 2011).

The effects of OV on the wider HCC microenvironment are complex and have recently been reviewed elsewhere (Altomonte & Ebert, 2014).

Enhancing viral delivery and viral survival

Perhaps the biggest challenge to successful oncolytic virotherapy in HCC is the ability to infect sufficient numbers of malignant hepatocytes with a sufficiently high m.o.i. and to maintain viral propagation. It is well established that the immune response to OVs is likely to play a dual role: simultaneously clearing the virus and hence limiting efficacy, whilst becoming more activated and primed to attack malignant cells (Melcher et al., 2011). It is known that adenovirus is rapidly removed following IV delivery by Kupffer cells, liver-resident macrophages, and the same may be true of other viruses (Tao et al., 2001). A number of novel methods have been employed to enhance systemic viral delivery to the desired target, including Kupffer cell depletion using replication-defective adenovirus prior to replication-competent adenovirus therapy, and warfarinization to block coagulation factor and complement-dependent binding of adenovirus to hepatocytes (Shashkova et al., 2008). Combined Kupffer cell depletion and warfarinization resulted in decreased hepatotoxicity and increased anti-tumour potency, albeit in subcutaneous xenografts (Shashkova et al., 2008). A different approach that has been tested in preclinical models of HCC is to engineer OVs to evade immune inactivation (Table 3). These engineered OVs are yet to be tested in clinical trials and it remains to be seen whether they paradoxically result in reduced immune-mediated anti-cancer efficacy.

Engineered OVs tested in HCC-directed clinical trials

In addition to the plethora of engineered oncolytic adenoviruses, a large number of WT and recombinant OVs have been investigated in preclinical models of HCC, but are yet to enter HCC-directed clinical trials (Table 2). Some of these viruses are clinical-grade agents that have been employed in other anti-cancer clinical trials, and are hence the more likely to proceed to HCC-directed trials.

The following sections describe the OVs that have entered HCC-directed clinical trials to date.

JX-594

JX-594 was first filed for patent in 2005 by Jennerex Biotherapeutics, a company that entered into a commercialization and development agreement for JX-594 with Transgene in 2010 and was later acquired by SillaJen in 2013 (Kirk, 2006; Transgene, 2010, 2013a). The Wyeth strain of vaccinia virus, which forms the backbone of JX-594, was derived from the poorly pathogenic New York City Board of Health strain. The Wyeth strain was extensively employed as a smallpox vaccine in the US until routine vaccination was rescinded in 1971 (Modlinard, 2001). JX-594 has been genetically modified by the homologous recombination of a pSC65 plasmid with the vaccinia virus TK gene. The plasmid sequence contains the human GM-CSF gene under the control of a synthetic early late promoter and the lacZ reporter gene (Mastrangelo et al., 1999). GM-CSF induces direct anti-tumour effects and, importantly, influences the immune system through the stimulation, recruitment and maturation of DCs (Urdinguio et al., 2013; Mach et al., 2000).

The expression of TK, an enzyme of the DNA precursor pathway, is strictly regulated during the normal cellular cycle, but is much higher and permanently expressed in malignant growing cells (Hengstschläger et al., 1998). Being TK-deleted, JX-594 cancer selectivity was believed to be dependent on elevated cellular TK levels in cancers. However, recent work has shown JX-594 cancer specificity to be multi-mechanistic, with replication being dependent on epidermal growth factor receptor/Ras/mitogen-activated protein kinase (MAPK) pathway signalling and
<table>
<thead>
<tr>
<th>Virus species</th>
<th>Virus</th>
<th>Modifications</th>
<th>Assessed in clinical trials?</th>
<th>Preclinical HCC model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parvovirus H-1</td>
<td>H-1PV G207</td>
<td>WT</td>
<td>Yes, glioma</td>
<td>Cell lines</td>
<td>Moehler et al. (2001)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yes, glioma</td>
<td>Cell lines and subcutaneous murine xenografts</td>
<td>Song et al. (2006); Xue et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>Cgal-Luc</td>
<td>Derived by repair of ICP4 (positive and negative regulation of virus genome) from CgalA3 virus, insertion of lacZ gene into IGR54 and luciferase gene into IGR20</td>
<td>No</td>
<td>Subcutaneous murine xenografts</td>
<td>Argnani et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>H6-Luc</td>
<td>Derived from H6 mutant; syncytium-forming (Syn^2), benzhydrazine (glycosylation inhibitor)-resistant; luciferase cassette inserted into IGR20</td>
<td>Closely related HF10 mutant has been tested in multiple solid tumours</td>
<td>Orthotopic murine xenografts</td>
<td>Chung et al. (2006)</td>
</tr>
<tr>
<td>Blue tongue virus</td>
<td>BTV-10 WT, cell-culture adapted</td>
<td>No</td>
<td>Hep3B cell line</td>
<td>Hu et al. (2008)</td>
<td></td>
</tr>
<tr>
<td>Measles virus (Edmonston)</td>
<td>BTV-HC3 WT, cell-culture adapted</td>
<td>No</td>
<td>Cell lines</td>
<td>Chen et al. (2007)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MV-CEA Expresses extracellular domain of human carcinoembryonic antigen (CEA)</td>
<td>Yes, glioma and ovarian cancer</td>
<td>Cell lines and subcutaneous murine xenografts</td>
<td>Blechacz et al. (2006)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MV-NIS Expresses human sodium iodide symporter (hNIS)</td>
<td>Yes, myeloma and multiple solid tumours</td>
<td>Orthotopic murine xenografts</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MV-GFP Expresses GFP; human bone-marrow-derived mesenchymal stem cells were infected with MV-GFP and systemically delivered in passively immunized mice</td>
<td>No</td>
<td>Orthotopic patient-derived HCC tissue xenografts</td>
<td>Ong et al. (2013)</td>
<td></td>
</tr>
<tr>
<td>Newcastle disease virus</td>
<td>NDFLtag-EGFP Derived from WT LaSota vaccine strain; carrying enhanced GFP</td>
<td>No</td>
<td>Human and murine hepatic stellate cells</td>
<td>Li et al. (2009)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NDV-Italian WT</td>
<td>No</td>
<td>Immunocompetent orthotopic murine model</td>
<td>Altomonte et al. (2010)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>rNDV/F3 aa(L289A) L289A mutation within F (fusion) glycoprotein</td>
<td>No</td>
<td>Cell lines and subcutaneous immunocompetent murine model</td>
<td>Wu et al. (2014)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NDV/Anh-EGFP Derived from WT Anhinga strain; carrying enhanced GFP</td>
<td>No</td>
<td>Cell lines and murine xenografts</td>
<td>Gentschev et al. (2011)</td>
<td></td>
</tr>
<tr>
<td>Vaccinia virus</td>
<td>GLV-1h68 Derived from Lister strain and carries three gene cassettes: Renilla luciferase-GFP (RUC-GFP) fusion cassette at F14.5L locus, reverse-inserted human transferrin receptor and β-galactosidase cassette at J2R locus (encodes TK), and β-glucuronidase cassette at A56R locus (encodes haemagglutinin)</td>
<td>Yes, multiple solid tumours</td>
<td>Cell lines and murine xenografts</td>
<td>Gentschev et al. (2011)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>JX963 Western reserve expressing GM-CSF, with double-deleted TK and vaccinia growth factor genes</td>
<td>Closely related vVDD-CDSR expressing cytosine deaminase and somatostatin receptor is being tested in solid tumours</td>
<td>Orthotopic immunocompetent rabbit model</td>
<td>Lee et al. (2010)</td>
<td></td>
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</table>
cancer cell resistance to type I IFNs, as well as on cellular TK levels (Parato et al., 2012).

**VSV-hIFN-β**

VSV is a negative-strand RNA virus that is non-pathogenic to humans. Effective immune defence to VSV is dependent on the host IFN response, with mice harbouring defective IFN systems succumbing to normally harmless VSV exposure (Durbin et al., 1996). Insertion of genes between the viral glycoprotein and polymerase genes does not affect the fitness of the resultant recombinant virus (Fernandez et al., 2002). Generation of VSV-hIFN-β is achieved by insertion of the hIFN-β gene into the same position in the full-length viral antigenic cDNA, pVSV-XN2, using unique restriction enzyme sites (Obuchi et al., 2003). The expression of hIFN-β renders successful virus propagation dependent on defective cellular IFN response pathways, as found in many cancers (Barber, 2004). In addition, expression of hIFN-β is envisaged to activate NK and T-cells and facilitate the maturation of DCs for immune-mediated anti-tumour therapy, as well as directly inhibiting malignant cell proliferation (Oda et al., 2001; Ferrantini & Belardelli, 2000; Kadowaki et al., 2000). VSV-hIFN-β is patented and being developed by the Mayo Foundation for Medical Education and Research (Federspiel et al., 2010).

**dl1520 (ONYX-015) and H101 (Oncorine)**

The adenovirus type 5 early regions 1A (E1A) and 1B (E1B) can be exploited to engineer cancer specificity; the protein products of E1A induce cellular DNA synthesis and transformation, but trigger apoptosis mediated by the mammalian tumour-cell suppressor protein p53, with a resultant reduction in the yield of progeny (Bayley & Mymryk, 1994; Debas & White, 1993). The 55 kDa E1B protein binds to the p53 protein and blocks p53-mediated transcriptional activation, hence limiting p53-dependent cell cycle arrest and apoptosis (Sarnow et al., 1982; Yew & Berk, 1992). Early gene-therapy adenoviral type 5 vectors were modified to disable productive infection by the deletion of both E1A and E1B. These replication-deficient adenovirus vectors were extensively used in cancer gene therapy trials; however, evidence for efficacy was restricted owing to self-limiting transgene expression, poor target-cell transduction and lack of tumour-cell targeting (Vile et al., 2000). On the other hand, disabling the E1B region alone theoretically leads to selective replication in p53-deficient cells. One of the first such replication-selective type 5 adenoviruses, dl1520, has an 827 bp deletion in the E1B region and a point mutation at codon 2022 that generates a stop codon preventing expression of a truncated protein from the deleted gene (Barker & Berk, 1987).

Initial data suggested that dl1520 does indeed selectively replicate in TP53-deficient cells (Bischoff et al., 1996). However, it is now accepted that TP53 status is in fact a poor predictor of the sensitivity of tumour cells to dl1520, with tumour specificity being determined by other factors such as the inhibition of viral RNA export in non-malignant cells (Edwards et al., 2002; O’Shea et al., 2004). An incomplete understanding of the mechanisms of OV cancer specificity can hamper clinical progress, as exemplified by a trial testing dl1520 in hepatobiliary cancers, where patients with HBV infections were in hindsight unnecessarily excluded owing to theoretical risks that HBV protein X can inactivate p53 protein in non-malignant hepatocytes, rendering them susceptible to dl1520-productive infection (Makower et al., 2003).

dl1520 was clinically developed by Onyx Pharmaceuticals under the name ONYX-015 until 2003, when a promising phase 3 trial in head and neck cancer was suspended. Exclusive rights to ONYX-015 were sold to Shanghai Sunway Biotech in 2005 (Investis, 2005). In the years preceding this acquisition, Shanghai Sunway Biotech was simultaneously developing H101 (Oncorine), a recombinant human adenovirus type 5 similar to ONYX-015. In November 2005, the Chinese State Food and Drug Administration approved H101 for advanced nasopharyngeal carcinoma in combination with chemotherapy (Waknine, 2005). Like dl1520, H101 is E1B-gene-deleted, but unlike dl1520, H101 has an additional partial E3 78.3–85.8 μm gene-segment

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Description</th>
<th>Potential advantages</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viral surface modification using polymers</td>
<td>Arginine-grafted bioreducible polymer or high molecular mass polyethylene glycol chemically conjugated to oncolytic adenovirus surface</td>
<td>Reduced hepatocyte infection and liver toxicity</td>
<td>Kim et al. (2011); Doronin et al. (2009)</td>
</tr>
<tr>
<td>Virus-mediated inhibition of NK and NKT cells</td>
<td>VSV expressing a protein from human cytomegalovirus known to downregulate CD155</td>
<td>Reduced neutralization by antibodies; Reduced NK and NKT cell recruitment to site of viral infection, reducing virus inactivation</td>
<td>Altomonte et al. (2009)</td>
</tr>
<tr>
<td>Virus-mediated expression of chemokine-binding proteins</td>
<td>Recombinant VSV expressing high-affinity chemokine-binding proteins; M3, from murine gammaherpesvirus-68, or equine herpes virus-1 glycoprotein G</td>
<td>Reduced neutrophil, NK and NKT cell recruitment to site of viral infection, enhancing virus titres</td>
<td>Wu et al. (2008); Altomonte et al. (2008)</td>
</tr>
</tbody>
</table>
deletion (Lu et al., 2004). E3 gene products prevent T-cell and NK cell recognition of infected cells by preventing transport of MHC class I to the plasma membrane and by sequestration of MHC class I-related molecules A and B, respectively (Burgert & Kvist, 1985; McSharry et al., 2008). The partial E3 gene deletion in H101 is thought to enhance its safety profile, although this may be at the cost of decreased anti-cancer potency (Suzuki et al., 2002).

**Clinical experience of OV-based therapy in HCC**

To date, only four HCC-directed clinical trials using two different OVs, JX-594 and dl1520, have been undertaken and completed follow-up (Table 4). Early-phase trials that include a mixed population of patients with digestive tract tumours have typically recruited very small numbers of patients with HCC, making it difficult to adequately characterize the performance of these agents (Park et al., 2008; Habib et al., 2001). It is also noteworthy that patients with significant chronic infections, including HIV, HBV and HCV infection, are frequently excluded from trials of OVs that include multiple disease sites, primarily owing to the perceived risk of increased adverse events (Pecora et al., 2002; Vidal et al., 2008). Encouragingly, at least three other OV trials exclusively for HCC are under way (Table 5).

**Route of delivery**

The safety and efficacy of OV therapy is dependent not only on viral specifics, but also on numerous clinical considerations, including the administered dose of virus, the rate of infusion, the anatomical distribution of disease and the route of delivery.

**Intratumoral (ITu) injection.** Numerous ITu therapies have been trialled in liver tumours, and ITu injection is a popular OV delivery method in HCC (see Tables 4 and 5) (Venook, 2000). The advantages of the ITu route are the delivery of a high concentration of drug to the target, whilst minimizing off-target side-effects, an important consideration in HCC, where the background liver is frequently cirrhotic, with reduced functional capacity. However, direct ITu injection carries significant risks of bleeding, infection and peritoneal tumour seeding as well as technical challenges. It is frequently impossible to inject all HCC foci, but this is not necessarily a limitation of the technique; Park et al. (2008) reported that ITu injection of JX-594 led to the initial release of virus into the bloodstream, which was rapidly cleared. This was then followed by the re-emergence of circulating JX-594 days to weeks later, consistent with productive infection. In keeping with these observations, replicating JX-594 infection was found in a non-injected HCC focus metastatic to the neck following ITu liver injection (Park et al., 2008).

**IV injection.** The IV delivery of OVs avoids the local injection-site side-effects associated with invasive ITu therapy. IV injection is also more likely to be acceptable

<table>
<thead>
<tr>
<th>Virus</th>
<th>Study design</th>
<th>Delivered dose</th>
<th>Route</th>
<th>Delivered dose (p.f.u.)</th>
<th>Anticancer effect</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>JX-594</td>
<td>Single treatment group; IV day 1, ITu days 8 and 22, sorafenib day 25</td>
<td>10⁸ or 10⁹</td>
<td>ITu</td>
<td>10⁸ or 10⁹</td>
<td>mRECIST disease control rate 62% for JX-594 and 59% after initiation of sorafenib</td>
<td>Heo et al. (2013a)</td>
</tr>
<tr>
<td>JX-594</td>
<td>Randomized comparison between low- and high-dose JX-594</td>
<td>10⁸ or 10⁹</td>
<td>ITu</td>
<td>10⁸ or 10⁹</td>
<td>OS 14.1 months in high-dose group vs 6.7 months in low-dose group (P=0.002)</td>
<td>Heo et al. (2013a)</td>
</tr>
<tr>
<td>Ad5</td>
<td>Randomized comparison between PEI and Ad5 dl1520</td>
<td>3×10¹⁰⁰</td>
<td>ITu</td>
<td>3×10¹⁰⁰</td>
<td>No significant overall survival advantage</td>
<td>Jennerex (2013b)</td>
</tr>
<tr>
<td>Ad5 dl1520</td>
<td>One patient had PR by RECIST and four had PD</td>
<td></td>
<td>ITu</td>
<td></td>
<td></td>
<td>Habib et al. (2002)</td>
</tr>
</tbody>
</table>

Searches were performed on http://www.ClinicalTrials.gov, Current Controlled Trials, EU Clinical Trials Register and Medline.

OS, Overall survival; PR, partial response; PD, progressive disease; RECIST, Response Evaluation Criteria in Solid Tumours; mRECIST, modified RECIST.

Table 4. Completed HCC-directed clinical trials using OVs

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to both patients and their physicians when administered at regular intervals as part of a scheduled course of treatment. Intravenous administration of JX-594 has been shown to result in viral delivery to tumours, with the key determinant of tumour infection being the administered dose (Breitbach et al., 2011). Of the patients treated with doses $\geq 1.5 \times 10^7$ p.f.u. kg$^{-1}$ and subsequently biopsied, 87% showed JX-594 positivity in tumour by immunohistochemistry or quantitative PCR, whereas those treated with lower doses were negative. All patients in this trial had a history of vaccination with live vaccinia virus as children, and delivery was demonstrated in a patient despite the presence of neutralizing antibodies at baseline. This finding lends support for the need to establish the maximum tolerated dose in trials of oncolytic virotherapy, and to use the maximum tolerated dose in subsequent phase 2 and 3 trials. The IV route is further supported by a translational trial where oncolytic reovirus was recovered post-surgery from colorectal cancer liver metastases following IV delivery and shown to be capable of plaque formation \( \textit{ex vivo} \) (Adair et al., 2012). In the same trial, no replicating reovirus was recovered from normal liver samples, but faint staining for reovirus sigma 3 protein was seen by immunohistochemistry, supporting the notion of preferential productive infection in cancerous tissue.

Several trials have employed an initial IV injection of OV followed by ITu injections. The theory behind this approach is that initial IV injection will prime an immune response, which is then amplified at the target site upon further ITu injections.

**Hepatic artery injection (HAI).** HAI using cytotoxic agents is in routine clinical practice for patients with HCC and warrants further investigation in oncolytic virotherapy. This is commonly employed in the form of transarterial chemo-embolization (TACE), either as a palliative technique per se, or as a ‘bridging’ modality before liver transplantation (Jelic & Sotiropoulos, 2010). The TACE principle employs HAI of cytotoxic drug combinations followed by lipoidal or degradable microsphere injection for vessel occlusion, resulting in tumour-cell ischaemia and necrosis.

It is debatable whether HAI enhances viral delivery to localized targets over the simpler method of ITu injection. HAI also does not prevent systemic side-effects, as was significantly highlighted by the well-publicized death of the teenager Jesse Gelsinger secondary to systemic inflammatory response syndrome induced by the hepatic artery injection of $3.8 \times 10^{10}$ virus particles of replication-incompetent adenovirus type 5 (E1- and E4-deleted) encoding ornithine transcarbamylase cDNA (Raper et al., 2003). The strength of HAI lies in the opportunity to improve on existing locoregional therapies in combination with TACE, and, encouragingly, a phase 3 trial of H101 in combination with TACE in patients with HCC is currently recruiting (Table 5). Clearly, further trials testing OV by HAI are warranted and it remains to be seen which route of delivery is preferable in terms of safety, efficacy and patient acceptability.

**Table 5.** Ongoing HCC-directed clinical trials using OVs

<table>
<thead>
<tr>
<th>Virus</th>
<th>Phase</th>
<th>No. patients</th>
<th>Route</th>
<th>Study design</th>
<th>Study identifier</th>
<th>Primary objective(s)</th>
<th>Progress</th>
</tr>
</thead>
<tbody>
<tr>
<td>JX-594</td>
<td>2</td>
<td>21</td>
<td>IV</td>
<td>Single treatment group, 5 infusions at weekly intervals</td>
<td>NCT01636284</td>
<td>Tumour response</td>
<td>Enrollment completed</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>21</td>
<td>IV</td>
<td>HA1, Randomization to adenovirus and TACE or TACE only</td>
<td>NCT01636088</td>
<td>Overall survival</td>
<td>Recruiting</td>
</tr>
<tr>
<td>H101 recombinant human adenovirus</td>
<td>3</td>
<td>120</td>
<td>HAI</td>
<td>Modified 3+3 Fibonacci dose escalation</td>
<td>NCT01628640</td>
<td>Maximum tolerated dose</td>
<td>Recruiting</td>
</tr>
<tr>
<td>VSV-hIFN- ( \beta )</td>
<td>3</td>
<td>48</td>
<td>ITu</td>
<td>Modified 3+3 Fibonacci dose escalation</td>
<td></td>
<td>Maximum tolerated dose</td>
<td>Recruiting</td>
</tr>
</tbody>
</table>

Searches were performed on [http://www.ClinicalTrials.gov](http://www.ClinicalTrials.gov), Current Controlled Trials and EU Clinical Trials Register. Searches were performed on [http://www.ClinicalTrials.gov](http://www.ClinicalTrials.gov), Current Controlled Trials and EU Clinical Trials Register.
Clinical safety data

As can be seen from Table 4, both ITu and IV injections of JX-594 have been tested in patients with HCC. The most common adverse events are an influenza-like illness comprising headache, nausea, vomiting and fatigue (Park et al., 2008; Breitbach et al., 2011; Heo et al., 2013a). A mild fever occurs in all patients and is dose-related (Heo et al., 2013a). A maximum tolerated dose was reached at $10^9$ p.f.u. owing to grade III hyperbilirubinaemia subsequent to transient tumour swelling inducing biliary obstruction (Park et al., 2008). Peri-tumoral oedema, induced by acute inflammation, has been commonly reported in trials using OVsm and, in fact, response after initial tumour flare is a class effect of immune therapies in general (Pecora et al., 2002; Senzer et al., 2009; Wolchok et al., 2009). The absence of substantial changes in aspartate aminotransferase (AST) and alanine aminotransferase (ALT) levels suggests that direct destruction of healthy hepatocytes following JX-594 injection is mild (Park et al., 2008).

Habib et al. (2001) reported safety data from 10 patients with HCC treated with dl1520. Following a dose-escalation study in patients with either primary or secondary liver tumours in which no maximum tolerated dose was reached, a further small HCC-directed trial was undertaken in Egypt (Habib et al., 2001). In the latter study, 10 patients were randomized in a 1 : 1 ratio to receive either a single IV dose of $3 \times 10^{11}$ p.f.u. dl1520 followed by five ITu doses, or standard of care therapy with 95% ethanol by ITu injection (Habib et al., 2002). Of the five patients treated with dl1520, three suffered from CTCAE grade I–II fever and rigors, and two patients suffered from transient hypotension at the time of the infusions. Very minor changes in AST and ALT were observed for patients treated with dl1520, in comparison with the much higher levels of serum transaminases observed following ethanol treatment (Habib et al., 2002).

Assessing efficacy in OV therapy for HCC

For the approval of new anti-cancer drugs, the US Food and Drug Administration accepts improved survival, as well as surrogate markers that predict clinical benefit. The Response Evaluation Criteria in Solid Tumours (RECIST) use single linear summation of target lesions to define response to therapy (Therasse et al., 2000). However, the clinical benefit provided by anti-cancer therapy in HCC correlates poorly with conventional methods of response assessment (Llovet et al., 2008; Forner et al., 2009). In 2008, the American Association for the Study of Liver Diseases developed a set of guidelines, termed the modified RECIST or mRECIST criteria, aimed at providing a common framework for the design of clinical trials in HCC (Lencioni & Llovet, 2010). These guidelines consider estimation of the reduction in viable tumour area using contrast-enhanced radiological imaging to be the optimal method to assess treatment response in HCC. Nonetheless, both RECIST and mRECIST criteria must be employed with caution in trials using immunotherapies; in particular, OVsm may cause transitory tumour flare secondary to inflammatory cytokine release, leading to tumour enlargement and increased contrast enhancement, prior to tumour necrosis and shrinking (Senzer et al., 2009). Delaying radiological assessment following OV therapy could potentially avoid this issue (Hales et al., 2010).

Clinical evidence of anti-tumour efficacy

In a recent pivotal study, 30 patients with advanced HCC were randomized to low- ($10^8$ p.f.u.) or high-dose ($10^9$ p.f.u.) ITu JX-594 administered every 2 weeks (Heo et al., 2013a). The majority of patients in both groups had previously received locoregional therapy, but more patients in the high-dose group had previously failed sorafenib therapy, a poor prognostic factor. Median overall survival was 14.1 months for the high-dose arm and 6.7 months for the low-dose arm. Despite the relatively small sample size, a statistically significant survival benefit ($P=0.020$) was demonstrated because of the large effect size. Both doses were associated with mRECIST responses, decreased tumour perfusion and decreased tumour contrast enhancement. This is the first study to show a statistically significant benefit derived from OV therapy in patients with HCC.

JX-594 has been tested as second-line therapy in two phase 2 HCC trials (see Table 4). In the larger of these studies (TRAVERSE), patients who had previously failed sorafenib therapy were treated with JX-594 and BSC or BSC alone (Transgene, 2013b). Sadly, the primary endpoint of improved overall survival was negative. The failure of JX-594 in the TRAVERSE trial following promising randomized dose-finding trial data remains to be fully explained. Patients recruited to the TRAVERSE trial were more likely to have sorafenib-resistant cancers. Acquired cellular resistance mechanisms to sorafenib following long-term exposure include compensatory crosstalk between PI3K/ Akt and MAPK pathways, upregulation of the JAK-STAT pathway and enhanced epithelial–mesenchymal transition (Zhai & Sun, 2013). These changes could theoretically affect OV infection and anti-cancer efficacy, although recently, the modified Lister strain vaccinia virus GLV-1h68 was shown to effectively infect and kill sorafenib-resistant HCC cell lines (Ady et al., 2014). Alternatively, the failure of JX-594 in the TRAVERSE trial could be attributed to more advanced disease in the second-line setting; fitter patients carrying a smaller HCC disease burden are more likely to respond to OV therapy, as has been the experience with other immunotherapies (Coppin et al., 2005). Furthermore, the relatively small number of patients included in phase 2 trials presents a challenge when seeking outcomes of study drug superiority over standard care. Nonetheless, Transgene recently announced a shift in strategy, moving JX-594 trials away from the second-line setting in HCC. Instead, a phase 3 trial, which is expected to enrol approximately 600 patients and is...
anticipated to begin recruitment in 2015, will be testing whether first-line IT JX-594 (weeks 0, 2 and 4) followed by sorafenib (week 6 onwards) improves overall survival in comparison with sorafenib alone (Transgene, 2014).

In contrast, no meaningful efficacy data can be derived from the dl1520 trial by Habib et al. (2002). One patient who received dl1520 experienced a partial response with reduction in tumour volume from 306 to 22.5 cm³ associated with a concomitant decrease in α-fetoprotein (AFP) level from 7604 to 300 ng ml⁻¹. The remaining four patients demonstrated progressive disease with an increase in both tumour volume and AFP levels. Larger randomized trials are needed to determine whether recombinant type 5 adenoviruses are efficacious in HCC.

Clinical evidence of anti-cancer immune stimulation

Anti-cancer immune stimulation could be at least partially responsible for the reported decreases in the size and contrast enhancement of non-injected tumours following ITu JX-594 injection elsewhere (Park et al., 2008; Heo et al., 2013a). However, little ex vivo evidence has been gathered to date from clinical trials for anti-HCC immune responses. In their randomized dose-comparison phase 2 trial, Heo et al. (2013a) demonstrated HCC immune infiltration following JX-594 injection by both radiographic peripheral tumour enhancement and histologically confirmed diffuse lymphocyte infiltration from biopsied tumours. In the same trial, antibody-mediated complement-dependent cytotoxicity (CDC) was assessed by the addition of serum from JX-594-treated patients to HCC cell lines, resulting in cytotoxicity from 11 of the 16 subjects tested (Heo et al., 2013a). Indeed, CDC could be of vital importance in OV therapy, as evidenced by a recent JX-594 study in patients with a variety of cancer types, where patients with the longest survival duration had the highest CDC activity (Kim et al., 2013). Evidence was also gathered for antibody development and T-cell immunity against JX-594-encoded proteins, including β-galactosidase, an observation of likely importance in the elimination of virus-infected tumour cells (Heo et al., 2013a). Whilst encouraging, these results do not constitute an adaptive anti-HCC immune response. At least six different HCC-specific tumour-associated antigens (TAs) that are targeted by T-cells have been identified, and future OV trials should assess whether specific T-cell responses against these antigens are induced (Breous & Thimme, 2011).

Other evidence for immune stimulation is similarly encouraging, though sparse; both elevated TNF-α and IFN-γ have been observed in the serum of HCC patients treated with JX-594 (Liu et al., 2008; Park et al., 2008). These cytokines are likely to contribute to DC maturation, cancer growth inhibition and apoptosis. Of interest, the presence of type I IFNs, powerful stimulators of NK cell activity and DC maturation, has not been reported in JX-594-treated patients, perhaps owing to efficient vaccinia virus-mediated inhibition of the IFN system (Perdiguerò & Esteban, 2009). In contrast, other viruses, e.g. measles virus, reovirus and VSV, are known to efficiently induce type I IFNs, whetting the appetite for HCC clinical trials with thorough translational read-outs using such agents (Steele et al., 2011; Diaz et al., 2007; Donnelly et al., 2013). One potential concern is that co-infection of HCV-infected hepatocytes with OVs will not lead to robust IFN induction owing to the IFN evasion mechanisms employed by HCV. For example, HCV NS3/NS4a protease disrupts pattern recognition receptor signalling by cleaving the RIG-I and TLR3 downstream adaptors, MAVS and TRIF, respectively (Foy et al., 2005; Li et al., 2005b; Ferreon et al., 2005). NS3/NS4A also perturbs RIG-I downstream signalling through disruption of virus-induced NF-κB binding to the DNA PRDII element, hence limiting IFN-β gene expression (Foy et al., 2005; Li et al., 2005c). Realistically, however, the scenario of OV co-infection with HCV is unlikely to be a major factor in HCC patients, as the majority of patients only have detectable HCV proteins or genomes in a minority of clustered hepatocytes (Stiffler et al., 2009) A further concern is that HCV and HBV could suppress OV-mediated adaptive anti-tumour immune responses; however, no clinical evidence for this yet exists, and future HCC-directed trials cannot afford to exclude the majority of HCC patients, with a viral aetiology.

Future perspectives

The clinical progress of JX-594 in HCC therapy provides much optimism in the field. This agent appears to be transcending the barrier between novel laboratory science and credible clinical therapy. From this clinical progress have come clues to support existing laboratory research into the mechanisms of OV-mediated anti-HCC efficacy, including the direct, immune and anti-vascular effects. However, much remains to be discovered in terms of the differential response to OV therapy in subsets of patients, the optimal route of delivery and combinations with other anti-cancer therapies. Furthermore, biomarkers predictive of treatment response are greatly needed, as are continued efforts to establish early diagnoses of cirrhosis and HCC using technologies such as the non-invasive enhanced liver fibrosis test (Lichtinghagen et al., 2013).

The combination of OVs with sorafenib warrants particular mention. These drug combinations have non-overlapping toxicities and potentially synergistic mechanisms of action, hence forming the focus of past and future trials. For JX-594, the sequence of this combination is of paramount importance; upfront JX-594 therapy is thought to induce acute vascular disruption, sensitizing tumours to the anti-angiogenic effects of subsequent sorafenib treatment. In murine tumour models, sequential JX-594 followed by sorafenib therapy was superior to either simultaneous therapy or sorafenib followed by JX-594 (Heo et al., 2011). In vitro, sorafenib, a multi-kinase inhibitor, perturbs JX-594 productive infection of HCC cell lines, a result that can be predicted as sorafenib inhibits a wide range of cellular
kinases in addition to its principal targets, whereas vaccinia viruses are known to encode kinases, including B1R and TK, that are essential for productive infection (Rempel & Traktman, 1992; Parato et al., 2012; Kitagawa et al., 2013). The very fact that the cancer specificity of JX-594 is partially dependent on elevated TK levels in malignant cells highlights the reliance of this OV on functional viral and cellular kinases. Hence, sequential scheduling works best for this OV, as was employed in the second-line trial using JX-594 followed by sorafenib therapy, and a similar schedule is planned for the first-line phase 3 trial (Heo et al., 2011; Transgene, 2014).

The combination of other OVs that are less reliant on cellular kinase functions with sorafenib should form the focus of future studies. The precise scheduling should be determined by preclinical studies in immunocompetent animal models. Kottke et al. (2010) showed that tumours treated in vivo with vascular endothelial growth factor (VEGF) inhibitors became highly susceptible to systemic treatment with reovirus, but only if the drugs were withdrawn 24–48 h before virus delivery. The authors concluded that the rebound of VEGF signalling upon drug withdrawal conditions tumour-associated endothelium for productive infection of reovirus.

The complex immunomodulatory effects of sorafenib are also likely to be critical determinants of success. One report cited that sorafenib significantly reduced the number of NK cells and inhibited their reactivity against tumour targets in animal models, whilst a contradictory report stated that sorafenib enhances IL-12 secretion from human liver-derived macrophages, hence activating NK cells (Sprinzl et al., 2013; Zhang et al., 2013). The efficacy of OVs in combination with sorafenib will therefore be partially dependent on the stimulation or suppression of immune responses. Sorafenib could theoretically enhance OV therapy through a number of mechanisms, including the synergistic activation of NK cells and inhibition of the OV-directed humoral response, thus enhancing IV delivery, as has been the experience with chemotherapy (Lolkema et al., 2011). Alternatively, sorafenib-induced immunosuppression could limit the immune-mediated efficacy of OVs, whilst immune stimulation could limit virus propagation, both resulting in reduced efficacy. Orthotopic immunocompetent animal models could begin to answer these questions, but the lack of concordance between animal models and human research highlights the need to pursue early-phase clinical trials using sorafenib/OV combinations.

In addition to sorafenib, numerous successful preclinical studies have been conducted, using OVs in combination with cytotoxic agents, radiotherapy and targeted biotherapies, including other preclinical OVs (Mao et al., 2009; Zheng et al., 2009; Chung et al., 2002). More recently, antibodies targeting the immune checkpoint molecules CTLA-4 and PD-1/PD-L1 have been tested in early-phase HCC-directed clinical trials (Sangro et al., 2013a, b). CTLA-4 is expressed on T-cells and inhibits T-cell activation, whilst PD-1–PD-L1 interactions limit the activation of NK, B- and T-cells (Pardoll, 2012). Combinations of OVs with immune checkpoint inhibitors are being explored in solid and haematological malignancies and should also be tested in HCC, with the premise that OV-mediated tumour vaccination followed by immune activation through checkpoint inhibition may prove highly beneficial (Engeland et al., 2014; Minev et al., 2014). As with all combination regimens, overlapping side-effects are of concern, especially severe immune-related toxicity. HCC therapy provides the opportunity to limit systemic side-effects by HAI, a delivery method that is likely to become increasingly important in future trials.

Taking these combinations one step further, future studies should assess the efficacy of OVs carrying cDNA libraries, in combination with checkpoint inhibitors. Effective cancer immunotherapy requires the release of TAAs in the context of potent immune activation. Kottke et al. (2011) showed that a cDNA library of normal tissue, expressed from oncolytic VSV, acting as an immune adjuvant, cured established tumours of the same histological type from which the cDNA library was derived. In HCC therapy, such broad antigenic stimulation can potentially lead to the attack of healthy hepatocytes. This problem can be avoided by engineering OVs to express specific TAAs, including AFP, EpCAM and SSX-2. Clues to indicate the likely efficacy of the latter approach can be found in patients with HCC who have a better prognosis, associated with the expression of such TAAs (Liang et al., 2013). Unleashing specific T-cell responses against OV-expressed TAAs through combination with checkpoint inhibitors could prove to be a very valuable strategy.

Other than JX-594, a large number of clinically active and preclinical OVs have been tested in HCC models, yet precious few of these agents have progressed into HCC-directed clinical trials. As in other fields, OV laboratory science races well ahead of clinical practice, and in this respect anti-HCC oncolytic virotherapy is no different. The potential exists for the medicines regulatory authorities to approve multiple efficacious OVs in HCC clinical practice, paving the way for stratified therapy. In order to realize this potential and reap the rewards, we must first push these preclinical agents into the clinic.

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