Understanding pRb: toward the necessary development of targeted treatments for retinoblastoma

Uma M. Sachdeva, Joan M. O'Brien


Retinoblastoma is a pediatric retinal tumor initiated by biallelic inactivation of the retinoblastoma gene \(RB1\). \(RB1\) was the first identified tumor suppressor gene and has defined roles in the regulation of cell cycle progression, DNA replication, and terminal differentiation. However, despite the abundance of work demonstrating the molecular function and identifying binding partners of pRb, the challenge facing molecular biologists and clinical oncologists is how to integrate this vast body of molecular knowledge into the development of targeted therapies for treatment of retinoblastoma. We propose that a more thorough genetic understanding of retinoblastoma would inform targeted treatment decisions and could improve outcomes and quality of life in children affected by this disease.
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Retinoblastoma is a pediatric retinal tumor initiated by biallelic inactivation of the retinoblastoma gene (RB1). RB1 was the first identified tumor suppressor gene and has defined roles in the regulation of cell cycle progression, DNA replication, and terminal differentiation. However, despite the abundance of work demonstrating the molecular function and identifying binding partners of pRb, the challenge facing molecular biologists and clinical oncologists is how to integrate this vast body of molecular knowledge into the development of targeted therapies for treatment of retinoblastoma. We propose that a more thorough genetic understanding of retinoblastoma would inform targeted treatment decisions and could improve outcomes and quality of life in children affected by this disease.

RB1 mutations in retinoblastoma

RB results from biallelic inactivation or loss of the retinoblastoma 1 gene (RB1), located on the long arm of chromosome 13 (13q14.2). Roughly 40% of RB cases are heritable, with RB1 mutations occurring in the germline and present in all somatic cells, while 60% of RB cases are non-heritable, with mutations arising locally within the developing retina (15). Despite requiring loss of both RB1 alleles, the genetics of heritable RB demonstrate autosomal dominance, as almost all children who possess one mutated germline copy of RB1 develop the disease. In heritable cases, the initial mutated RB1 allele may be known to be present within the family (familial RB, 25% of heritable cases) or it may have occurred de novo in the parental gametes (sporadic heritable RB, 75% of heritable cases) (15). In both cases, mutation of the second allele occurs within the developing retina, resulting in the development of intraocular tumors. In sporadic, non-heritable RB, which comprises the majority of RB cases, both RB1 mutations occur locally within the affected retina. For this reason, most sporadic non-heritable cases are unilateral, while all bilateral cases have been found to result from heritable germline mutations (15). It remains unknown why the retina is so susceptible to mutation at the RB1 locus, and an enhanced understanding of why loss of heterozygosity frequently occurs at this locus would improve efforts to both treat and prevent this devastating disease.

The disease burden of patients affected with RB correlates with the mode of inheritance of their mutation. In familial RB, carriers of a null RB1 allele develop bilateral, multifocal tumors with very high penetrance (90%–100%), while carriers of uncommon partial function mutations more frequently develop “low-penetration retinoblastoma,” a less severe form of the disease characterized by unilateral involvement, benign retinoma, and decreased penetrance (16). Roughly 10% of children with heritable forms of RB also develop primary midline intracranial neoplasms, most commonly primitive neuroectodermal tumors, a condition referred to as “trilateral retinoblastoma” (17). Patients with heritable RB1 mutations also have an elevated lifetime risk for developing second primary malignancies, including osteogenic and soft tissue sarcomas, melanomas, and lung and bladder cancers (14, 17–19). These tumors collectively constitute the RB1 cancer syndrome. Further-
more, the predisposition toward secondary tumor development is significantly increased by the radiation therapy used to treat more advanced primary presentations of RB (14).

Since its discovery, pRb, the protein product of \textit{RB1}, has become one of the most studied proteins of all time. pRb plays critical roles in regulating multiple pathways that affect oncogenesis (Figure 1), including cell proliferation, death, and differentiation, through regulation of the cell cycle, apoptosis, senescence, and genome maintenance (20). pRb affects these pathways primarily through direct and indirect suppression of gene and protein expression.

Despite the tremendous progress in determining the cellular function and genetic inheritance patterns of mutations in \textit{RB1}, major questions regarding our understanding of RB as a disease remain, including the function of specific \textit{RB1} mutations and the potential for tailoring treatments to specific gene and protein defects. Furthermore, despite extensive research, the RB cell of origin remains a subject of continued debate, slowing the development of targeted approaches. This review highlights advances in our understanding of the molecular function of pRb, including its role in the development and progression of RB, as well as the major areas in RB research that remain to be explored, toward the necessary development of more targeted approaches for RB treatment. These targeted approaches should be more effective and less toxic when the myriad functions of pRb are fully elucidated and considered.

\textbf{pRb function in cell cycle arrest}

pRb is a transcriptional cofactor and adaptor protein that functions primarily as a regulator of gene expression, influencing...

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\textbf{Table 1}

\textbf{International classification system for retinoblastoma}

<table>
<thead>
<tr>
<th>Group</th>
<th>Clinical characteristics</th>
<th>Treatment (toxicities)</th>
<th>Prognosis</th>
</tr>
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<tbody>
<tr>
<td>A: Small</td>
<td>(\leq 3) mm height; (\geq 2) disc diameters from fovea; (\geq 1) disc diameter from optic nerve</td>
<td>Argon-YAG laser (vitreous seeding if power too high)A, Diode laser--induced hyperthermia (tissue damage, vitreous seeding)A, Cryotherapy (retinal tears, chorioretinal atrophy)A, Brachytherapy (radiation retinotherapy)A</td>
<td>Good visual and overall prognosis; usually eradicated</td>
</tr>
<tr>
<td>B: Medium</td>
<td>(&gt;3) mm height; clear subretinal fluid (&lt;3) mm from tumor margin</td>
<td>Vincristine + low-dose carboplatin, up to 6 cycles (neurotoxicity, hyponatremia, nephrotoxicity, ototoxicity)</td>
<td>Good visual prognosis</td>
</tr>
<tr>
<td>C: Confined, medium</td>
<td>Localized vitreous seeding or subretinal seeding or both</td>
<td>Vincristine + high-dose carboplatin + etoposide + G-CSF, up to 6 cycles (neurotoxicity, hyponatremia, nephrotoxicity, ototoxicity, secondary leukemias)</td>
<td>Visual prognosis variable</td>
</tr>
<tr>
<td>D: Diffuse, large</td>
<td>Diffuse vitreous seeding or diffuse subretinal seeding or both; subretinal fluid (&gt;3) mm from tumor margin</td>
<td>Vincristine + high-dose carboplatin + etoposide + G-CSF, up to 6 cycles (neurotoxicity, hyponatremia, nephrotoxicity, ototoxicity, secondary leukemias)</td>
<td>Variable visual prognosis; high morbidity from treatment</td>
</tr>
<tr>
<td>E: Enucleation, advanced</td>
<td>No visual potential or tumor in anterior segment/ciliary body or neovascular glaucoma or vitreous hemorrhage or phthisical eye or orbital cellulitis-like appearance or involvement of optic nerve or extraocular disease present</td>
<td>Enucleation; prophylactic 3-agent chemotherapy if high-risk features for disease dissemination observed on consensus pathologic evaluation (neurotoxicity, hyponatremia, nephrotoxicity, ototoxicity, secondary leukemias)</td>
<td>High morbidity from treatment; no visual potential</td>
</tr>
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\footnote{Focal therapies. Clinical characteristics associated with classification groups, current treatment strategies, and toxicities of current systemic chemotherapeutic approaches are shown.}
multiple cell processes required for embryonic growth and development. These processes include cell proliferation, senescence, apoptosis, differentiation, and chromatin remodeling (20). pRb is required for terminal differentiation of myocytes through transcriptional synergy with MyoD, and promotes its functional interaction with the coactivator myocyte enhancer factor 2 (MEF2) (21). pRb also binds directly to histone deacetylase 1 (HDAC1) and prevents it from associating with MyoD, indirectly promoting the expression of MyoD transcriptional targets by preventing their deacetylation (21). pRb also plays important roles in the fate determination, differentiation, survival, and migration of developing neurons (22, 23).

pRb and its related proteins p107 and p130 comprise the family of “pocket” proteins, categorized according to their structural and functional similarities, including the presence of a large pocket domain, which serves as the binding site for many of their interacting proteins. The large pocket of pRb is the site of the majority of naturally occurring mutations in RB1 and contains distinct sequences required for the binding of two critical mediators of pRb-induced cell cycle arrest, E2F and Skp2 (24–26). While pRb is the predominant pocket protein expressed in murine proliferating postnatal retinal progenitor cells, p107 is upregulated in response to loss of pRb in mice and can at least partially compensate for absence of this protein (27). This compensation has not been observed in humans, which may partially explain why RB is a uniquely human disease.

E2F transcription factors regulate the expression of multiple genes involved in the progression through G1 and S phases of the cell cycle, in DNA metabolism, and in cell proliferation. pRb binds to DNA-bound E2Fs and inhibits their effects on gene expression by preventing the binding of transcriptional co-activators, and through recruitment of HDACs, ATPas, and DNA methyltransferases to the promoters of target genes (ref. 28 and Figure 2). pRb specifically binds E2F1, -2, and -3 family members (28, 29). E2F1–E2F3 are transcriptional activators and have been found to play an oncogenic role in multiple human cancers, with increased expression levels observed in hepatocellular carcinoma, bladder cancer, glioblastoma, liposarcoma, and breast and ovarian tumors, in addition to RB (30). During the initial stages of G1, as well as in quiescent or growth-inhibited cells, pocket proteins bind E2F family members to inhibit their transcriptional effects, which would otherwise promote cell cycle progression. The cell cycle regulators under the control of E2F transcription factors include cyclins A and E, Cdc2, Cdc25C, and p21 (ref. 28 and Figure 2).

The F-box protein Skp2 also plays an important role in cell cycle progression, regulating the transition to S phase, as well as cellular senescence, through interaction with the cell cycle inhibitory protein p27. When activated, p27 blocks cell cycle progression through the G1–S transition by inhibiting the checkpoint cyclin-dependent kinase cyclin E–CDK2 (31–33). The cyclin E–CDK2 complex functions to inhibit pRb activity by phosphorylating pRb and preventing its association with E2F transcriptional activators (ref. 34 and Figure 3A). In the presence of growth-promoting signals, Skp2 binds p27, resulting in p27 degradation. In the absence of proliferative signals, pRb binds Skp2, resulting in Skp2 degradation, subsequent p27 accumulation, and G1 arrest (Figure 3B). The mechanism underlying pRb/Skp2/p27-mediated G1 arrest is independent of the pRb–E2F interaction (26), indicating that pRb exerts its antiproliferative, tumor-suppressive, and both pro- (35) and antiapoptotic (36, 37) activities through multiple parallel, though intersecting, pathways. A functional separation between the pRb/Skp2/p27 and pRb/E2F pathways in vivo is demonstrated by the presence of RB1 mutations that inhibit one of these pathways, but leave the other pathway intact.

Figure 1
Cellular functions of pRb. pRb is required for regulation of multiple critical cellular processes, including proliferation, differentiation, maintenance of genome integrity, quiescence, and senescence (47, 123).

Figure 2
Regulation of E2F-dependent gene expression by pRb. pRb binds to DNA-bound E2F transcriptional regulators and suppresses their target gene expression through recruitment of HDACs, co-repressors, and chromatin remodeling enzymes. It also serves to inhibit the binding of co-activating transcription factors to E2F-bound promoters. Genes regulated by pRb–E2F include regulators of cell cycle progression at the G1/S transition, enzymes required for DNA synthesis, proto-oncogenes, apoptosis regulators, and modifiers of pRb/E2F pathway activity (47, 57, 124, 125).
The RbR661W mutation is a naturally occurring partially penetrant mutation of RB1 that blocks the pRb/E2F pathway, but maintains the pRb/Skp2/p27 pathway (26). Patients harboring the R661W mutation either have unilateral disease or are unaffected carriers (38), which suggests that molecular genetic analysis of all patients with heritable RB1 mutations may inform treatment decisions, based on the severity of disease and penetrance associated with specific RB1 mutations.

In addition to E2F and Skp2 binding sites, the A/B pocket of pRb contains a separate binding domain, the LXCXE binding cleft (Figure 4), by which the pRb protein binds to partners that also share an LXCXE binding motif. These include several chromatin remodeling factors that participate in transcriptional repression of E2F target genes, including HDAC1, as well as Cdh1, the partner of APC (20, 39–41). The LXCXE binding cleft is highly evolutionarily conserved and is the target of multiple viral oncoproteins that inactivate pRb to induce tumorigenesis (42, 43). The discovery of models of RB, in which expression of viral transgenes was targeted be required to suppress the development of hepatocellular carcinoma following genotoxic stress in mice and to modulate the LXCXE motif does seem to play an important role in regulating the R661W mutation either have unilateral disease or are unaffected carriers (38), which suggests that molecular genetic analysis of all patients with heritable RB1 mutations may inform treatment decisions, based on the severity of disease and penetrance associated with specific RB1 mutations.

Despite its evolutionary conservation and its function as the binding site for multiple viral oncoproteins, the LXCXE motif of pRb does not appear to serve a critical tumor-suppressive function. Disease-causing mutations in this motif are exceedingly rare and have only been observed in one human cancer cell line (44, 45). Mice genetically engineered to lack this domain are viable and do not develop tumors (46). Interestingly, however, the LXCXE motif does seem to play an important role in regulating the cellular response to toxic exposures, including ionizing radiation and chemotherapeutic agents. This motif has been found to be required to suppress the development of hepatocellular carcinoma following genotoxic stress in mice and to modulate the sensitivity of cultured cells to cisplatin (47). Of note, loss of pRb has also been shown to increase mouse fibroblast sensitivity to etoposide and mitomycin C (48) and increase the sensitivity of human breast cancer cells to multiple chemotherapeutic agents, including 5-fluorouracil (5-FU), methotrexate, cisplatin, as well as ionizing radiation (49, 50).

Roughly 90% of pRb mutations resulting in hereditary RB are null alleles (16, 51), suggesting that multiple functional domains of pRb contribute to tumor suppression and that tumorigenesis may result from a diversity of mutations that function to globally inactivate pRb (52). Some partially inactivating pRb mutations do occur that confer a lower risk for RB and have provided clues to the discrete tumor-suppressive functions of pRb (16, 53). Mutant forms of RB1, such as the aforementioned RbR661W, have been isolated from patients with low-penetrance RB; these mutant proteins have lost the ability to bind E2Fs, but retain their ability to induce differentiation (54, 55). This finding suggests that different regions of the protein are responsible for regulating the diverse cellular functions of pRb and that the nature of the RB1 gene mutation may dictate disease severity. The elucidation of more precise relationships between specific genetic mutations in RB1 and the severity of disease phenotypes would therefore pave the way for the development of more targeted patient-specific therapies for RB.

### Regulation of pRb activity

The activity of pRb is regulated through control of its phosphorylation state, which is modulated throughout the proliferating cell cycle (56–60). During G1, and in quiescent cells that have exited the cell cycle, pRb is hypophosphorylated and able to bind E2F and other targets to function as an inhibitor of cell proliferation. In response to proliferative growth signals, pRb is successively phosphorylated by cyclin-dependent kinases (Figures 4 and 5), resulting in its inability to complex effectively with E2Fs (61). pRb is thus released from the promoters of E2F target genes, allowing binding of transactivators and expression of target genes that promote cell cycle progression into S phase (Figure 5). Among the E2F target genes transcribed following pRb phosphorylation is Skp2 (62), so that both the E2F- and Skp2-dependent pathways are activated to promote cell cycle progression. The pRb protein contains 16 potential CDK phosphorylation sites (ref. 63 and Figure 4), although not all of these have been found to be phosphorylated in vivo.

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**Figure 3**
The Skp2/p27/pRb pathway in the regulation of cell cycle progression. (A) In response to proliferative signals, cellular levels of Skp2 increase, resulting in Skp2 binding to p27 and targeting it for degradation. This degradation of p27 relieves p27-mediated inhibition of the cyclin E–CDK2 complex during late G1, allowing for phosphorylation and inactivation of pRb and promoting G1 progression to S phase. (B) In the absence of proliferative signals, pRb is hypophosphorylated and binds to Skp2, preventing it from binding to p27. Skp2 is then complexed with APC/C \(^{CIN}\) and is targeted for proteosomal degradation. Free p27 is then able to bind cyclin E–CDK2 and inhibit its activity, resulting in continued pRb activity and G1 cell cycle arrest.
Dephosphorylation and activation of pRb is controlled by phosphatases and cyclin-dependent kinase inhibitors (CDKIs) of the Ink4 (p15, p16, p18, and p19) and Cip/Kip (p21, p27, and p57) families (64). CDKIs respond to diverse antiproliferative signals, including DNA damage, senescence, and differentiation signals. Collectively, Ink4 and Cip/Kip CDKIs positively regulate pRb by inhibiting its negative regulators, the activated cyclin-CDK complexes (Figure 5). Inactivation of cyclin-CDKs by CDKIs therefore results in cell cycle arrest in a pRb-dependent manner. Interestingly, despite this highly regulated cycle of phosphorylation, few mutations have been identified that affect pRb phosphorylation, as most highly penetrant mutations result in null alleles (52).

**Addition roles for pRb in cell cycle regulation**

pRb may also play a role in protecting against the development of chromosomal rearrangements through several distinct mechanisms. Inactivation of pRb results in deregulated expression of the E2F target gene MAD2, encoding a mitotic spindle checkpoint protein (65). This results in mitotic defects and aneuploidy in vitro (66), and Mad2 overexpression has been found to promote aneuploidy and tumorigenesis in transgenic mice (67). Interestingly, Mad2 is also overexpressed in many tumors, including RB (65), suggesting that this mechanism could contribute to the pathogenesis of the disease.

pRb also ensures chromosomal integrity by directing heterochromatin formation through interactions with two LXCXE-containing histone methyltransferases, Suv4-20h1 and Suv4-2 (68). Disruption of these interactions can result in slowed progression through mitosis and centromere fusion, chromosomal missegregation, and genomic instability (46). pRb regulates chromatin condensation, cohesion, and stability by promoting the centromeric localization of the CAP-D3/condensin II protein complex, an interaction that is evolutionarily conserved (66, 69). These findings suggest that additional mechanisms may underlie the development of RB, including loss of the regulatory interactions between pRb and effectors of normal chromosomal segregation during mitosis. Aneuploidy of chromosomal arms 6p and 1q has been observed in heritable RB tumor samples (70) and has led to the identification of additional genes that might contribute to RB development and progression, as discussed below.

**Mouse models of retinoblastoma**

Despite the difficulty in generating accurate murine models of RB, much has been learned about the additional pathways required for the development of retinal tumors in animal models. The first heritable model of RB came from a transgenic system in which the SV40 T antigen was expressed under the control of a human leuteinizing hormone beta subunit promoter (LHβ-T-Ag).
Surprisingly, these mice develop retinal tumors at one to two months of age that are bilateral and multifocal, closely resembling heritable RB (71). The progression of disease displayed by these mice also closely reflected the natural history of human RB, with tumor spreading to invade the choroid, vitreous, optic nerve, and central nervous system. While strong expression of the LHβ promoter in the retina was unexpected, other transgenic models were developed using retina-specific promoters, including those of the interphotoreceptor retinoid-binding protein (IRBP), opsin, and alpha-A-crystallin genes, which demonstrated varying degrees of disease severity and fidelity to human disease phenotypes (refs. 72–75 and reviewed in ref. 76).

From these models came the critical finding that the p53 tumor suppressor pathway plays an important role in the development of murine RB and may play a significant role in human disease pathogenesis. Expression of the E7 oncoprotein by the IRBP promoter results in inactivation of pRb in developing photoreceptors, yet retinal tumors are observed only in mice also lacking p53 (77, 78). Animals expressing wild-type p53 display photoreceptor apoptosis during terminal differentiation, resulting in decreased differentiation and degeneration of the developing retina. While IRBP-E7 p53-null mice also display some photoreceptor apoptosis, this apoptosis is p53 independent, with proliferative foci emerging from the degenerating retina (77).

The critical role of p53 loss has been further supported by mouse models of genetic Rb1 deficiency. Similar to p53 wild-type IRBP-E7 mice, mice genetically lacking Rb1 displayed decreased retinal differentiation and increased retinal apoptosis (79, 80). It is not clear to what extent these ocular phenotypes might be attributable to an extra-embryonic function of pRb, as was demonstrated for other neurologic and hematopoietic phenotypes observed in these embryos (81). Nevertheless, embryos genetically lacking Rb1 displayed apoptosis of multiple retinal cell types, including ganglion cells, bipolar cells, and photoreceptors. In contrast to this primarily apoptotic phenotype, chimeric mice lacking both pRb and p107 display retinal tumors that express markers of amacrine cell differentiation, in addition to accelerated retinal degeneration (82). In these mice, photoreceptors committed to differentiation undergo apoptosis, while early retinal precursors form proliferative foci, resulting in a mixed phenotype of aberrant apoptosis and aberrant proliferation. In these pRb/p107-deficient chimeric mice, loss of p53 accelerates tumor formation. These results suggest both that p107 is able to compensate for loss of pRb in mice and that loss of p53 accelerates tumor formation but is not absolutely required for retinal tumor development.

It is possible that in this model, mice genetically wild-type for p53 undergo functional inactivation of the p53 pathway in the process of developing retinal tumors. In fact, genetic mutations in P53 have never been observed in RBs isolated from human patients. Rather, human tumor samples display mutations in regulators of p53 (83), suggesting functional, rather than genetic, loss of this surveillance pathway. Additionally, nuclear exclusion of p53, resulting in abnormal cytoplasmic staining, has been reported in more invasive portions of RB tumors and in RB cell lines (84). The molecular function of p53 in suppressing retinal tumor development is also still unclear. Inhibition of apoptosis is not observed in the developing retinas of pRb/p107 chimeric mice lacking p53, suggesting that the mechanism underlyling accelerated tumor formation is not loss of p53-mediated apoptosis (82). In this system, loss of p53 may accelerate tumor formation through enhanced mutagen-
The role of p53-mediated apoptosis following pRb loss. Loss of pRb through genetic mutation results in activation of E2F transcription factors. Deregulated E2Fs can promote cell proliferation through transcription of cell cycle and DNA synthesis genes, but can also induce apoptosis through upregulation of ARF and p53 activity. This control mechanism is lost in the absence of p53. While loss of p53 is rare in RB tumors, amplification of the p53 inhibitors Mdm2 or MdmX (blue) can result in decreased p53 activity, thus inhibiting apoptosis and promoting cell proliferation. Inhibitors of Mdm2 and MdmX, such as nutlin-3 (red), can restore p53 activity to RB tumor cells by preventing association of Mdm2 and MdmX with p53, thus promoting p53-mediated apoptosis. Topotecan (green), another targeted therapy, functions by inhibiting topoisomerase I and creating DNA double-strand breaks, which triggers apoptosis through both p53-dependent and p53-independent pathways (128). Through alternative pathways, deregulated E2F activity resulting from pRb loss can also result in p53-independent apoptosis, as well as escape from senescence and de-differentiation.

Associated chromosomal alterations in RB

RB is associated with a discrete set of chromosomal alterations that are frequently seen in combination with mutations of the RB1 locus. These alterations include +1q, +6p, and −16q, and these chromosomal regions may harbor genes that are critical for RB pathogenesis (95). MdmX, a protein related to Mdm2 that also functions to inhibit p53 (Figure 6), is located in a region of amplification at 1q32, making it a promising candidate as a contributor to RB development. MDMX and MDM2 are both candidate oncogenes for RB development, as the gain or amplification of these genes has been reported in 65% and 10% of RB cases, respectively (83). Amplification of these genes would be expected to functionally inactivate the p53 pathway and may explain the lack of genetic alterations observed at the p53 locus in human RB. However, some reports have demonstrated a lack of correlation between genomic amplification of MdmX and levels of its expressed mRNA (96). Nevertheless, amplification of MdmX has been shown to suppress p53-mediated cell death in retinoblasts lacking RB1 and to promote their clonal cell proliferation (83). KIF14, a putative oncogene and regulator of mitosis, is another candidate gene located in the amplified region of chromosome 1 (97, 98). The expression of KIF14 is higher than that of MDMX in retinoma and RB samples, and expression of this gene is more frequently elevated (99). Nevertheless, complete understanding of the contribution of either of these proteins to disease development and progression requires further study.

Additional candidate genes identified by chromosomal analysis include those encoding the transcription factor E2F3 and the chromatin remodeling factor and histone chaperone protein DEK (98), both of which are located on the amplified region of chromosome 6p. DEK has been identified as a proto-oncogene in multiple malignancies and may be associated with apoptosis inhibition (100–102). Its overexpression is associated with de-differentiation and proliferation (103), in addition to repair of DNA double-strand breaks (104) and inhibition of cellular senescence (101, 105). Other genes proposed as candidates for the progression of RB include the adhesion factor cadherin-11, P130, and MYCN (95). The precise roles of these genes in retinoblastoma pathogenesis remain unknown.

New treatments based on molecular pathway analysis

Improved understanding of the molecular pathways intersecting with pRb has led to the development of new therapies to better target RB and other tumors harboring RB1 mutations. Nutlin-3 is a small molecule inhibitor of Mdm2 that also binds MdmX and prevents the association of both of these proteins with p53 (ref. 83 and Figure 6). Treatment with nutlin-3 restores the p53 pathway in RB cells that lack both pRb and p53 activity. The ability of nutlin-3 to inhibit the MdmX-p53 interaction is independent of its inhibition of Mdm2-p53 (83). When used in combination with the p53 inducer topotecan (Figure 6), nutlin-3 functions synergistically to kill RB cells in vitro and results in an 82-fold reduction in tumor burden following subconjunctival injection in mouse models (83, 106). The combination of nutlin-3 and topotecan does not produce any noted side effects in animal models, in contrast to systemic chemotherapeutic regimens. Nutlin-3 is currently in phase I clinical trials for the treatment of RB, with results eagerly anticipated.

Another class of targeted therapies currently in phase I clinical trials for RB are the HDAC inhibitors (HDACi). Cells with elevated E2F1 activity have been found to be uniquely sensitive to HDACi
through overexpression of proapoptotic factors (107). Cells lacking pRb have increased E2F1 activity, and RB-derived cell lines have demonstrated particular sensitivity to HDACi-induced apoptosis (108). In preclinical trials, HDACi inhibited growth of RB-derived tumors in both transgenic and xenograft murine models of RB, with minimal off-target effects (108), suggesting that HDACi may specifically inhibit the proliferation of RB tumor cells and thus have lower systemic toxicities relative to currently used chemotherapeutic agents.

An additional approach would be to target the initial precursor cell from which the tumor derives. The cell of origin of RB, however, remains quite controversial. There is some evidence that RB tumors express markers specific to cone precursor cells, including RXRγ and TRβ2, and the long and medium wavelength (L/M) opsins (109). Furthermore, it has been reported that both cone precursors and RB cells express high levels of Mdm2 and N-Myc, which are required for their proliferation, and that the cone-specific RXRγ induces Mdm2 expression in RB cells in vitro (109), which fits well with data describing loss of the p53 pathway in RB pathogenesis, as discussed above. However, while MDM2 expression has been observed in RB tumor samples, overexpression of this gene relative to normal retina has not been frequently observed (110). Alternatively, some data suggest that the p53 pathway may be inhibited in RB through precurors through overexpression of activating E2F transcription factors, which decrease p53 activity by promoting p53 deacetylation (111). Therefore, while RB tumor cells have some resemblance to cone cells, definitive evidence that cone-specific genes contribute to tumor development is still lacking. The presence of a cone precursor to RB tumors might suggest that these tumors would be more concentrated in the fovea, the portion of the retina with highest cone density; in contrast, patients who present with unilateral disease is known to harbor a germline mutation, this would argue against enucleation as a primary treatment, because bilateral disease will almost inevitably develop in the future, so systemic chemotherapy would be favored. In contrast, patients who present with unilateral disease and no underlying germline mutation do not have the risk for RB development in the second eye. These infants can therefore be spared the toxicity of chemotherapy or radiation therapy by undergoing enucleation of the involved eye.

Conclusions
Since the discovery of RB1, there have been profound advances in our understanding of the genetic and molecular dysfunctions underlying the development of RB. Although the role of pRb in inducing cell cycle arrest and its involvement in regulating cell proliferation, genome integrity, and apoptosis have been extensively studied, the research has led to surprisingly few new targeted therapies for this disease. Similarly, identification of additional discrete genetic lesions associated with loss of RB1 has not been translated into targeted treatment approaches. We propose that with the development of high-throughput sequencing methods, widespread genetic analysis of RB1 mutations may provide valuable information regarding disease severity, molecular pathophysiology, and treatment responses for patients with RB. Through this combination of molecular and genetic approaches, the development of more targeted, less toxic approaches to treatment should be achievable for this devastating childhood disease.

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