DiSCoVERing Innovative Therapies for Rare Tumors: Combining Genetically Accurate Disease Models with In Silico Analysis to Identify Novel Therapeutic Targets

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Abstract

Purpose: We used human stem and progenitor cells to develop a genetically accurate novel model of MYC-driven Group 3 medulloblastoma. We also developed a new informatics method, Disease-model Signature versus Compound-Variety Enriched Response (“DiSCoVER”), to identify novel therapeutics that target this specific disease subtype.

Experimental Design: Human neural stem and progenitor cells derived from the cerebellar anlage were transduced with oncogenic elements associated with aggressive medulloblastoma. An in silico analysis method for screening drug sensitivity databases (DiSCoVER) was used in multiple drug sensitivity datasets. We validated the top hits from this analysis in vitro and in vivo.

Results: Human neural stem and progenitor cells transformed with c-MYC, dominant-negative p53, constitutively active AKT and hTERT formed tumors in mice that recapitulated Group 3 medulloblastoma in terms of pathology and expression profile. DiSCoVER analysis predicted that aggressive MYC-driven Group 3 medulloblastoma would be sensitive to cyclin-dependent kinase (CDK) inhibitors. The CDK 4/6 inhibitor palbociclib decreased proliferation, increased apoptosis, and significantly extended the survival of mice with orthotopic medulloblastoma xenografts.

Conclusions: We present a new method to generate genetically accurate models of rare tumors, and a companion computational methodology to find therapeutic interventions that target them. We validated our human neural stem cell model of MYC-driven Group 3 medulloblastoma and showed that CDK 4/6 inhibitors are active against this subgroup. Our results suggest that palbociclib is a potential effective treatment for poor prognosis MYC-driven Group 3 medulloblastoma tumors in carefully selected patients. Clin Cancer Res; 22(15); 3903-14. ©2016 AACR.

Introduction

Our knowledge of the biology of rare tumors and the development of new therapies is hampered by the lack of biologically relevant or genetically and functionally accurate models. Patient-derived tumor cell lines may be difficult, if not impossible, to grow in culture (1), and even if cell lines can be maintained in culture, high serum or other in vitro conditions can result in genetic changes that diverge from the original tumor, reducing the cell line’s utility as a model (2). Serial xenografts from primary human tumors represent another promising approach (3), but because cultured cells and serial xenografts are often genetically complex, it can be difficult to elucidate the key drivers of tumor formation.

Mouse models have led to great advances in our understanding of the biology of a variety of tumors. However, murine cells are not always transformed in a fashion equivalent to human ones (4), and expression profiles can be challenging to reconcile between mouse and human. We propose an alternative strategy starting with a human tissue of origin and adding or ablating hypothesized key genetic drivers of the tumor of interest to allow...
Translational Relevance

Genetically accurate model systems are crucial to expanding our knowledge of rare tumor subtypes and to developing new therapeutics. The strategy we present here, based on adding key transformative oncogenic elements to stem cells from the tissue of a cancer’s origin, could have great utility in many tumor types. Screening external existing drug sensitivity data-sets provides a way to identify in silico candidate therapeutic agents that does not require the use of large-scale in vitro drug screens. Using human cerebellar-derived neural stem and progenitor cells, we created a genetically and phenotypically accurate model of the most aggressive subgroup of medulloblastoma. There is an urgent need to improve medulloblastoma treatment, especially for patients with high-risk disease. We have identified and validated cyclin-dependent kinase (CDK) inhibition in general, and CDK 4/6 inhibition in particular, as a candidate therapy for treating patients with MYC-driven, aggressive Group 3 medulloblastoma.

Materials and Methods

Generation of CB NSC model

Human cerebellar neural stem cells were derived as described (22) and obtained in concordance with German law and Ethics Board evaluation. The study was also approved by the Johns Hopkins Institutional Review Board. The cells were obtained by dissecting the cerebellar anlage and were cultured as neurospheres. Cells were transduced using lentiviral and retroviral vectors. The R248W-TP53 plasmid (Addgene plasmid 16437) and MYC plasmid (Addgene plasmid 17758) were subcloned into pWPI (Addgene 12254; ref. 23). For hTERT and constitutively active AKT, Addgene plasmids 12245 and 15294 were used. The SV40 plasmid is described in Raabe and colleagues (24). Lentivirus was produced by transfecting 293T cells with VSV-G envelope plasmid, Δ8.9 gag/pol plasmid and the plasmid containing the gene of interest as described in (24) using FuGENE (Roche) per the manufacturer’s instruction. Retrovirus was produced by transfecting 293T-GP cells with VSV-G plasmid and the plasmid containing the gene of interest using FuGENE. 24 hours posttransfection, 293T cells were switched to EGF-FGF media and the supernatant was collected at 48 and 72 hours. The collected supernatant was filtered with a 0.45 μm filter and stored at −80°C until use.

Cerebellar neural stem cells were dissociated using Accutase (Sigma) and gentle titration, and then incubated with viral MYC, SV40; or MYC, hTERT and R248W-TP53 (DNp53) viral supernatants for 24 hours. After approximately 1 week in culture, spheres were identified and individually placed into wells of 24-well plates. Expression of the introduced oncogenes was verified by Western blot and qPCR. Cells successfully transduced with MYC, hTERT, and R248W-TP53 (DNp53) were then incubated with AKT viral supernatant for 24 hours. The cells were then placed under puromycin selection for 72 hours, following which sub-clones were generated as described above.

Cell culture

The human medulloblastoma cell lines D425Med and D238Med were both established at Duke University (18).
D283Med is available through the ATCC. Both lines are cultured in MEM media supplemented with 10% FBS. The neural stem cell lines grow as neurospheres in media composed of 30% Ham’s F12, 70% DMEM, 1% antibiotic–antimycotic, 20% B27 supplement, 5 μg/mL heparin, 20 ng/mL EGF, and 20 ng/mL FGF2. Lines transformed with AKT are grown under puromycin selection. All cells were verified to be Mycoplasma free by PCR testing. Cell lines were authenticated by STR DNA identity testing by the Johns Hopkins Genetic Resources Core Facility.

Histology

Brains were removed from mice immediately following euthanasia and fixed in 10% buffered formalin. The brains were processed and hematoxylin and eosin slides prepared by the Johns Hopkins Pathology Reference Laboratory.

Immunohistochemistry/TMA

IHC was performed on deparaffinized sections of brain xenografts as described previously (23). The following primary antibodies were used: human specific NESTIN (1:500; Millipore, #MAB5326); GFAP (1:1,000; DAKO #Z0334); MAP2 (Santa Cruz Biotechnology #20172); MYC (1:300; Epitomics #14721); phospho-AKT (1:50; Cell Signaling Technologies); TP53 (Sigma, #BP-5312), phospho-RB (1:250; Cell Signaling Technologies #D20B12). For the TMA of 65 primary medulloblastoma samples, IHC was performed on deparaffinized arrays followed by antigen retrieval, using MYC and phospho-AKT antibodies at dilutions of 1:300 and 1:70, respectively. The array was stained for TP53 by Johns Hopkins Clinical Pathology following a Ventana standard protocol. The TMA was scored by intensity (scale of 0 to 2) and percentage stained; an H-score was calculated by multiplying intensity by the percentage of cells positive.

Gene-expression analysis

RNA was extracted from cells and xenograft tumors using TRIzol according to the manufacturer’s directions. RNA was assessed for quality and integrity using a Bioanalyzer (Agilent Technologies) and samples had a RNA Integrity Number score of higher than 8.2 (25). Gene-expression data were generated using Affymetrix High Throughput (HT) U1332 þ Chip according to the

Figure 1.

A, diagram illustrating the creation of novel cancer models using human stem cells and oncogenic elements of interest. B, human cerebellar neurosphere. C, Western blot indicating the expression of stem cell markers in the human cerebellar neural stem and progenitor cells. D, 65-sample medulloblastoma TMA reveals that Group 3 samples have the highest MYC expression. Bottom, an example of MYC staining in a Group 3 sample. E, staining the TMA reveals that Group 3 samples also have the highest expression of TP53, indicating inactivation of this pathway. Bottom, an example of TP53 staining in a Group 3 sample. F, phospho-AKT, which indicates activation of AKT, is expressed in all three subgroups present on the array. Bottom, an example of phospho-AKT staining in a Group 3 sample. Magnification of all TMA images ×400.
manufactured’s guidelines. Raw data were processed and analyzed using GenePattern as previously described (12, 26). The dataset will be made available as dataset GSE77475 at GEO (Gene Expression Omnibus).

**In vitro drug treatments**

Palbociclib was purchased from Selleckchem and diluted in water according to the manufacturer’s instructions.

**DiSCoVER analysis method**

The main analysis components of DiSCoVER (Disease-model Signature vs. Compound-Variety Enriched Response) are shown in Supplementary Fig. S1. The murine xenografts of transformed hNSC G3 samples and controls were profiled using Affymetrix arrays (see Gene expression analysis above). The gene probe identifiers were mapped into gene symbols using the Collapse Dataset tool (“max probe”) of the GSEA software (27). The top 150 upregulated genes between the murine xenografts of transformed hNSC G3 samples and controls were used to create an hNSC G3 oncogenic transcriptional signature (Supplementary Table S1). We used this gene set to project two large mRNA expression datasets. The Cancer Cell Line Encyclopedia (CCLE; ref. 28) and the Sanger Dataset (29). This projection is made using single-sample GSEA (30) to produce enrichment profiles of the hNSC G3 signature in each sample of those datasets. Once this projection is completed, we match the signature profile versus drug-sensitive profiles corresponding to drug sensitivity datasets: The Cancer Therapeutics Response Portal (CTRP v2; ref. 31), the CCLE Pharmacological Profiling Drug Data (28); and the Genomics of Drug Sensitivity in Cancer (29). Therefore, there are three comparisons we performed between the transcriptional profile of the hNSC G3 signature and the drug sensitivity profiles (see Supplementary Fig. S1 Comparison I, II, and III). There are only two mRNA datasets because the CCLE and CTRP v2 sensitivity datasets share the same mRNA samples. The matching scores between the signature, and each drug sensitivity profile, were computed using the Information Coefficient (IC), an information theoretic-measure of association, similar to the measure of association we used in Abzeed and colleagues (32) to compare radiation sensitivity versus pathway expression. Once we obtained the matching scores of each drug against the hNSC G3 signature, we performed a permutation test on the signature profile with 10,000 permutations. These values are used to create an empirical null distribution from which nominal P values and FDRs (33) are computed. We focus in the top scoring compounds with FDR below 0.33 in the three comparisons and look for overlaps in compounds or compound classes (Supplementary Table S2). This is the way we noticed the appearance of cyclin-dependent kinase (CDK) inhibitors for each dataset (Fig. 4B and Supplementary Fig. S2). In Supplementary Fig. S2, we show that CDK inhibitors are top hits in the 3 drug sensitivity datasets by plotting the Information score (IC) in the y-axis and the correlation coefficient (between signature and drugs) in the x-axis. This comparison of correlation versus ICs provides Supplementary Information about how linear or non-linear is the relationship between the signature and a given drug. The DiSCoVER method will be made publicly available as an analysis module in GenePattern.

**Immunofluorescence**

Bromodeoxyuridine (BrdUrd) incorporation and cleaved caspase-3 assays were performed as described previously (34).

**Western blot**

Protein was extracted by lysing cell pellets with RIPA buffer and quantified using a Bradford assay. Antibodies against GAPDH (6C5: sc-32233) and Actin (C4: sc-47778) are from Santa Cruz Biotechnology. Antibodies for total Rb (#9309), Phospho-Rb Ser780 (#8180), Phospho-Rb Ser807/811 (#8516), and cleaved PARP (#5625) are from Cell Signaling Technology. The Nestin (10C2, MAB5326) and SOX2 antibodies are from Millipore. The following antibody dilutions were used: GAPDH (1:1,000), Actin (1:1,000), GFAP (1:2,000), SOX2 (1:200), Nestin (1:1,000), total Rb (1:1,000), phospho-Rb Ser780 (1:1,000), phospho-Rb Ser807/811 (1:1,000), and cleaved-PARP (1:800). Peroxidase-labeled secondary antibodies were diluted 1:5,000 and are from KPL or Cell Signaling Technology. Quantification was performed using ImageJ.

**Animal studies**

“Principles of laboratory animal care” (NIH publication No. 86-23, revised 1985) was followed, using a protocol approved by the Johns Hopkins Animal Care and Use Committee, in compliance with the United States Animal Welfare Act regulations and Public Health Service Policy. Orthotopic brain xenografting was performed as described previously (23). Cerebellar coordinates were –2 from lambda, +1 laterally, and 1.5 mm deep. Palbociclib was prepared in a pH 4.0 50 mmol/L sodium lactate solution and administered by oral gavage in a 100 μL bolus. Animals received a 150 mg/kg dose 5x a week, which is a widely used dosing schedule in preclinical murine xenograft models (35–38). All animals were monitored daily. Symptomatic animals were euthanized and their brains removed and fixed in formalin.

**Results**

**Group 3 primary medulloblastomas tumors express MYC, phospho-AKT, and TP53**

To generate a genetically defined model of aggressive medulloblastoma, we began with human neural stem and progenitor cells obtained as described in ref. 22 (Fig. 1A and B). These cells express the stem cell marker CD133 and the neural stem cell markers NESTIN, SOX2, and GFAP (Fig. 1C).

We used a tissue microarray (TMA) containing 65 primary human medulloblastoma samples that was previously characterized with respect to subgroup (9) to interrogate the expression of oncogenic elements associated with Group 3/C1 medulloblastoma. Group 3 tumors are known to overexpress MYC at the mRNA level (8), but MYC protein expression has not been extensively investigated in primary tumors. Immunohistochemical analysis of MYC on our TMA showed that expression was highest in Group 3 tumors (Fig. 1D), with 50% expressing MYC, whereas only 27% of MYC on our TMA showed that expression was highest in Group 3 tumors and 6% of Group 4 tumors had detectable MYC protein levels.

In addition to MYC, Group 3 samples had significantly higher expression of TP53 (Fig. 1E), indicating dysfunction of the TP53 pathway. Among Group 3 tumors, 56% were positive for increased TP53 expression, whereas only 25% of SHH tumors and 23% of Group 4 tumors were positive for TP53. Our group has demonstrated that anaplastic medulloblastoma tumors have elevated TP53 expression (39, 40), suggesting inactivation of the TP53 pathway. We and others have shown that increased TP53 protein levels or TP53 mutations are associated with worse clinical outcomes in a subgroup-dependent fashion (41).

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We next investigated the expression of phospho-AKT as an indicator of mTOR status. The mTOR pathway is active in multiple medulloblastoma subgroups, including Group 3 and is associated with increased metastasis (42). We identified increased phospho-AKT staining in all subgroups represented in our TMA. Although there was a trend for increased AKT signaling in Group 3, it did not reach statistical significance (Fig. 1F). In addition to MYC, TP53 and phospho-AKT, human telomerase (hTERT) has been identified as being highly expressed in embryonal tumors, and was included as a transforming element (43, 44).

Neural stem cells transduced with MYC, dominant-negative TP53, hTERT, and AKT form aggressive tumors that phenocopy Group 3 medulloblastoma

The addition of MYC alone or with constitutively active (myristoylated) AKT, BW244W-TP53 (hereafter referred to as DNp53) and human telomerase (hTERT) has been identified as being highly expressed in embryonal tumors, and was included as a transforming element (43, 44).

**Figure 2.**

A, stem cells transduced with MYC have increased proliferation compared with untransduced neural stem cells and those immortalized with SV40. B, cerebellar neural stem cells transduced with DNp53, hTERT (hT), AKT and MYC form tumors that kill mice in 117 days. Cells transduced with SV40 alone do not form tumors. C, these tumors express the introduced oncogenes. Images show tumor adjacent to normal brain. D, tumors formed from cerebellar neural stem cells transduced with all four oncogenes form aggressive, anaplastic tumors (i), that spread to the leptomeninges (ii), and metastasize to the spine (iii). E, the tumors are positive for MAP2 and NESTIN expression and negative for GFAP expression.

**Using Stem Cell Models to Find New Therapeutic Targets**

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The addition of MYC alone or with constitutively active (myristoylated) AKT, BW244W-TP53 (hereafter referred to as DNp53) and human telomerase (hTERT) increases proliferation compared with normal neural stem cells and to cells immortalized with SV40 (Fig. 2A). The human MYC transformed cells were ATOH negative (data not shown), consistent with prior murine models of MYC-driven medulloblastoma (14). Cerebellar-derived neural stem and progenitor cells transduced with DNp53, MYC, AKT, and hTERT formed aggressive tumors when injected into the brains of nude mice (Fig. 2B). Cerebellar stem cells immortalized with SV40 did not form tumors (Fig. 1B).

The tumors expressed TP53, MYC, and phospho-AKT, indicating that the oncogenic elements used to drive transformation were maintained (Fig. 2C). Tumors formed by cells transduced with all four oncogenic elements also had anaplastic features (Fig. 2D, i) and could spread to the leptomeningeal space (Fig. 2D, ii). Approximately 20% of mice had spinal metastases (Fig. 2D, iii). Metastasis is associated with Groups 3 and 4, the most aggressive subgroups of medulloblastoma (45). The DNp53 hTERT AKT MYC orthotopic xenografts expressed NESTIN and MAP2 and were negative for GFAP (Fig. 2E), indicating a primarily progenitor and neuronal phenotype consistent with medulloblastoma. Because no effective antibody exists for hTERT immunohistochemistry, we verified high-level expression of this hallmark in our 4-gene–transduced cells by qPCR (data not shown).

**Human neural stem cell models of Group 3 medulloblastoma share mRNA expression profile with human primary tumors**

To further confirm that our model replicates Group 3 medulloblastoma, we performed Affymetrix mRNA expression profiling...
on our human cerebellar neural stem and progenitor cell models and two of our DNP53 hTERT AKT MYC tumor orthotopic xenografts. Specifically, we examined the expression of 32 pathways that have been previously associated with each of the six Cho subgroups (13). High expression of a specific subset of each of these 32 pathways is characteristic of each subgroup. We performed single-sample gene-set enrichment analysis (ssGSEA) on our model in culture and as xenografts to obtain an enrichment score for each of the medulloblastoma associated pathways. This analysis was also performed for the primary medulloblastoma tumor dataset of Tamayo and colleagues (13), allowing us to compare the profiles of our xenografts and cultured cells against human medulloblastoma tumors.

The pathway enrichment file of our cells and xenografts closely matches the profile of C1 primary tumors, the most aggressive subclass of patients within MYC-driven Group 3 (Fig. 3A; ref. 12). Samples from cells transduced with only MYC expressed the Group 3–associated mRNAs and corresponding pathway enrichment (Fig. 3B). The addition of DNP53, hTERT, and AKT to MYC increased the expression of these Group 3–associated pathways (Fig. 3B). The orthotopic xenografts of cells transduced with MYC, DNP53, hTERT, and AKT most highly expressed the Group 3–associated mRNAs (Fig. 3B).

We also generated an association matrix that compares the pathway enrichment scores of xenografts and cell models against each tumor subtype (Fig. 3C). The association is estimated using the IC, an information-theoretical counterpart to the correlation coefficient (see Materials and Methods). Primary cultures of untransduced cerebellar neural stem and progenitor cells associate most closely with the C6/WNT subgroup. The sequential addition of MYC, DNP53, hTERT, and AKT increases the association with the C1 subtype. Growth of these cells as orthotopic xenografts also increases their association with the C1 subgroup.

**Figure 3.** Human neural stem cell models of medulloblastoma have similar expression profiles to the aggressive C1 component of Group 3. Red indicates high expression and blue indicates low expression of the pathways labeled on the left A and B. A, C1 samples have high levels of the pathways indicated by the green box. Subtype-specific pathway expression profiles are separated by yellow lines. Patient expression from data from Cho et al., 2011 (12). B, a close-up of the human neural stem cell heat map indicates that increasing the number of oncogenes increases the expression of C1-associated pathways. The samples most highly expressing C1-associated pathways are from intracranial xenografts. C, an association metric compares the pathway enrichment subtypes (columns) to xenografts and cell models (rows). Metric is scored using IC with red indicating higher correlation.
xenograft tumors further increases the association with the subtype C1 (Fig. 3C).

Analysis of drug sensitivity databases with a profile created by analyzing the human neural stem cell model of Group 3 medulloblastoma reveals CDK inhibitors as a potential therapeutic modality

The human neural stem cell model of medulloblastoma was used as a test subject for a novel computational analysis technique, DiSCOVER, that we briefly describe here (additional details in Materials and Methods). We created a gene set called the ‘hNSC G3 signature’ of the 150 most upregulated genes in the murine xenografts of the human neural stem cell line transformed with DN p53, hTERT, constitutively active AKT and MYC (Supplementary Table S1). We then analyzed the gene expression datasets of two mRNA datasets (see Materials and Methods) using single-sample gene set enrichment analysis (ssGSEA). This analysis allowed us to obtain an hNSC G3 signature enrichment score for each sample in the two mRNA datasets. We then matched the signature enrichment scores against drug sensitivity profiles that have been generated for the same samples. In this way, we identified compounds that killed cells sharing a high hNSC G3 enrichment score. We performed this comparison against three different drug sensitivity datasets and looked for overlaps in the top scoring compounds or their compound varieties. A summary of the procedure is shown in Fig. 4A and the full workflow can be seen found in Supplementary Fig. S1.

In this analysis, we focused on the top scoring compounds with FDRs below 0.33 (see Supplementary Table S2 and Supplementary Fig. S2). The overlap analysis across datasets revealed that cancer cell lines that highly express the hNSC G3 signature are sensitive to the CDK inhibitors (Fig. 4B and Supplementary Fig. S2). These inhibitors include the pan-CDK inhibitor flavopiridol/alvocidib (PubChem CID: 5287969; ref. 46), CDK 1/2/5/7 inhibitor CGP-60474 that was developed as a PKC inhibitor (PubChem ID: 644215; ref. 47), CDK4 inhibitor CGP-082996 (PubChem CID: 24825971), and the CDK4/6 inhibitor PD-0332991/palbociclib (PubMed ID: 5330286; ref. 35). MYC expression is known to increase the expression of CDKs, so CDK inhibition is biologically congruent with the in silico screen (48).

The CDK4/6 inhibitor palbociclib decreases proliferation in the human neural stem cell model of medulloblastoma and patient-derived medulloblastoma cell lines

Of the CDK inhibitors identified by the DiSCOVER analysis, we decided to test palbociclib (PD-0223991) because of its clinical relevance. In addition to cerebellar neural stem cells transformed with MYC, DNp53, AKT and hTERT, we used cerebellar neural stem cells transformed with MYC alone and two patient-derived medulloblastoma lines (D425Med and D283Med) to test the effects of palbociclib on medulloblastoma. Inhibition of CDK4/6 activity prevents the phosphorylation of the retinoblastoma protein (Rb; ref. 35). Western blotting showed that 5 μmol/L palbociclib treatment led to a decrease in phosphorylation of Rb at two different phosphorylation sites (Ser780 and Ser807/811). Phosphorylation at S780 decreased by 96% in cells transformed with MYC alone, by 62% in cells transformed with all four oncogenes, by 24% in D425Med cells, and by 33% in D283Med cells. The phosphorylation at S807/811 decreased by 99% in MYC alone cells, 55% in cells transformed with all four oncogenes, by 33% in D425Med cells and by 43% in D283Med cells (Fig. 5A).
Palbociclib treatment caused a significant decrease in proliferation in all four medulloblastoma models, as determined by BrdUrd incorporation (Fig. 5B). Palbociclib treatment for 72 hours caused the percentage of BrdUrd-positive cells to drop from 32% to 12% in D425Med (P = 0.000004 by Student t test), from 40% to 21% in D283Med (P = 0.004 by Student t test), from 41% to 3% in cells transformed with MYC alone (P = 0.00000009 by Student t test), and from 30% to 13% in cells transformed with all four oncogenic elements (P = 0.02 by Student t test; Fig. 5B). In SV40 immortalized cells, palbociclib caused a nonsignificant decrease in BrdUrd incorporation—34% to 24% (P = 0.06 by Student t test; Fig. 5B). The pan-CDK inhibitor flavopiridol, which was also identified by DiSCoVER, also decreased proliferation in MYC-driven cell lines and MYC-transduced neural stem cells (Supplementary Fig. S3A).

Palbociclib induces apoptosis in human MYC-driven medulloblastoma cell lines

Treatment of our MYC-driven human models of medulloblastoma with 5 μmol/L of palbociclib for 72 hours caused the percentage of cleaved caspase-3-positive cells to increase from 6% to 21% in D425Med (P = 0.0005 Student t test), from 3% to 9% in D283Med (P = 0.011 Student t test), from 20% to 70% in cells immortalized with MYC alone (P = 0.0000004 Student t test) and from 21% to 45% in cells transformed with all four oncogenic elements (P = 0.000002 by Student t test; Fig. 5B). In SV40 immortalized cells, palbociclib caused a nonsignificant increase in the percentage of cleaved-caspase-3-positive cells—10% to 15% (P = 0.14 by Student t test; Fig. 5C). Treatment with 1 or 5 μmol/L of palbociclib for 24 hours caused an increase in the expression of cleaved-PARP (as measured by Western blotting), indicating increased levels of apoptosis (Fig. 5D). Similar to palbociclib, flavopiridol also caused an increase in apoptosis (Supplementary Fig. S3B).

Palbociclib significantly improves survival of mice with medulloblastoma orthotopic xenografts

We next tested the efficacy of palbociclib as a monotherapy in vivo. Palbociclib treatment has been shown to increase survival in a mouse model of brainstem glioma and glioblastoma (36, 37). Palbociclib treatment significantly extended survival of mice with D425Med intracranial xenografts by 48% from 25 to 37 days (P = 0.003 by log-rank test; Fig. 6A). To verify that palbociclib was
Discussion

Group 3 medulloblastoma is a highly lethal disease. Our human neural stem and progenitor cell model phenotypically, histologically, and genetically mimics the C1 component of Group 3, the most lethal subgroup of medulloblastoma (13). Although our model shares MYC activation and TP53 pathway inhibition with murine neural stem cell systems created by Pei and colleagues and Kawauchi and colleagues, the addition of activated AKT, which is a known driver of medulloblastoma metastasis and resistance to therapy as well as hTERT, which reflects the high frequency of TERT promoter mutations in medulloblastoma, adds a richness to our model (43, 49). The increasing fidelity of our human neural stem cells to Group 3 with the sequential addition of oncogenic elements as demonstrated in Fig. 3 highlights this point. Alterations in MYC and TP53 occur together in relapsed medulloblastoma of all subtypes (17), so our cells can also serve as a model of relapsed disease.

We here present a novel method for in silico prediction of drug sensitivity, which we believe may significantly accelerate the identification of novel therapeutics for rare cancer types. Our DiSCoVER approach differs from existing in silico methods such as Connectivity MAP (CMAP) in that DiSCoVER uses the actual drug response cell viability profiles (e.g., IC50 or AUC) of multiple drug screening datasets involving hundreds of cell lines treated with each drug, rather than the transcriptional changes, for example, as detected by 1,000 “landmark” genes induced by drug perturbations in a few selected cell lines as it is done in CMAP. The drug screening responses are more accurate at representing the effect of a drug in terms of affecting cell viability and not only transcriptional changes that may, or may not, impinge on cell viability.

CMAP matches the gene set representing the disease signature against transcriptional profiles of drug perturbations in a few cell lines using the Kolmogorov–Smirnov enrichment statistic. This is a useful approach in general, but sometimes it does not easily allow the detection of more subtle disease versus drug associations in a broader context involving a large number and diversity of cellular states. In DiSCoVER, we first produced an enrichment score for the disease signature in each cell line (using single-sample GSEA); and then we match the pattern of these scores across hundreds of cell lines, against the drug sensitivity profiles for the same cell lines, using an information-theoretic metric of association. This approach provides a high degree of sensitivity and specificity in finding drug responses that match the disease signature, even when the relationship, (i) is restricted to a few cell lines representing a relevant but narrowly represented biologic state, (ii) when this relationship is not strictly linear or, (iii) when it is very weak. DiSCoVER also repeats the analysis in multiple external datasets and then compares the results across them, for example, considering drug classes, and not only individual instances as occurs in CMAP.

One identified therapeutic target in our in silico preclinical drug screen was CDKs. MYC plays a significant role in regulating the cell cycle through variety of mechanisms (50). CDKs, cyclins and E2F transcription factors are all directly regulated by MYC (50). MYC-driven murine lymphoma and hepatoblastoma are sensitive to CDK1/2 inhibition, further highlighting CDKs as a potential Achilles’ heel in MYC-driven malignancies (51, 52). Other groups have demonstrated the use of CDK inhibitors in treating brain tumors (36, 37). Faria and colleagues (53) showed the efficacy of

causing this effect by inhibiting CDK function, we performed IHC for phospho-Rb on tumors from animals that were given a single dose of vehicle or palbociclib 4 hours before euthanasia. Tumors from mice given palbociclib had a significantly lower percentage of phospho-Rb–positive cells compared with mice given the vehicle control (38% vs. 54%, P = 0.00025 by Student t test), indicating that the drug crosses the blood brain barrier and penetrates the tumor (Fig. 6B). Images of two tumors from mice given vehicle are in Fig. 6C, left. Images of two tumors from mice given palbociclib are in Fig. 6C, right.

Figure 6.

A, Palbociclib treatment (50 mg/kg 5x per week) significantly increases survival of mice with D425Med orthotopic xenografts. * P = 0.003 by log-rank Test. B, one 150 mg/kg dose of palbociclib deceased the percentage of phospho-Rb–positive cells in D425Med xenografts from 53% to 38% (* P = 0.00025 by Student t test). Mice were euthanized 4 hours after dosing. C, IHC for phospho-Rb. Left column shows tumors from two separate animals treated with vehicle. Right column shows tumors from two separate animals treated with a single dose of 150 mg/kg 4 hours before euthanasia; magnification, ×400.
an investigational CDK1/5/GSK3b inhibitor, alsterpaullone, in MYC-driven medulloblastoma cell lines, though much of the tumor suppressing effect was demonstrated to be mediated through mTOR inhibition. Palbociclib is a CDK4/6 inhibitor approved for treatment of advanced estrogen receptor–positive breast cancers (54). Palbociclib decreased the growth of high-serum medulloblastoma cell lines in vitro (55). We chose an in vitro dose of palbociclib consistent with that given in other preclinical models (35–38). A phase I clinical trial of palbociclib in pediatric brain tumor patients is currently ongoing (NCT02255461), and the MTD has yet to be reported.

Methotrexate and cytarabine were among other top hits revealed by the DiSCoVER analysis (Supplementary Table S2). These drugs are currently in use in medulloblastoma treatment and are structurally similar to pentamethox and gemcitabine, which were recently identified as being active in medulloblastoma xenografts (56). The identification of biologically plausible targets and compounds that are being explored by other scientists validates our in silico strategy of using the hNSC G3 signature to probe available datasets of drug sensitivity data.

Identification of increased apoptosis downstream of palbociclib in our cell lines and neural stem cell models differs from the standard response to CDK inhibitors, which are largely viewed as cytostatic agents in other cancer types (38, 57–60). However, in combination with cytarabine, dexamethasone, and bortezomib, palbociclib enhances cytotoxicity (38, 59, 60). In our model, palbociclib induces apoptosis as a monotherapy, so it is possible that we will see synergy and enhanced cell killing when it is used in combination with other cytotoxic agents commonly used to treat MYC-driven medulloblastoma.

In conclusion, we present a novel strategy for creating new models of tumors and for preclinical screening of drug targets. We created a human neural stem cell model of Group 3 medulloblastoma and used this model to screen drug sensitivity databases and validate an identified target. Palbociclib may be an effective treatment for poor prognosis medulloblastoma in carefully selected patients. Our overall strategy of using tissue-specific human stem and progenitor cells may be useful for developing models of other tumor types.

References

Disclosure of Potential Conflicts of Interest
J Maciacyczk reports receiving speakers bureau honoraria from Boston Scientific. P. Clemons is a consultant/advisory board member for FORMA Therapeutics. No potential conflicts of interest were disclosed by the other authors.

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DiSCoVERing Innovative Therapies for Rare Tumors: Combining Genetically Accurate Disease Models with In Silico Analysis to Identify Novel Therapeutic Targets


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