Lamin A/C Binding Protein LAP2α Is Required for Nuclear Anchorage of Retinoblastoma Protein

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Submitted February 27, 2002; Revised July 31, 2002; Accepted August 29, 2002

Monitoring Editor: Jennifer Lippincott-Schwartz

The phosphorylation-dependent anchorage of retinoblastoma protein Rb in the nucleus is essential for its function. We show that its pocket C domain is both necessary and sufficient for nuclear anchorage by transiently expressing green fluorescent protein (GFP) chimeras of Rb fragments in tissue culture cells and by extracting the cells with hypotonic solutions. Solid phase binding assays using glutathione S-transferase-fusion of Rb pockets A, B, and C revealed a direct association of lamin C exclusively to pocket C. Lamina-associated polypeptide (LAP) 2α, a binding partner of lamins A/C, bound strongly to pocket C and weakly to pocket B. When LAP2α was immunoprecipitated from soluble nuclear fractions, lamins A/C and hypophosphorylated Rb were coprecipitated efficiently. Similarly, immunoprecipitation of expressed GFP-Rb fragments by using anti-GFP antibodies coprecipitated LAP2α, provided that pocket C was present in the GFP chimeras. On redistribution of endogenous lamin A/C and LAP2α into nuclear aggregates by overexpressing dominant negative lamin mutants in tissue culture cells, Rb was also sequestered into these aggregates. In primary skin fibroblasts, LAP2α is expressed in a growth-dependent manner. Anchorage of hypophosphorylated Rb in the nucleus was weakened significantly in the absence of LAP2α. Together, these data suggest that hypophosphorylated Rb is anchored in the nucleus by the interaction of pocket C with LAP2α–lamin A/C complexes.

INTRODUCTION

Vertebrate nuclei are highly organized structures in which chromosomes occupy discrete territories (Croft et al., 1999), and activities such as DNA replication, transcription, and RNA processing occur within discrete nuclear bodies (Lamond and Earnshaw, 1998). This level of organization implies that architectural proteins link chromatin to the nuclear envelope (NE) or to a nucleoskeleton, and similar proteins also anchor regulators of transcription and DNA replication to nuclear bodies. The recent description of human genetic diseases that arise as a result of mutations in nuclear architectural proteins (Hutchison et al., 2001; Wilson, 2000) highlights the importance of the structure of the nucleus in relation to its function.

The major structural framework in the nucleus is the nuclear lamina, which determines both the size and shape of the nucleus and its mechanical stability (reviewed by Moor and Goldman, 1995; Vaughan et al., 2000). The major components of the lamina are the nuclear lamins, which are members of the intermediate filament family, and lamina-associated polypeptides (LAPs). Lamins have reported functions in DNA replication (Meier et al., 1991; Jenkins et al., 1993; Ellis et al., 1997; Spann et al., 1997; Moir et al., 2000) and nuclear pore organization (Lenz-Bohme et al., 1997; Liu et al., 2000; Smythe et al., 2000). In addition, one member of the LAP family, LAP2β, has also been reported to influence NE growth (Yang et al., 1997) and DNA replication (Gant et al., 1999). A second member of the LAP family, emerin, when mutated gives rise to Emery-Dreifuss muscular dystrophy, implying that it also has important functions, possibly in tissue-specific transcription regulation (reviewed by Morris and Manilal, 1999; Cohen et al., 2001).

A recently described member of the LAP family is LAP2α. The LAP2 protein originally described in rat nuclear envelopes (Foissner and Gerace, 1993) has now been shown to be one member of a family of nuclear proteins derived from a single gene by alternative splicing (Harris et al., 1994; Berger et al., 1996). Three abundant proteins are expressed from the human LAP2 gene, namely, LAP2α (75 kDa), LAP2β (51 kDa), and LAP2γ (39 kDa) (Harris et al., 1995). Of these
proteins, LAP2β and γ are both type II transmembrane proteins that differ only by the insertion of a β-specific domain of 109 amino acids in LAP2β. In contrast, LAP2α shares a 187-amino acid N-terminal domain with LAP2β and γ, but this is followed by a 506-amino acid α-specific domain lacking transmembrane regions. LAP2α has been shown to be distributed throughout the nucleus, rather than at the NE (Dechat et al., 1998). Complexes of LAP2α and A-type lamins form architectural, interchromosomal structures (Dechat et al., 1998, 2000). The interaction of LAP2α with chromatin seems to require the α-specific domain (Vlcek et al., 1999) and is likely regulated by cell cycle-dependent phosphorylation (Dechat et al., 1998). These important findings imply that LAP2α may have a number of functions in higher order chromatin interactions. This includes functions in the mitotic assembly/disassembly of the nucleus and/or as an anchorage protein for transcription regulators.

The retinoblastoma protein p110RB (Rb) controls progression through the cell cycle by negatively regulating the E2F transcription factor in a phosphorylation-dependent manner (Chellappan et al., 1991). Rb has a well-characterized domain structure consisting of an N-terminal domain followed by three C-terminal pocket domains termed A, B, and C (Figure 1). The N-terminal domain is capable of oligomerization (Henessy et al., 1994) and binds to an 84-kDa protein that colocalizes with centers of RNA processing (Durlee et al., 1994). The large A/B pocket binds to the E2F transcription factor (Cao et al., 1992; Lees et al., 1993) and D-type cyclins (Dowdy et al., 1993; Ewen et al., 1993). It also forms a complex with histone deacetylase (Brehm et al., 1998; Luo et al., 1998; Magnaghi-Jaulin et al., 1998), presumably leading to long-range silencing of genes required for cell division (Zhang et al., 2000). Pocket C has been shown to contain a nuclear localization signal sequence (NLS; Zacksenhaus et al., 1993) and binds both the c-Ab1 tyrosine kinase (Welch and Wang, 1993, 1995) and MDM2 (Xiao et al., 1995).

Binding of Rb to its targets is regulated by phosphorylation in a cell cycle-dependent manner (Lees et al., 1991; reviewed by Wang et al., 1994). Anchorage of Rb in the nucleus is also regulated by phosphorylation in that hypo-phosphorylated Rb, capable of binding E2F, is anchored in the nucleus during G1 phase of the cell cycle (Mittnacht and Weinberg, 1991; Mancini et al., 1994). Internal deletions or mutations of Rb within a region spanning pockets B and C promote tumorigenesis and prevent nuclear anchorage of the protein (Mittnacht and Weinberg, 1991), giving rise to the hypothesis that nuclear anchorage of Rb as well as binding to E2F are both essential for its function. Clearly, if the identity of the protein (or proteins) that anchor Rb to the nucleoskeleton were known, a test of this hypothesis would be possible. Previous reports have revealed that Rb binds to A-type lamins in blot overlay assays through its large pocket domain (Ozaki et al., 1994), suggesting that lamin A might anchor Rb within the nucleus. Herein, we report that LAP2α, which we have previously identified as an interaction partner for nucleoskeletal lamin A/C, binds to Rb within a region spanning pockets B and C. Disruption of the normal distribution of lamins A/C and LAP2α leads to a similar disruption of Rb distribution, and hypophosphorylated Rb is not retained in the nucleus of cells expressing low levels of LAP2α. Taken together, these data suggest that LAP2α–lamin A/C complexes have an important role in the nuclear anchorage of Rb.

**Materials and Methods**

**Cell Cultures**

Cells were cultured in DMEM (Invitrogen, Paisley, United Kingdom). Human embryonic kidney (HEK) 293 cells were supplemented with 10% fetal calf serum (FCS). Human dermal fibroblasts (HDF) were supplemented with 10% newborn calf serum (NCS) as recommended. The osteosarcoma cell line SAOS-2 was supplemented with 10% FCS. Cultures were maintained at 60–70% confluence. To induce quiescence in HDF, cultures were transferred to medium containing 0.5% NCS for 5 d. To stimulate HDF to reenter the cell cycle, quiescent cultures were transferred to medium containing 10% NCS.

**Transient Expression of Fusion Constructs in Cells**

HEK293 cells were grown on DMEM supplemented with 10% fetal calf serum (FCS). Cell cultures were maintained in an incubator with 5% CO₂ at 37°C. For transfections, cells were grown to 25–30% confluence in 45-mm dishes. A mixture of 5 μg of plasmid DNA, 0.12 M CaCl₂, and HBS (70 mM NaCl, 0.5 mM Na₂HPO₄, pH 7.0) was added to 2 ml of culture medium. The medium was replaced after 24 h, and fusion proteins were transiently expressed in cells for an additional 24 h.

**Immunofluorescence and Confocal Microscopy**

Cells grown on glass coverslips were either fixed with 4% formaldehyde in phosphate-buffered saline (PBS) for 15 min at room temperature and permeabilized in PBS/0.1% Triton X-100 for 5 min or extracted with hypotonic buffer (10 mM HEPES-KOH, pH 7.9, 10 mM KCl, 1.5 mM MgCl₂, 0.1% Triton X-100, 0.5 mM dithiothreitol [DTT]) followed by fixation. Primary and secondary antibodies were applied in PBS/1% NCS (PBS/NCS) for 1 h at room temperature. Primary antibodies used were as described in Table 1 and diluted in PBS/NCS. Secondary antibodies were donkey antimouse, goat, or rabbit IgG conjugated to tetramethylrhodamine B isothiocyanate (TRITC) or Cy5 (Jackson Immunoresearch, West Grove, PA) and diluted 1:100 in PBS/NCS. After several washes in PBS, samples were mounted in Mowiol/4,6-diamidino-2-phenylindole (DAPI)/DABCO and viewed with an inverted fluorescent microscope Axiosvert 10 (Zeiss, Oberkochen, Germany), fitted with a 12-bit charge-couple device camera controlled with IPLab software or with a Radiance 2000 confocal microscope imaging system with LaserSharp software (Bio-Rad, Hercules, CA).

**Solid Phase Overlay Assay**

Lamin C cDNA in pBluescript KS+ (a gift from G. Krohne, University of Würzburg, Würzburg, Germany) and LAP2α cDNA in pET23a plasmid (Dechat et al., 1998) were transcribed in vitro by using T7 polymerase (Promega, Madison, WI), and RNAs were translated in vitro by using rabbit reticulocyte lysate (Promega) and [³⁵S]methionine (PerkinElmer Life Sciences, Boston, MA), according to the manufacturers’ instructions. Glutathione S-transferase (GST)-fusion constructs of Rb corresponding to pocket A (aa 379–612), pocket B (aa 612–792), and pocket C (aa 792–928), and GST fusion of lamin C covering its C-terminal domain (aa 319–572) were separated by SDS-PAGE (Laemmli, 1970). Gels were stained with Coomassie or transblotted onto nitrocellulose (0.2 μm; Schleicher & Schuell, Dassel, Germany) in 48 mM Tris-HCl, pH 9.4, 39 mM glycin by using the Mini Trans blot system (Bio-Rad). Nitrocellulose membranes were incubated in overlay buffer (10 mM HEPES, pH 7.4, 100 mM NaCl, 5 mM MgCl₂, 2 mM EGTA, 0.1% Triton X-100, 1 mM DTT) for 1 h. Filters were then blocked with 2% bovine...
serum albumin (wt/vol) in overlay buffer for 1 h and probed with reticulocyte lysate containing in vitro translated 35S-labeled proteins, diluted 1:50 in overlay buffer plus 1% bovine serum albumin (wt/vol) and 1 mM phenylmethylsulfonyl fluoride, for 3 h at room temperature. After extensive washing in overlay buffer, nitrocellulose was air dried, and bound proteins were detected by autoradiography.

**Preparation of Cell Extracts**

Cells were grown in 90-mm petri dishes. Medium was aspirated from the petri dishes and the cultures were washed twice with PBS.

Cultures were extracted by incubation with hypotonic buffer (10 mM HEPES-KOH, pH 7.9, 10 mM KCl, 1.5 mM MgCl₂, 0.1% Triton X-100, 0.5 mM DTT) for 30 min at 4°C. The buffer was removed and the cells were washed twice with fresh hypotonic buffer and then scraped directly into radioimmunoprecipitation assay buffer for SDS-PAGE.

**Immunoprecipitation**

Mouse IgG Dynabeads (Dynal Biotech, Oslo, Norway) were coupled to lamin A/C or LAP2α-specific antibody by incubation for 12 h at 4°C in the presence of 1% bovine serum albumin. Asynchronously
Table 1. Antibodies used in this study

<table>
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GFP-Rb deletion constructs were expressed in HEK293 cells and their distribution between the nucleus and the cytoplasm was observed before and after extraction with hypotonic buffer. +, the presence of a fusion protein within a compartment; −, the absence of fusion protein within a compartment.

RESULTS

C-Terminal Domain of Rb Is Both Necessary and Sufficient for Nuclear Anchorage

A series of N- and C-terminal deletion constructs of Rb fused to GFP (Figure 1a) were created and transiently expressed in HEK293 cells. The molecular weights and the expression levels of GFP-Rb fusion proteins were investigated by Western blotting of whole cell lysates by using either a monoclonal anti-GFP antibody (Figure 1b) or anti-Rb antibodies. As expected all constructs were expressed at high levels and corresponded to the expected mobility of the GFP chimeras. To investigate the cellular localization of the transiently expressed constructs we performed immunofluorescence microscopy by using cells fixed 72 h after transfection. Wild-type GFP-Rb was distributed throughout the nucleus (Figure 2a and Table 2) identical to endogenous Rb (Figure 2c). In contrast, GFP-N terminus was restricted to the cytoplasm and was excluded from the nucleus (Figure 2a and Table 2). Identical patterns were observed with the constructs GFP-NA, GFP-A, and GFP-AB (our unpublished data; but see Table 2). Because the NLS has been mapped to the C terminus of Rb (Zacksenhaus et al., 1993) the cytoplasmic localization of these constructs was expected. Unexpectedly, the construct GFP-NAB was distributed between the cytoplasm and the nucleus (Figure 2a and Table 2). Finally, the constructs GFP-ABC, GFP-BC (Table 2), and
GFP-C (Figure 2a and Table 2) were restricted to the nucleus, consistent with the presence of a functional NLS in pocket C. In summary, it can be concluded that all constructs containing the C-terminal domain (and hence the NLS) localize to the nucleus where their distribution is indistinguishable from that of wild-type GFP-Rb. Domains lacking the C-terminal domain do not localize to the nucleus, except for GFP-NAB, which localized to the

**Figure 2.** Cellular localization of GFP-Rb chimeras. HEK293 were transiently transfected with GFP-Rb fusion constructs and fixed with 4% formaldehyde with or without prior extraction with hypotonic buffer. Cells were processed for immunofluorescence microscopy. The DNA was stained with DAPI. Each micrograph shows the distribution of DNA (left) or GFP (middle) in black and white or merged images (right) in color. Rb-wt, wild-type Rb fused to GFP; N, N-terminal domain fused to GFP; NAB, N terminus + pockets A and B fused to GFP; C, pocket C fused to GFP. (a) Distribution of GFP chimeras in fixed cells. (b) Distribution of GFP chimeras in cells fixed after extraction with hypotonic buffers. (c) Distribution of endogenous Rb in cells fixed after hypotonic extraction. Bar, 10 μm.
indicates the absence of fusion protein within a compartment.

<table>
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<th>Construct</th>
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<td>Nuclear + Cytoplasmic +</td>
</tr>
<tr>
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<td>Nuclear + Cytoplasmic +</td>
</tr>
<tr>
<td>GFP-NA</td>
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<td>Nuclear + Cytoplasmic +</td>
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<tr>
<td>GFP-NAB</td>
<td>Nuclear + Cytoplasmic +</td>
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<tr>
<td>GFP-A</td>
<td>Nuclear + Cytoplasmic +</td>
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<tr>
<td>GFP-AB</td>
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<tr>
<td>GFP-ABC</td>
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<tr>
<td>GFP-BC</td>
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<tr>
<td>GFP-C</td>
<td>Nuclear + Cytoplasmic +</td>
<td>Nuclear + Cytoplasmic +</td>
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</table>

GFP-Rb deletion constructs were expressed in HEK293 cells and their distribution between the nucleus and the cytoplasm was observed before and after extraction with hypotonic buffer. + indicates the presence of a fusion protein within a compartment; − indicates the absence of fusion protein within a compartment.

nuclear anchorage, HDF (our unpublished data) and HEK293 cells that had been transfected with GFP-Rb chimeras were extracted with hypotonic solutions. As expected wild-type GFP-Rb was retained in the nuclei of numerous cells, similar to endogenous protein (Figure 2b and Table 2). For those cells transfected with constructs that localized to the cytoplasm (e.g., GFP-N terminus; Figure 2b and Table 2) cytoplasmic staining was retained in some but not all cells. Importantly, for the construct GFP-NAB, which localized to the cytoplasm and the nucleoplasm, only the cytoplasmic staining was retained after extraction with hypotonic solutions and the nucleoplasmic staining was abolished completely (Figure 2b and Table 2). All chimeras containing pocket C, including GFP-ABC, GFP-BC (Table 2), and GFP-C (Figure 2b and Table 2) were mostly retained in nuclei, after extraction with hypotonic solutions. Thus, all constructs possessing pocket C were retained in the nucleus, whereas the construct GFP-NAB, which was partially localized within the nucleus, was not retained. These data suggest that pocket C contains a motif that is both necessary and sufficient for anchorage of Rb in the nucleus.

LAP2α and Lamin C Both Bind to C Terminus of Rb

In a previous investigation, lamin A was shown to interact with the pocket domain of Rb in blot overlay assays (Ozaki et al., 1994). To test whether A-type lamins and their nucleoskeletal interaction partner LAP2α interact directly with Rb pocket C, and might thus be responsible for the nuclear anchorage of Rb, we used similar assays. Furthermore, because binding of pRb to lamin A has been demonstrated previously using this assay (Ozaki et al., 1994), herein we concentrated on lamin C. Three different GST-fusion constructs of Rb corresponding to pocket A (aa 379–612), pocket B (aa 612–792), and pocket C (aa 792–928) were resolved on SDS-PAGE (Figure 3b). The resolved proteins were then transferred to nitrocellulose and overlayed with [35S]methionine-labeled LAP2α or lamin C (Figure 3a). Neither LAP2α (Figure 3b) nor lamin C (Figure 3c) interacted...
with pocket A of Rb. Although lamin C did not interact with pocket B of Rb (Figure 3c), LAP2α showed a weak interaction (Figure 3b). Both lamin C (Figure 3c) and LAP2α (Figure 3b) interacted strongly with pocket C of Rb. A GST fusion protein containing the tail domain of lamin C (aa 319–572; Figure 3d) represented a positive control in this experiment, because we have shown previously that LAP2α and lamin C both interact with this domain (Dechat et al., 2000). Taken together, these data reveal that LAP2α and lamin C are both capable of interacting with the nuclear anchorage domain in Rb and suggest that these proteins are involved in the nuclear anchorage of Rb.

To confirm that these interactions also occur under more physiological conditions in cell lysates, GFP-Rb chimeras were expressed in HEK293 cells. Cell extracts were then prepared and the GFP-Rb chimeras immunoprecipitated with anti-GFP antibodies. Immunoprecipitates were resolved on SDS-PAGE, transferred to nitrocellulose, and blotted with either an LAP2α-specific antibody (Figure 4a). As expected, LAP2α coimmunoprecipitated with GFP-Rb, GFP-ABC, and GFP-C. In contrast, LAP2α did not coimmunoprecipitate with GFP-NAB. In contrast, lamin B2, the major lamin in HEK293 cells, did not coprecipitate with GFP-C, excluding the possibility that pocket C is a sticky domain (Figure 4d).

To determine whether endogenous Rb interacts with either LAP2α or lamin C in cells, we prepared cell extracts from HDF. LAP2α was immunoprecipitated from the extracts by using an LAP2α-specific antibody (Figure 5a). Fractions of lamin A/C and Rb both coimmunoprecipitated with LAP2α (Figure 5c). Lamin B2, however, did not coimmunoprecipitate with LAP2α (Figure 5b). Two forms of Rb with slightly different mobility were detected in cell extracts (Figure 5c). A faster migrating underphosphorylated form and a slower migrating, more heavily phosphorylated form. The faster migrating form coimmunoprecipitated more efficiently with LAP2α, suggesting that LAP2α binds preferentially the underphosphorylated form of Rb. To confirm that the two Rb isoforms were differentially phosphorylated, we blotted LAP2α immunoprecipitates with phosphospecific Rb antibodies. Even though the faster migrating form was quantitatively the largest component of the immunoprecipitate (Figure 5c), it was detected less efficiently with the phospho-antibodies (Figure 5d). Thus, the Rb isoform that coprecipitated preferentially with LAP2α was indeed hypophosphorylated.

As a control, immunoprecipitation reactions were performed in parallel with an anti-lamin B2 antibody. Lamin B2 was efficiently precipitated from the extract (Figure 5e). Although some lamin A/C did coinmune precipitate with lamin B2 (Figure 5f), neither LAP2α (Figure 5g) nor Rb (Figure 5h) was detected in lamin B2 immunoprecipitates.

Because lamin C and LAP2α both seemed to bind to pocket C of Rb we predicted that Rb would not associate with LAP2α–lamin A/C complexes in cell lines containing certain Rb deletion mutants. SAOS-2 is an osteosarcoma cell line expressing an Rb mutant containing a C-terminal deletion, covering pocket C (Mittnacht and Weinberg, 1991). Cell extracts were prepared from SAOS-2 cells and immunoprecipitated with the LAP2α antibody. LAP2α and lamin A/C were both recovered efficiently in LAP15 immunoprecipitates (Figure 5, i and k).

However, the Rb deletion mutant was absent (Figure 5j), suggesting that pocket C is essential for the interaction between Rb and LAP2α–lamin A/C complexes.
Dominant Negative Lamin Mutants Sequester Rb and LAP2α within Nuclear Aggregates

Our data suggest that LAP2α and lamins A/C interact with the nuclear anchorage domain of Rb in blot overlay assays and in cell extracts. To obtain evidence for an interaction of the proteins in vivo, we investigated whether induced LAP2α/lamin A/C redistribution influences the distribution of Rb in the nucleus. In recent publications, we have shown that dominant negative lamin mutants that sequester endogenous A-type lamins into nuclear aggregates (Izumi et al., 2000; Vaughan et al., 2001) also sequester LAP2α into the same aggregates (Dechat et al., 2000). If LAP2α and lamins A/C do influence the distribution of Rb, sequestration of LAP2α and lamins A/C into nuclear aggregates should result in a similar sequestration of Rb but not other nuclear matrix proteins. HEK293 cells were transfected with the dominant negative lamin mutant GFP-delta 2+. Transfected cells were costained with different combinations of antibodies to detect lamins A/C, LAP2α, Rb, and lamin C or as controls with lamin B1 or NuMa. GFP-delta 2+ formed aggregates in transfected cells (Figure 6b, f, j, n, s, and v). In the cells containing aggregates, lamin A/C (Figure 6c), lamin C (Figure 6, i and r), LAP2α (Figure 6, g and w), and a fraction of Rb (Figure 6, m and t) were all sequestered to the aggregates. Other nuclear matrix proteins such as NuMa (Figure 6, k and o) and lamin B1 (Figure 6, a and e), however, remained normally distributed. The use of triple fluorescence in these experiments clearly demonstrated that Rb but not other nuclear matrix proteins (NuMa and lamin B1) were seque-
Figure 6. Redistribution of LAP2α and Rb by expression of dominant negative mutants. The dominant negative mutant GFPΔ2+ (GFP-delta2+) was transiently expressed in HEK293 cells. Cells were processed for triple immunofluorescence microscopy by using the following combinations of antibody. Goat anti-lamin B1 followed by TRITC donkey anti-goat to detect lamin B1 (a and e). JoL2 followed by Cy5 donkey anti-mouse to detect lamin A/C (c). LAP15 followed by Cy5 donkey anti-mouse to detect LAP2α (g and w). Ab5 followed by Cy5 donkey anti-mouse to detect Rb (m and k). Anti-lamin C followed by TRITC donkey anti-rabbit to detect lamin C (i, r, and u). Anti-NuMa followed by Cy5 donkey anti-mouse to detect number (k and o). GFP-Δ2+ was detected using fluorescein isothiocyanate filters (b, f, j, n, s, and v). Individual staining patterns are presented in black and white. Merged images (d, h, l, p, u, and x) are displayed in color with TRITC staining presented in red the GFP signal in green and the Cy5 signal in blue. Yellow indicates areas of spectral overlap between red and green. Cyan indicates areas of spectral overlap between red blue and green. Bars, 10 μm.
tered (Figure 6, a–p). Triple fluorescence also demonstrated that LAP2α, lamin C, and Rb were all present in the same aggregates (Figure 6, r–x). Taken together, these experiments show that, when the distribution of lamins A/C is perturbed, the distribution of LAP2α and a fraction of Rb are also specifically disturbed, supporting the existence of a complex of these three proteins in the nucleus.

Hypophosphorylated Rb Is Not Anchored in Nucleus of Cells Lacking LAP2α

LAP2α is expressed in a growth-dependent manner in primary skin fibroblasts. By using immunoblotting, LAP2α is readily detected in exponentially dividing cultures of HDF along with phosphorylated forms of Rb (Figure 7a). When HDF were induced to enter quiescence by serum starvation (judged by absence of expression of Ki67; Figure 6c), neither LAP2α nor phospho-isoforms of Rb were detected (Figure 7a). In contrast, expression of hypophosphorylated Rb, lamins A/C, and lamin B1 did not change as cells progressed from a proliferating to a quiescent state (Figure 7a and e). When HDF were induced to reenter the cell cycle by serum restimulation, LAP2α expression was slowly increasing between 12 and 30 h after serum restimulation, whereas total Rb protein remained constant within 30 h of restimulation (Figure 7b). Phospho-isoforms of Rb were first detected 18 h after serum restimulation (Figure 7b). Cells entered S phase between 24 and 30 h after serum restimulation as judged by staining with proliferating cell nuclear antigen, a marker for DNA replication (Figure 7d). Consequently, there is a 12-h period after serum restimulation when hypophosphorylated Rb is present in HDF in the absence of LAP2α.

We predicted that hypophosphorylated Rb would be susceptible to extraction between 6 and 12 h after serum restimulation, if LAP2α is required for its nuclear anchorage. To test this prediction, HDF were extracted to remove nonanchored Rb and then costained with DAPI (to detect chromatin) and either anti-Rb or anti-LAP2α antibodies (Figure 8, a and b). Six hours after serum restimulation, little or no LAP2α was detected in the nuclei of HDF, and Rb was no longer detected after extraction. LAP2α was more readily detected 12 h after serum restimulation, and at this time Rb could be detected after extraction. Between 18 and 24 h after serum restimulation, LAP2α was readily detected and Rb was retained throughout the nucleus of extracted cells (Figure 8, a and b). Thirty hours after serum restimulation as cells entered S phase and Rb became hypophosphorylated (Figure 7, b and d), Rb was no longer detected in the nucleus after extraction, although LAP2α was present in the nucleus (Figure 8, a and b). To confirm and extend these findings, HDF were extracted at

Figure 7. Changes in the expression of LAP2α and phospho-Rb in proliferating and quiescent HDF. Exponentially dividing HDF where induced to enter a quiescent state by withdrawal of serum (a and e). Cells were stained with Ki67 before and after serum withdrawal to confirm that cells had entered a quiescent state (c). Cell extracts were prepared from proliferating (P) and quiescent cells (Q) and prepared for immunoblotting. Immunoblots were probed with IF8 to detect total Rb, Rb780 to detect phospho-Rb, LAP15 to detect LAP2α (all in a), and JoL2 to detect lamins A/C or anti-lamin B1 (both in e). Quiescent cells were induced to reenter the cell cycle by readdition of serum to growth media (b and d). Reentry into the cell cycle was monitored by immunostaining with anti-proliferating cell nuclear antigen antibodies (d). Cell extracts were prepared at 6-h intervals after serum restimulation and used for immunoblotting (b). Immunoblots were probed with IF8 to detect total Rb, Rb780 to detect phospho-Rb, and LAP15 to detect LAP2α. Asterisk (*) indicates slowly migrating phosphorylated forms of Rb.
the same time intervals after serum restimulation but were prepared for immunoblotting rather than immunofluorescence. Six and 12 h after serum restimulation, only a fraction of Rb was insoluble after hypotonic extraction (Figure 8c) when levels of LAP2α had increased (Figure 7b). Thirty hours after serum restimulation, the amount of insoluble Rb declined (Figure 8d) as cells entered S phase (Figure 8d). These data support the hypothesis that expression of LAP2α is essential for the nuclear anchorage of hypophosphorylated Rb before cells enter S phase.

**DISCUSSION**

**LAP2α and Lamin A/C Anchor Rb in Nucleus**

In this investigation, we showed the C pocket to be necessary and sufficient for anchorage of GFP-Rb chimeras in the nucleus. Two nuclear architectural proteins, lamin C and LAP2α, bind across this domain in blot overlay assays. LAP2α binds efficiently to hypophosphorylated Rb and lamins A/C in cell extracts, provided that pocket C is present. When LAP2α and lamins A/C are forced to accumulate into aggregates formed by dominant negative lamin mutants, Rb also accumulates in those aggregates. Finally, when LAP2α is not present in cells entering G1 phase from a quiescent state, hypophosphorylated Rb is not anchored in the nucleus. Taken together, these data suggest that LAP2α and lamins A/C have an important role in the nuclear anchorage of Rb.

In a previous study, hypophosphorylation of Rb was correlated with its anchorage (defined by resistance to extraction with hypotonic buffers) in the nucleus (Mittnacht and Weinberg, 1991). The N terminus of Rb had been shown to be involved in its oligomerization (Hensey et al., 1994). These findings gave rise to the suggestion that this domain of Rb may facilitate binding to nuclear bodies. However, loss of nuclear anchorage of Rb occurs in mutant proteins carrying deletions spanning pockets B and C (amino acids 702–767; Mittnacht and Weinberg, 1991). The behavior of GFP-Rb chimeras in our study suggests that sequences located in pocket C (amino acids 750–928) are both necessary and sufficient for nuclear anchorage. In our studies, GFP-chimeras expressing pocket C are resistant to extraction with hypotonic solution consistent with the Mittnacht and Weinberg data. Although we cannot exclude the possibility that Rb is anchored in the nucleus through both its C-terminal and N-terminal domains, pocket C does have an essential role.

LAP2α binds to GST-Rb fragments corresponding to pockets B and C; therefore, it seems likely that binding of LAP2α occurs across these two pocket domains. Moreover, LAP2α binds preferentially (but not exclusively) to hypophosphorylated Rb. In a previous report, lamin A was identified as an Rb binding protein that also associated with the large pocket domain (Ozaki et al., 1994). We can confirm that A-type lamins associate with Rb in blot overlay assays, through pocket C. Based upon this evidence LAP2α and lamins A/C both seem to be involved in nuclear anchorage of Rb. Because lamins A/C and LAP2α have overlapping binding sites but also seem to be present in the same Rb complexes, we propose that the two proteins cooperate in anchoring Rb within the nucleus.

**Form and Function of Lamin–LAP2α–Rb Complexes**

Specific nuclear processes occur within organizational centers referred to as nuclear bodies (reviewed by Lamond and Earnshaw, 1999). Some authors have favored the view that nuclear metabolism occurs on a nucleoskeleton with properties resembling the intermediate filament cytoskeleton (Hozak et al., 1993). Others have suggested that a more local organization is

![Figure 8](image-url)
probable in which architectural proteins such as NuMa may assemble into mini-platforms, providing surfaces for transcription or splicing (Harborth and Osborn 1999). If the proposal of Harborth and Osborn is true, proteins capable of forming oligomeric complexes on chromosome surfaces might be sufficient to tether regulatory proteins at those sites. LAP2α and lamins A/C both possess the properties necessary for formation of oligomeric complexes. LAP2α contains a chromosome binding domain and its association with chromosomes is regulated by protein phosphorylation (Dechat et al., 1998; Vlcek et al., 1999). It also exists as oligomers on the surface of chromosomes in cell extracts (Dechat et al., 1998). Similarly, lamins A and C have distinct self-assembly properties and are also capable of forming oligomers on the surface of chromosomes in vitro (Glass and Gerace, 1990). Finally, lamin A/C localization influences the distribution of LAPα in the nucleus (Dechat et al., 2000), suggesting that both proteins interact at the same sites. Therefore, one possible mechanism by which LAP2α and lamin A/C may function is by forming local oligomeric complexes on chromosome surfaces. Lamin-LAP2α oligomers would have the capacity to bind Rb at a site (in pocket C) adjacent to its E2F binding domains in pockets A and B. Lamin/LAP2α oligomers may thus provide a mechanism for enhanced silencing. The presence of lamin/LAP2α oligomers on the surface of chromosomes might provide a platform that tethers one or more Rb molecules besides or across a promoter. These oligomers would be expected to be highly stable and therefore may be capable of forming an effective silencing complex.

**Nuclear Tethering and Tumor Formation**

Nuclear tethering of Rb seems to be important for its function because forms of Rb identified in certain tumors carry deletions spanning pockets B and C. These forms of Rb are not tethered in the nucleus (Mittnacht et al., 1991) and do not associate with LAP2α and lamins A/C (Figure 5). If anchorage of Rb to chromatin is necessary for its silencing activities, loss of this activity might be oncogenic. Because lamins A/C and LAP2α are involved in nuclear anchorage of Rb, loss of expression of one or more of these proteins might also be oncogenic. Consistent with this hypothesis is the loss of expression of lamin A in a wide range of human cancers (Venables et al., 2000) We hope to test this hypothesis directly using LAP2α −/− mice, which are currently being produced or with the existing lamin A/C −/− mice. The nuclear anchorage domain in Rb is also the site of interaction with the c-Abl tyrosine kinase (Welch and Wang, 1993, 1995) and MDM2 (Xiao et al., 1995). Therefore, LAP2α and lamins A/C might compete with c-Abl and MDM2 for binding to Rb. If this is true, an alternative function for nuclear anchorage may be to regulate the interactions between Rb and c-Abl and/or MDM2.

**ACKNOWLEDGMENTS**

We thank Prof. Howard Worman (Columbia University, New York, NY), Prof. David Lane and Dr. Joost Zomerdiick (University of Dundee, Dundee, United Kingdom) for the supply of lamin and Rb constructs and for the gift of antibodies. We also thank Dr. William Whitfield for help and advice. This work was generously supported by grants from the Cancer Research Campaign and the Wellcome Trust (to C.J.H.), with a grant from The International Association for Cancer Research (to C.J.H. and R.F.), and by a grant from the Austrian Science Research Fund (FWF P13374) to R.F.

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