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Development/Plasticity/Repair

The RNA-Binding Protein Human Antigen R Controls Global Changes in Gene Expression during Schwann Cell Development

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An important prerequisite to myelination in peripheral nerves is the establishment of one-to-one relationships between axons and Schwann cells. This patterning event depends on immature Schwann cell proliferation, apoptosis, and morphogenesis, which are governed by coordinated changes in gene expression. Here, we found that the RNA-binding protein human antigen R (HuR) was highly expressed in immature Schwann cells, where genome-wide identification of its target mRNAs in vivo in mouse sciatic nerves using ribonomics showed an enrichment of functionally related genes regulating these processes. HuR coordinately regulated expression of several genes to promote proliferation, apoptosis, and morphogenesis in rat Schwann cells, in response to NRG1, TGFβ, and laminins, three major signals implicated in this patterning event. Strikingly, HuR also binds to several mRNAs encoding myelination-related proteins but, contrary to its typical function, negatively regulated their expression, likely to prevent ectopic myelination during development. These functions of HuR correlated with its abundance and subcellular localization, which were regulated by different signals in Schwann cells.

Introduction

The myelinating Schwann cells in the peripheral nervous system (PNS) are derived from the neural crest via two transitional stages. First, neural crest cells generate Schwann cell precursors, which then give rise to immature Schwann cells that surround large bundles of axons. Schwann cells then initiate radial sorting of axons by selectively segregating large-diameter axons and establishing one-to-one relationships with them. This prerequisite for myelination requires the matching of Schwann cell number to axons by proliferation and apoptosis, and cytoskeletal-mediated Schwann cell morphogenesis, processes controlled by three major signals: Neuregulin-1 (NRG1), transforming growth factor-β (TGFβ), and laminins (Jessen and Mirsky, 2005; Woodhoo and Sommer, 2008).

Global changes in gene expression accompany the profound phenotypic changes associated with Schwann cell development. Thus, genes associated with proliferation and apoptosis, which reach a peak in immature Schwann cells, are highly expressed at this stage. With subsequent development, as the cells exit the cell cycle and lose susceptibility to apoptosis, these genes are downregulated. Conversely, many myelination-related genes are significantly upregulated as immature Schwann cells differentiate into myelinating Schwann cells (Verheijen et al., 2003; D’Antonio et al., 2006a). Recent studies have started to unravel the transcriptional and posttranscriptional molecular mechanisms that control these coordinated changes in gene expression. Chromatin remodeling, via HDAC1 and HDAC2, and micro-

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RNAs have been shown to be essential for the control of Schwann cell numbers and induction of myelination (Chen et al., 2011; Dugas and Notterpek, 2011; Jacob et al., 2011).

Cytoplasmic control of mRNA turnover and translation rates, mediated by RNA-binding proteins (RBPs), is a major post-transcriptional mechanism that promotes rapid and appropriate spatiotemporal expression of encoded proteins in response to environmental and internal cues. Human antigen R (HuR), a member of the ELAV/Hu family of RBPs, is a ubiquitously expressed protein that is essential for embryonic development and plays an important role in a number of disorders, including cancer (Himnan and Lou, 2008; Vázquez-Chantada et al., 2009). HuR binds to the U- and AU-rich elements in the 3′-untranslated region (UTR) of many mRNAs, generally promoting their stability and translation (Lebedeva et al., 2011; Mukherjee et al., 2011).

In this study, we found that HuR was highly expressed in immature Schwann cells, where genome-wide identification of its target mRNAs showed an enrichment of mRNAs encoding proteins with functions in regulating proliferation, apoptosis, and morphogenesis. Using in vitro silencing experiments, we found that HuR contributed to enhancing the expression of several genes induced by NRG1, TGFβ, and laminins, the three major signals involved in these processes. Chromatin immunoprecipitation analysis showed that p65 and SMAD2/3 bind to the HuR promoter in vivo to regulate its expression, likely to be triggered by NRG1 and TGFβ, respectively. Significantly, we found that HuR is a negative regulator of myelination since, although it is bound to several mRNAs encoding myelination-related proteins, it negatively regulated their expression. Finally, we found that HuR protein is greatly reduced in vivo as myelination progresses, a process likely to be controlled by Egr2-mediated ubiquitin proteolysis.

Materials and Methods

Animals. Mice and rats of either sex were housed at the Animal Unit at CIC bioGUNE, and all procedures were approved by the institutional review committee on animal use. The Animal Unit of CIC bioGUNE is an Association for Assessment and Accreditation of Laboratory Animal Care-accredited facility.

RNA immunoprecipitation. Immunoprecipitation (IP) protocol of endogenous mRNA-transfected HuR complexes was performed as described by Keene et al. (2006). In brief, 500 µg of whole-cell lysate obtained from a pool of newborn (NB) or postnatal day 5 (P5) sciatic nerves from C57BL/6J mice of either sex were incubated with a suspension of protein A-Sepharose beads (Sigma-Aldrich), precoated with 15 nM of antibodies. For RNA immunoprecipitation (RIP)-association, cells were first cultured overnight in Minimal Medium (MM) (DMEM/F12, 5% FBS, and N2 supplement) before NRG1 (20 ng/ml) or TGFβ (2 ng/ml) stimulation at appropriate time points. For cell shape experiments, cells were cultured overnight in MM before replating onto poly-l-lysine (PDL)- or laminin-coated dishes. For apoptosis assays, freshly isolated Schwann cells from NB nerves were isolated, plated onto coverslips in Simple Medium (SM) [DMEM/F12 and BSA (0.3 mg/ml)].

Viral infection. For HuR knockdown, cells were treated with short-hairpin lentiviral particles against HuR (CUGGCCCAAAATGTTAGCACCCTT CTCGAAATTTGTCAATTTTGTGGTTTTTG) in the presence of hexadimethrine bromide (8 µg/ml). After 24 h transduction, the cells were selected using puromycin (1.25 µg/ml) and puromycin-resistant HuR-knockdown cell clones were grown, analyzed, and frozen for future use. For adenosine infections, cells were cultured in MM, adenosine particles were added (amount added determined by titration), and 24 h later the medium was changed. Adenosine constructs used were as follows: GFP/Krox-20 (Ad-K20) and its matched GFP control (Ad-GFP) (a gift from J. Milbrandt, Department of Genetics, Washington University School of Medicine, St. Louis, MO) (Parkinson et al., 2004), SMAΔ7 (Ad-SMAΔ7) (Blaney Davidson et al., 2006), and HuR (Ad-HuR) (Xiao et al., 2007).

Inhibitors. Specific inhibitors in our culture experiments were obtained from Calbiochem and were used at the following concentrations: 10 µM...
1,4-diamino-2,3-dicyano-1,4-bis(2-aminophenylthio)butadiene (U0126) (ERK1/2 inhibitor), 10 μM 4-[4-(4-fluorophenyl)-2-(4-methyl-sulfinylphenyl)-1H-imidazol-5-yl]pyridine (SB203580) (p38 inhibitor), 10 μM 2-(4-morpholinyl)-8-phenyl-4-H-1-benzopyran-4-one (LY294002) (PI3K inhibitor), 10 μM N-(benzoyloxycarbonyl)leucinylleucinylleucinal (MG132) (proteosome inhibitor), and 2 μM 3-[(4-methylphenyl)sulfonyl]-(2-E)-propenenitrile (BAY11-7082) (NF-κB inhibitor).

Migration assay. Migration using the "scratch assay" was performed as described previously (Liagg et al., 2007). In brief, control and HuR-silenced cells were seeded onto PDL- or laminin-coated dishes and cultured overnight in MM. A scratch was performed using a p200 pipette tip, culture medium was changed, and pictures were taken at time 0, 6, 12, 18, and 24 h. The gap distance was measured at each time point, and data were expressed as percentage gap distance over time.

cAMP myelination assay. A CAMP analog, dibutyl-cAMP (Sigma-Aldrich) was added to cultures (10^−5 m), and protein or mRNA was obtained 24 h later.

Immunohistochemistry and immunocytochemistry. For teased nerves, nerves were dissected out, immediately fixed in 4% PFA for 10 min, teased on microscope slides, and allowed to dry. The samples were incubated in 0.2% Triton in blocking solution (BS) (PBS containing 10% calf serum, 0.1% lysine, and 0.02% sodium azide) followed by overnight incubation at 4°C with the following primary antibodies: HuR (1:100) and TUJ1 (1:5000) followed by secondary antibodies conjugated with FITC or Cy3 (Cappel/Jackson ImmunoResearch Laboratories). Talin immunocytochemistry has been described previously (Nodari et al., 2007), and in vitro BrDU incorporation and TUNEL labeling described previously (Parkinson et al., 2001; D’Antonio et al., 2006b). Images were acquired with an AxioImager D1 fluorescent microscope (Zeiss).

Chromatin immunoprecipitation. Rat Schwann cells or whole nerves were cross-linked with 1% formaldehyde (v/v) at 25°C for 10 min. After sonication into 200–500 bp fragments using Bioruptor (Diagenode), chromatin was immunoprecipitated with 2 μg of anti-p65 antibody (sc-372; Santa Cruz Biotechnology) or 5 μg of anti-Smad2/3 antibody (3102; Cell Signaling Technology) using the Magna ChIP G kit (Millipore). The recovered DNA was subjected to PCR amplification. Chromatin that was immunoprecipitated with mouse IgG was used as a negative control. The abundance of target genome DNA was calculated as the percentage of input. Primer sequences are available on request.

Antibodies. Antibodies used were from the following: HuR and p65 (Santa Cruz Biotechnology), Gapdh (Abcam), β-actin and Talin (Sigma-Aldrich), p-ERK1/2, p-AKT, p-p38, Smad2/3 (Cell Signaling Technology), Egr2 and TuJ1 (Covance), MPZ (Astexx), Periaxin (gift from P. Brophy, Centre for Neuroregeneration, University of Edinburgh, Edinburgh, UK), and MBP (Eurogentec). Fluorescent-conjugated secondary antibodies were from Jackson ImmunoResearch, and HRP-conjugated secondary antibodies were from Bio-Rad.

Assessment of mRNA stability. mRNA stability was determined by actinomycin D chase experiments, following a standard protocol described previously (Chang et al., 2010). Briefly, control and HuR-silenced cells were treated with db-CAMP for 24 h, which significantly increased expression of all mRNAs analyzed. Actinomycin D was added to a final concentration of 5 μg/ml to block further transcription. At 0, 30, 60, 120, and 240 min after actinomycin D treatment, the cells were harvested and mRNA was quantified by qPCR. The mRNA decay was recorded as the percentage of mRNA remaining over time compared with the amount before the addition of actinomycin D.

Statistical analysis. All data are presented as arithmetic mean ± SEM, unless otherwise stated. Statistical significance was estimated by Student’s t test.

Results

HuR is highly expressed in immature Schwann cells

HuR is a ubiquitously expressed RBP that binds to and regulates expression of thousands of mRNAs (Lebedeva et al., 2011; Mukherjee et al., 2011), playing fundamental roles in proliferation, apoptosis, and differentiation in several systems and cell types (Hinman and Lou, 2008). To investigate whether HuR might have a role in Schwann cell development, we first examined its expression in rat sciatic nerves at different ages, as immature Schwann cells differentiate into myelinating Schwann cells (Woodhoo et al., 2009).

We found that HuR mRNA was highly expressed in NB nerves, which contain mostly immature Schwann cells, and P5, which contain a mixture of immature Schwann cell and actively myelinating Schwann cells. There was a small but significant downregulation in P10 nerves, which contain an enriched population of actively myelinating Schwann cells (Fig. 1a). This was confirmed by examining its expression in total protein extracts (Fig. 1b), although the decrease at protein level seen at P10 (~70% bydensitometry analysis) was much more significant than at mRNA level (~25%). A similar pattern of expression was found when nuclear and cytoplasmic protein subcellular fractions were analyzed (Fig. 1c). We confirmed that HuR was expressed in Schwann cells by immunohistochemistry in P5 teased nerves (Fig. 1d).

Our results indicate that HuR may have a functional role in early postnatal nerves since its abundance and cytoplasmic export both critically control expression of its target genes (Hinman and Lou, 2008).

RIP-chip identifies several HuR target genes

To examine the biological significance of the high levels of HuR in NB and P5 Schwann cells, we analyzed the mRNAs bound to it on a genome-wide scale. For this, IP of ribonucleotide complexes (ribonucleoproteins) from cytoplasmic lysates of freshly isolated NB and P5 mouse sciatic nerves using an affinity-purified HuR antibody was performed, followed by purification and genome-wide microarray analysis of bound mRNAs (RIP-chip).

Two populations of mRNAs were detected in our analysis: an enriched population corresponding to the HuR-bound mRNAs and a nonenriched population representing background (control IP using mouse IgG) (Fig. 2a). To identify transcripts significantly associated with HuR, we used median log ratios of signal from RNA immunoprecipitation with HuR antibody versus the control IgG. HuR bound to 275 and 90 transcripts in NB and P5 nerves, respectively (Fig. 2b,c). Next, we examined the relation-
ship between the levels of each HuR-bound transcript relative to its total cellular level. There was little correlation between the probability of HuR association and the transcriptome, with only \( \sim 25\% \) of total identified transcripts (HuR IP/IgG IP) found to be significantly enriched relative to total mRNA levels (HuR IP/input) in both cases (Fig. 2b). This shows that detection of transcripts in HuR IP fraction is not dependent on mRNA abundance and that there is no bias toward identification of highly abundant or transcribed genes, as shown in other systems (Hieronymus and Silver, 2003; Mukherjee et al., 2009).

Comparison of the identified transcripts in the NB and P5 nerves showed that approximately two-thirds of targets identified in P5 nerves were commonly present in NB nerves, whereas the large majority of transcripts identified in NB nerves were uniquely expressed (Fig. 2c). Using the data set of gene expression profiling in nerves of mice at different ages across the Schwann cell lineage (Verheijen et al., 2003), we found that \( \sim 25\% \) of these unique HuR targets in NB nerves were also significantly downregulated in older nerves compared with NB nerves (50 of 215).

Since it was proposed that RBPs coordinate the expression of transcripts encoding biologically related proteins (Keene, 2007), we performed Gene Ontology (GO) analyses of differentially regulated HuR mRNA targets in NB and P5 nerves. Functional classification into molecular and cellular function (MF) showed that most of the enriched genes fell into several categories related to proliferation, apoptosis, and morphogenesis (Fig. 2d).

To validate our results from the RIP-chip analysis, fresh IPs were performed, and expression of several genes related to proliferation, apoptosis, and morphogenesis was quantified by quantitative RT-PCR (RIP-qPCR). We found that, with some rare exceptions, there was a similar trend of enrichment of these HuR targets using both analyses (Table 1). Our RIP-chip analysis also revealed a significant enrichment of mRNAs encoding RBPs, including HuR itself, and Thoc4 and Hnrpl among others, in line with other studies (Pullmann et al., 2007; Mansfield and Keene, 2009). This was confirmed by RIP-qPCR for selected genes (data not shown).

In summary, we find that HuR is bound to several mRNA targets in peripheral nerves in vivo, with decreasing binding af-
finity as development proceeds. The identified targets generally fall into categories that most closely characterize the immature Schwann cell stage (i.e., proliferation, apoptosis, and motility/morphogenesis), suggesting that HuR may have a functional role in regulating these processes.

HuR mediates laminin-induced motility and morphogenesis

As mentioned above, before myelination, immature Schwann cells migrate extensively along axons and send processes within axon families to segregate and ensheath them. Laminin, one of the critical components of the basal lamina, plays a predominant role in the process (Chernousov et al., 2008; Feltri et al., 2008).

To examine whether HuR mediated laminin-induced function in Schwann cells, we used a lentiviral vector to silence HuR (see Fig. 7b for effectiveness of HuR knockdown) and examined its effect on migration and morphogenesis. Using the cell scratch assay, we found that the migratory rate on laminin substrate was reduced in HuR-silenced cells compared with control cells (Fig. 3a,b), whereas no such effect was seen on PDL substrate, which promotes non-receptor-specific cell adhesion (data not shown). Similarly, on laminin substrate but not on PDL, HuR-silenced cells spread less and elaborated fewer lamellipodia than control cells (Fig. 3c,d). The length of axial lamellipodia on laminin substrate, which favors directional cell migration (Pankov et al., 2005), was reduced after HuR silencing (Fig. 3e), likely causing the defects in migratory rates seen above. In addition, we found that there was reduction in number of radial lamellipodia (Fig. 3e), which are important for the insertion of processes within axons during radial sorting (Nodari et al., 2007). These results show that HuR is an important mediator of laminin-induced function in Schwann cells.

Next, we investigated the mechanisms involved in these processes. First, by qPCR, we examined the expression of several of the validated HuR targets, associated with cell movement and morphogenesis in Schwann cells or in other systems, including Pten (Witke, 2004), Marcks (Larsson, 2006), Igfbp5 (Yano et al., 1999), Ncam1 (Yu et al., 2009), Actin (Chernousov et al., 2008), Ahnak (Salim et al., 2009), Lamc1 (Chen and Strickland, 2003), and Calm3 (Larsson, 2006). We found that culture on laminin substrate, compared with PDL, upregulated expression of several of these HuR targets (Fig. 3f). Ahnak, Lamc1, and Calm3 were not regulated by laminin (data not shown). Using RIP-qPCR analyses, we also found that culture on laminin substrate significantly increased binding of HuR to only the regulated mRNAs (Fig. 3g) and that HuR silencing reduced their expression (Fig. 3h), likely explaining the defects in laminin function.

HuR-mediated stabilization and translational upregulation of target mRNAs are closely linked to its subcellular localization. It is predominantly (>90%) localized in the nucleus but, in response to different stimuli, is exported to the cytoplasm, a process modulated by several posttranslational modifications, which also affects its binding to target mRNAs (Doller et al., 2008). We found that laminin increased the nucleo-cytoplasmic translocation of HuR (Fig. 4a), an effect controlled by p38 phosphorylation (Fig. 4b), which has previously been shown to be important for laminin-induced cell shape changes (Fragoso et al., 2003; Berti et al., 2011). Treatment with the p38 inhibitor also significantly reduced Schwann cell migration on laminin substrate (Fig. 4c).

In summary, we show that laminin induces translocation of HuR from the nucleus to the cytoplasm and increases HuR-mediated stabilization of several mRNAs that regulate cell motility and morphogenesis in Schwann cells.

Table 1. Validation of RIP-ChIP by RIP-qPCR

<table>
<thead>
<tr>
<th>Gene symbol</th>
<th>Gene name</th>
<th>NB Array</th>
<th>NB qPCR</th>
<th>P5 Array</th>
<th>P5 qPCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ccn3</td>
<td>Cyclin D1</td>
<td>5.54*</td>
<td>5.17*</td>
<td>1.32 n.s.</td>
<td>1.12 n.s.</td>
</tr>
<tr>
<td>Ccn3</td>
<td>Cyclin D2</td>
<td>1.56*</td>
<td>2.31*</td>
<td>1.41 n.s.</td>
<td>1.19 n.s.</td>
</tr>
<tr>
<td>Cd22</td>
<td>Cyclin-dependent kinase 2</td>
<td>2.55*</td>
<td>3.55*</td>
<td>1.20 n.s.</td>
<td>1.63 n.s.</td>
</tr>
<tr>
<td>Serpin2</td>
<td>Serine (or cysteine) peptidase inhibitor, clade E, member 2</td>
<td>1.78*</td>
<td>3.74*</td>
<td>-1.04 n.s.</td>
<td>1.61 n.s.</td>
</tr>
<tr>
<td>Brd4</td>
<td>Brd4 homodomain containing 4</td>
<td>2.13*</td>
<td>3.73*</td>
<td>1.20 n.s.</td>
<td>1.12 n.s.</td>
</tr>
<tr>
<td>Erbb2</td>
<td>v-erb-b2 erythroleukemia viral oncogene homolog 2</td>
<td>1.76*</td>
<td>5.17*</td>
<td>1.00 n.s.</td>
<td>1.00 n.s.</td>
</tr>
<tr>
<td>Sox9</td>
<td>Sox9 containing gene 9</td>
<td>3.38*</td>
<td>7.86*</td>
<td>1.70*</td>
<td>3.93*</td>
</tr>
<tr>
<td>Shc1</td>
<td>Shc homology 2 domain-containing transforming protein C1</td>
<td>3.19*</td>
<td>6.52*</td>
<td>1.35 n.s.</td>
<td>1.09 n.s.</td>
</tr>
<tr>
<td>Actb</td>
<td>Actin, beta</td>
<td>59.1*</td>
<td>63.9*</td>
<td>26.3*</td>
<td>29.5*</td>
</tr>
<tr>
<td>Ncam1</td>
<td>Neural cell adhesion molecule 1</td>
<td>2.34*</td>
<td>4.65*</td>
<td>1.38 n.s.</td>
<td>1.06 n.s.</td>
</tr>
<tr>
<td>Ptn1</td>
<td>Ptn 1</td>
<td>3.98*</td>
<td>4.65*</td>
<td>5.56*</td>
<td>5.08*</td>
</tr>
<tr>
<td>Ahnak</td>
<td>AHNK nuclear protein (desmoyokin)</td>
<td>16.5*</td>
<td>12.7*</td>
<td>6.79*</td>
<td>6.89*</td>
</tr>
<tr>
<td>Lamc1</td>
<td>Lamc1, gamma 1</td>
<td>2.32*</td>
<td>4.45*</td>
<td>1.06 n.s.</td>
<td>1.35 n.s.</td>
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<tr>
<td>Calm3</td>
<td>Calmodulin 3</td>
<td>6.62*</td>
<td>16.1*</td>
<td>2.66*</td>
<td>7.18*</td>
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<tr>
<td>Igfbp5</td>
<td>Insulin-like growth factor binding protein 5</td>
<td>4.29*</td>
<td>3.86*</td>
<td>1.69 n.s.</td>
<td>1.51 n.s.</td>
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<tr>
<td>Marcks</td>
<td>Marcks Myristoylated alanine-rich protein kinase C substrate</td>
<td>4.57*</td>
<td>9.83*</td>
<td>1.15 n.s.</td>
<td>1.60 n.s.</td>
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<tr>
<td>Casp2</td>
<td>Caspase 2</td>
<td>1.99*</td>
<td>5.11*</td>
<td>1.14 n.s.</td>
<td>1.87 n.s.</td>
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<tr>
<td>Casp9</td>
<td>Caspase 9</td>
<td>1.89*</td>
<td>3.68*</td>
<td>1.32 n.s.</td>
<td>1.68 n.s.</td>
</tr>
<tr>
<td>Aatk</td>
<td>Apoptosis-associated tyrosine kinase</td>
<td>7.08*</td>
<td>12.6*</td>
<td>2.74*</td>
<td>5.20*</td>
</tr>
<tr>
<td>Btg1</td>
<td>B-cell translocation gene 1</td>
<td>2.82*</td>
<td>4.71*</td>
<td>1.13 n.s.</td>
<td>1.58 n.s.</td>
</tr>
<tr>
<td>Map3k1</td>
<td>Mitogen-activated protein kinase kinase 1</td>
<td>1.7*</td>
<td>4.51*</td>
<td>1.12 n.s.</td>
<td>1.14 n.s.</td>
</tr>
<tr>
<td>Cd44</td>
<td>Cd44 antigen</td>
<td>1.99*</td>
<td>6.24*</td>
<td>1.47 n.s.</td>
<td>5.01*</td>
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<tr>
<td>Pdcd4</td>
<td>Programmed cell death 4</td>
<td>2.57*</td>
<td>8.60*</td>
<td>2.11*</td>
<td>7.48*</td>
</tr>
<tr>
<td>Vdac1</td>
<td>Voltage-dependent anion channel 1</td>
<td>3.09*</td>
<td>6.14*</td>
<td>1.82 n.s.</td>
<td>3.63*</td>
</tr>
</tbody>
</table>

*p < 0.05; n.s., not significant.
HuR mediates NRG1- and TGFβ-induced proliferation

Immature Schwann cell proliferate vigorously during late embryonic to perinatal stages (Stewart et al., 1993), a process thought to be critical for radial sorting and dependent on axonally derived mitogens, including NRG1 and TGFβ (Chernousov et al., 2008; Feltri et al., 2008; Woodhoo and Sommer, 2008).

Using established cell culture conditions that promote the mitogenic effect of NRG1 and TGFβ in vitro (Atanasoski et al., 2004), we found that HuR silencing significantly reduced proliferation induced by these two growth factors (Fig. 5a, b). The percentage of BrdU⁺ cells was significantly reduced from 77.6 ± 2.7% in control cells to 44.6 ± 2.5% in HuR-silenced cells after NRG1 treatment, and from 30.1 ± 1.5 to 17.8 ± 1.1% after TGFβ treatment (p < 0.01). To investigate the mechanisms involved in this function of HuR, we first examined expression of HuR targets associated with proliferation, including Cyclin D1 (Kim et al.,
2000), *Cyclin D2* (Jena et al., 2002), *Cdk2* (Tikoo et al., 2000), *Serpine 2* (Lino et al., 2007), *Shc1* (War et al., 1999), *Sox9* (Lincoln et al., 2007), *Erbb2* (Raphael et al., 2011), and *Brd4* (Houzelstein et al., 2002). We found that NRG1 and TGFβ treatment upregulated expression of several of these targets (Fig. 5c). RIP-qPCR analysis showed that NRG1 and TGFβ treatment significantly increased HuR binding to these mRNAs (Fig. 5d), the expression of which were significantly reduced by HuR silencing (Fig. 5e,f). We also found that NRG1 and TGFβ promoted the nucleo-cytoplasmic translocation of HuR (Fig. 6a). ERK1/2 and AKT phosphorylation controlled both NRG1-induced translocation of HuR and proliferation (Fig. 6b), whereas ERK1/2 and p38 phosphorylation controlled TGFβ-induced translocation of HuR and proliferation (Fig. 6c).

In summary, we show that HuR increases stability of genes in response to NRG1 and TGFβ, regulating their function on proliferation.

**HuR mediates TGFβ-induced apoptosis**

Natural cell death, like proliferation, is a feature of immature Schwann cells, which is induced by TGFβ in vivo (D’Antonio et al., 2006b).

Using established cell culture conditions that promote the apoptotic effect of TGFβ in Schwann cells (Parkinson et al., 2001), we found that silencing of HuR significantly reduced apoptotic cell death (Fig. 7a,b). The percentage of surviving cells increased from 29.5 ± 8.5% in control cells to 68.5 ± 7.8% in HuR-silenced cells, whereas the percentage of apoptotic TUNEL+ cells decreased from 49.2 ± 6.7% to 13.5 ± 2.3% (% p < 0.01). Of note, these culture conditions are different from proliferation-inducing conditions (above). To investigate the mechanisms involved, we first examined expression of HuR targets associated with apoptosis, including *Aatk* (Tomonoura et al., 2001), *Btg1* (Lee et al., 2003), *Casapse 2* (Kumar, 2009), *Casapse 9* (Riedl and Salvesen, 2007), *Vdac1* (Shoshan-Barmatz et al., 2010), *Pcdc4* (Lankat-Buttgereit and Göke, 2009), *Map3k1* (Parkinson et al., 2004), and *Cdh44* (Rouschop et al., 2006). We found that TGFβ treatment upregulated expression of several of these HuR targets (Fig. 7c). RIP-qPCR analysis showed that TGFβ treatment significantly increased HuR binding to them (Fig. 7d), the expression of which was significantly reduced by HuR silencing (Fig. 7e). We also found that TGFβ induced the nucleo-cytoplasmic translocation of HuR (Fig. 7f), an effect controlled by p38 phosphorylation but not by ERK1/2 phosphorylation, which was not activated in these culture conditions (Fig. 7g). Treatment with specific inhibitors also had a similar effect on TGFβ-induced apoptosis (Fig. 7h).

Thus, we show that TGFβ-induced apoptosis is controlled by HuR-mediated stabilization of several apoptosis-related genes.

**HuR is a negative regulator of myelination**

In our RIP-chip analysis, we found several myelination-related proteins (e.g., *Pmp22, Mpz*) encoded by mRNAs whose abundance was enriched in HuR IP samples, especially at the NB stage (Fig. 2b). We confirmed this observation for the *Pmp22* gene by RIP-qPCR (Fig. 8a) and showed that HuR specifically bound to its 3′-UTR by biotin pull-down assays (Fig. 8b). By RIP-qPCR, we also validated the binding of HuR to other myelination-related mRNAs (i.e., *Egr2, Pdx, Mbp, Mpz*) with significantly decreased binding affinity in P5 nerves (Fig. 8c). This was a surprising observation since this pattern is inversely correlated to their total mRNA levels, which increase postnatally reaching a peak at approximately P10 (Verheijen et al., 2003).

To further examine the role of HuR in the process of myelination, we silenced HuR in cultured Schwann cells and examined expression of some of these myelination-related proteins by Western blotting. HuR silencing induced a significant increase in their levels, both under myelinogenic conditions and strikingly under basal conditions as well (Fig. 8d). By qPCR analysis, we also found increased levels of myelination-related mRNAs after HuR silencing both under basal (Fig. 8e) and myelinogenic conditions (Fig. 8f), which was opposite to its effects seen above for morphogenesis-, proliferation-, and apoptotic-related genes. Exposure to actinomycin D in CAMP-treated cells showed that the half-life of each mRNA was significantly longer in HuR-silenced cells than control cells (Fig. 8g), suggesting that HuR could be destabilizing these mRNAs, instead of its typical role as a stabilizing factor for target mRNAs.

These data indicate that HuR could be a negative regulator of myelination (Jessen and Mirsky, 2008). To show this, we examined myelination in dorsal root ganglion (DRG) cocultures, seeded with Schwann cells with altered levels of HuR. We found that HuR silencing significantly increased the number of MBP+ segments in the cocultures (16.5 ± 2.1% in HuR-silenced cells compared with 8.1 ± 1.6% in control cells; p < 0.01) (Fig. 9a), accompanied by a significant increase in transcript expression (Fig. 9b). Conversely, enforced expression of HuR by adenoviral vectors decreased the number of MBP+ segments (5.9 ± 0.6% in control cells compared with 4.3 ± 0.4% in HuR-overexpressing cells; p < 0.05) (Fig. 9c), accompanied by a small but significant decrease in the expression of some of these transcripts (Fig. 9d).

The above data argue for a potential role of HuR in inhibiting myelination, similar to Notch and c-Jun (Parkinson et al., 2008; Woodhoo et al., 2009).

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**Figure 4.** Laminin induces nucleo-cytoplasmic translocation of HuR. (**a**) Western blot showing nucleo-cytoplasmic translocation of HuR after replating of Schwann cells onto laminin. (**b, c**) Western blot showing that treatment with SB203580 (to block p38 phosphorylation) prevents the nucleo-cytoplasmic translocation of HuR after 4 h culture onto laminin (b) and reduces the migration rate on laminin (c). a, b, β-Actin, Loading control. a, Gapdh, Cytoplasmic marker; Histone H3, nuclear marker. Cyto, Cytoplasmic fractions; Nucl, nuclear fractions.
HuR transcription is regulated by p65 and Smad2/3

HuR abundance plays a critical role in its function (Hinman and Lou, 2008). We showed that HuR mRNA levels decrease with development (Fig. 1a), and we wanted to examine the mechanisms that control this.

It has previously been shown in other systems that HuR transcription is positively regulated by the transcription factors (TFs) NF-κB (Kang et al., 2008) and Smads (Jeyaraj et al., 2010). We tested the recruitment of NF-κB to the HuR promoter in chromatin extracts from NB, P5, and P10 nerves by chromatin immunoprecipitation (ChIP) using antibodies against the p65 subunit of NF-κB followed by qRT-PCR. We found significant binding of p65 to different putative consensus sites, with reduced affinity in P10 nerves compared with NB or P5 nerves (Fig. 1c).

ChIP of Smad2/3 showed similar results (Fig. 1b), whereas no recruitment was seen with ChIP of Smad4 (data not shown). The decreased binding of p65 or Smad2/3 to the HuR promoter in P10 nerves is likely due to reduced nuclear expression of these TFs in these nerves (Fig. 1d).

Next, we examined the signaling pathways that could potentially regulate this mechanism. It was previously shown that NRG1 is sufficient to activate NF-κB in Schwann cells (Limpert Figure 5. HuR mediates NRG1- and TGF-β-induced proliferation. a, b, HuR silencing significantly reduces NRG1- (a) and TGF-β-induced (b) proliferation compared with sh control-infected cells as determined by BrdU incorporation (BrdU+ cells, red; DAPI nuclei, blue). c, qPCR showing expression of different transcripts after NRG1 or TGF-β treatment with time, expressed as fold change relative to untreated cells. d, RIP-qPCR analysis shows significant enrichment of proliferation-associated genes bound to HuR in NRG1- and TGF-β-treated cells compared with cells cultured in MM. e, f, HuR silencing leads to a significant reduction in expression of proliferation-associated genes after NRG1 (e) and TGF-β (f) treatment. Data are mean ± SEM. *p < 0.01.

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and Carter, 2010). We thus tested whether NRG1 was responsible for p65-mediated HuR transcription. We found that NRG1 treatment induced a transient increase in HuR mRNA and protein levels (Fig. 10d) and ChIP experiments showed that p65 was recruited to the HuR promoter after treatment with NRG1 for 1 h, but not for 12 h (Fig. 10e), following the kinetics of NRG1-induced HuR transcription (Fig. 10d). NRG1-induced increase in HuR levels was significantly attenuated by treatment with the NF-κB-specific inhibitor BAY11-7082, which prevents nuclear localization of p65 (Fig. 10f), confirming the role of NF-κB in NRG1-induced HuR transcription.

Similarly, we found that TGFβ, which induces nuclear translocation of Smad2/3 in Schwann cells (D’Antonio et al., 2006b), increased HuR mRNA and protein levels (Fig. 10g) and ChIP of Smad2/3 showed its recruitment to the HuR promoter after treatment for 1 h, but not 12 h later (Fig. 10h), following the kinetics of NRG1-induced HuR transcription (Fig. 10g). TGFβ-induced increase in HuR levels was significantly attenuated by enforced expression of Smad7 by adenoviral infection (Ad-Smad7), which prevents phosphorylation of Smad2/3 and its subsequent activation and translocation (Fig. 10i), confirming the role of Smad2/3 in TGFβ-induced HuR transcription. Combined treatment of NRG1 and TGFβ did not lead to an enhanced up-regulation of HuR levels seen by separate treatments of these growth factors at 2 h (Fig. 10j) and at 4 h (data not shown). Laminin treatment also had no effect on HuR transcription (data not shown).

Our data show that HuR transcription is dependent on the TFs NF-κB and Smad2/3 in vivo, likely to be regulated by NRG1 and TGFβ, respectively. Reduced expression of these TFs results in decreased HuR mRNA levels during development.

Egr2 (Krox20) induces proteosomal degradation of HuR

Earlier, we found that HuR protein levels were significantly reduced in P10 nerves compared with NB or P5 nerves, whereas there was only a slight reduction in mRNA levels (Fig. 1a–c). Since we found previously that the TF Egr2, which plays a critical role in the myelination process (Topliko et al., 1994), can also suppress expression of several negative regulators of myelination, including Notch and c-Jun (Parkinson et al., 2008; Woodhoo et al., 2009), we examined whether it was responsible for this downregulation of HuR expression. We found that enforced Egr2 expression was sufficient to suppress HuR protein levels (Fig. 10k) without affecting mRNA levels (data not shown). This effect was dependent on the ubiquitin-proteosomal degradation pathway since treatment with the proteosome inhibitor MG132 diminished this effect (Fig. 10l).

Discussion

Radial sorting plays a critical role in PNS myelination. We show that the RNA-binding protein HuR is highly expressed during this stage, where it is bound to and regulates expression of numerous genes regulating proliferation, apoptosis, and morphogenesis. This supports the view that RBPs such as HuR perform their overall biological functions by coordinately regulating expression of multiple functionally related mRNAs, known as “RNA operons” (Keene, 2007). This association of HuR with mRNAs is dynamic, with a significant decrease in the population of target mRNAs in P5 nerves compared with NB nerves, coinciding with a general decrease in mRNA expression of some of them (Verheijen et al., 2003). This is in line with other studies, which show dynamic changes in the association of HuR with target mRNAs (Mazan-Mamczarz et al., 2008; Mukherjee et al., 2009), and supports the view that RNA accessibility partially determines the formation of RBP–mRNA complexes (Kazan et al., 2010).

Schwann cell morphogenesis

Laminins play a major role in radial sorting with severe defects seen after in vivo ablation of laminin isoforms, receptors, and downstream signaling pathways (Chernousov et al., 2008; Feltri et al., 2008). Our data suggest that HuR could be an important mediator of laminin-induced function in Schwann cells by binding to and stabilizing laminin-induced mRNAs. HuR silencing in vitro results in decreased migration and significantly leads to morphological phenotypes, similar to cells lacking the laminin receptor β1-integrin or its downstream effector Rac1 (Benninger et al., 2007; Nodari et al., 2007). This effect is likely controlled by p38-mediated nucleo-cytoplasmic translocation of HuR, which is an important determinant of its function (Doller et al., 2008).

Schwann cell proliferation

Schwann cell proliferation is critical for matching axon and Schwann cell numbers during radial sorting, a process dependent on axonally derived mitogens (Chernousov et al., 2008; Feltri et al., 2008). We thus tested whether NRG1 was responsible for p65-mediated HuR transcription. We found that NRG1 treatment induced a transient increase in HuR mRNA and protein levels (Fig. 10d) and ChIP experiments showed that p65 was recruited to the HuR promoter after treatment with NRG1 for 1 h, but not for 12 h (Fig. 10e), following the kinetics of NRG1-induced HuR transcription (Fig. 10d). NRG1-induced increase in HuR levels was significantly attenuated by treatment with the NF-κB-specific inhibitor BAY11-7082, which prevents nuclear localization of p65 (Fig. 10f), confirming the role of NF-κB in NRG1-induced HuR transcription.

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Figure 7. HuR mediates TGFβ-induced apoptosis. a, b, HuR silencing leads to a significant reduction in TGFβ-induced apoptosis as seen by the number of surviving cells identified by nuclear condensation viewed by DAPI (blue) and number of apoptotic cells viewed by TUNEL labeling (green) (a), and Western blot of PARP cleavage and active caspase-3, 48 h after treatment (Figure legend continues.)
NRG1 is likely to play a major role, as shown in vitro (Morrissey et al., 1995) and in vivo in zebrafish (Lyons et al., 2005; Raphael et al., 2011). Indirect evidence also exists in mice models in vivo, as shown in mutants lacking the downstream effector of NRG1 signaling Cdc42 (Benninger et al., 2007) and in mice with neuronal overexpression of TGFβ2. We show that NRG1 and TGFβ increase expression and binding of HuR to several proliferation-associated genes. HuR silencing decreases expression of these genes and consequently proliferation. Both signals induce nucleo-cytoplasmic translocation of HuR, an effect mediated by several kinases such as ERK1/2, which also regulate proliferation, in line with other studies for NRG1 (Maurel and Salzer, 2000; Echave et al., 2009) and TGFβ (Xie et al., 2007). This suggests that these kinases could regulate proliferation induced by these two growth factors, by increased nucleo-cytoplasmic translocation of HuR and stabilization of critical target genes.

Schwann cell apoptosis

TGFβ is also a death signal for Schwann cells (D’Antonio et al., 2006b). We show that it increases expression and binding of HuR
HuR regulates myelination in DRG cocultures. A, B, HuR silencing increases myelination in Schwann cell-DRG cocultures, as seen by number of MBP+ myelin segments (red) (a), and qPCR analysis of myelination-related genes (b). C, D, Enforced HuR expression induced a small but significant decrease in myelination in Schwann cell-DRG cocultures, as seen by number of MBP+ myelin segments (red) (c), and qPCR analysis of myelination-related genes (d). Gapdh, Loading control. Data are mean ± SEM. *p < 0.01.

Control of HuR expression

Finally, we show that the TFs NF-κB and Smad2/3 are bound to specific sites in the HuR promoter in vivo, as shown in other systems (Kang et al., 2008; Jeyaratnam et al., 2010). The decreased expression of HuR mRNA levels in P10 nerves is likely due to a reduced activation of these TFs, as shown previously for NF-κB (Nickols et al., 2003), resulting in a decreased binding to the HuR promoter. We also identify NRG1 and TGFβ as the signals that respectively recruit NF-κB and Smad2/3 to the HuR promoter. This is likely to be important in vivo to maintain high levels of HuR in early postnatal nerves.

In addition, HuR has been found to autoregulate its levels by binding to HuR mRNA, stabilizing it (Al-Ahmadi et al., 2009), and enhancing its cytoplasmic export (Yi et al., 2010). In our RIP-chip assay, we found an enrichment of HuR mRNA in both NB and P5 nerves, showing that HuR is likely to be regulating its stability during Schwann cell development. We also found a significant reduction of HuR protein in P10 nerves, which is unlikely to be due to the small decrease in HuR mRNA levels. We show instead that this could depend on ubiquitin-proteosomal degradation, as described previously (Abdelmohsen et al., 2009), mediated by the transcription factor Egr2, which similarly represses expression of other negative regulators of myelination, including Notch (Woodhoo et al., 2009), and c-Jun and Sox2 (Parkinson et al., 2008). miRNAs could also potentially play a significant role in this process since HuR translation can be blocked by two different miRNAs, miR-519 (Abdelmohsen et al., 2008) and miR-125a (Guo et al., 2009), and miRNAs play a significant role in radial sorting, proliferation, and apoptosis during early postnatal Schwann cell development (Dugas and Notterpek, 2011).

In vivo functions of HuR?

It would be important to examine HuR function in vivo. Since HuR knock-out mice are embryonically lethal (Katsanou et al., 2009), Schwann cell–specific ablation of HuR would need to be performed using established cre mouse lines (Woodhoo et al., 2009). These mice could be characterized by peripheral nerve...
defects, including impairment in radial sorting and/or premature myelination, given the range of features, such as laminin-induced morphological functions that HuR controls in immature Schwann cells in vitro. This would be similar to mice lacking different laminin isoforms, laminin receptors, and downstream targets such as Rac1 (Chernousov et al., 2008; Feltri et al., 2008). These pleiotropic functions of HuR and the range of mRNAs it interacts with, also raise the possibility that it could have important functions in adult nerves, controlling features such as de-differentiation. Following nerve injury, for example, Schwann cells de-differentiate to a phenotype closely resembling immature Schwann cells (Jessen and Mirsky, 2008). They downregulate myelination genes, break down their myelin, and proliferate rapidly, and some of the supernumerary ones undergo apoptosis (Yang et al., 2008). HuR could be mediating injury-induced responses of Schwann cells, including proliferation and apoptosis, as some of

Figure 10. HuR expression is controlled by p65 and Smad2/3-induced transcription. a, b, Schematic diagram of the promoter region of HuR showing NF-κB consensus binding sites (green ovals) and regions analyzed (A1 and A2) (a) and Smad2/3 consensus binding sites (yellow ovals) and regions analyzed (B1 and B2) (b). ChIP analysis shows a decreased binding of p65 and Smad2/3 to the regions analyzed, in P10 nerves compared with NB and P5 nerves. c, Western blot showing reduced p65 and Smad2/3 expression in nuclear fractions of P10 nerves compared with NB and P5 nerves. d–f, NRG1 increases HuR transcription through NF-κB activation. d, Treatment with NRG1 increases HuR mRNA (top panel) and HuR protein levels (bottom panel), as seen by qPCR and Western blotting, respectively. e, ChIP analysis shows that p65 is recruited to the HuR promoter regions (indicated in a) after treatment with NRG1 for 1 h, but not in cells cultured in MM, or with NRG1 for 12 h. f, Western blot showing that treatment with the NF-κB inhibitor BAY11-7082, which prevents the nuclear translocation of p65, inhibits the NRG1-induced increase in HuR levels. g–i, TGFβ increases HuR transcription through Smad2/3 activation. g, Treatment with TGFβ increases HuR mRNA (top panel) and HuR protein levels (bottom panel), as seen by qPCR and Western blotting, respectively. h, ChIP analysis shows that Smad2/3 is recruited to the HuR promoter regions (indicated in b) after treatment with TGFβ for 1 h, but not in cells cultured in MM, or with TGFβ for 12 h. i, Western blot showing that adenoviral infection of cells with SMAD7 adenovirus (Ad-SMAD7), which prevents the nuclear translocation of Smad2/3, inhibits the TGFβ-induced increase in HuR levels. j, Combined treatment of NRG1 and TGFβ of Schwann cells plated onto laminin did not lead to an enhanced upregulation of HuR, induced by the two growth factors alone, as seen by qPCR (top panel) and Western blot (bottom panel), 2 h after treatment. k, l, Western blots showing that adenoviral infection of cells with Egr2 adenovirus (Ad-Egr2) decreases HuR levels after 48 h (k), an effect reduced with treatment with the proteosome inhibitor MG132 (f). β-Actin/Gapdh, Loading control. Nuc, Nuclear fractions. Data are mean ± SEM. *p < 0.01.
the identified HuR targets in Schwann cells such as Cyclin D1 are reexpressed upon injury and have important physiological functions during the de-differentiation process (Kim et al., 2000; Atanasoski et al., 2001).

Notes
Supplemental material for this article is available at http://www.ebi.ac.uk/arrayexpress/experiments/E-MEXP-3519. Raw and processed microarray data are publicly accessible at EMBO-EBI ArrayExpress database under accession number E-MEXP-3519. This material has not been peer reviewed.

References


