

SCIENTIFIC REPORTS



OPEN

Interactome analyses revealed that the U1 snRNP machinery overlaps extensively with the RNAP II machinery and contains multiple ALS/SMA-causative proteins

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Mutations in multiple RNA/DNA binding proteins cause Amyotrophic Lateral Sclerosis (ALS). Included among these are the three members of the FET family (FUS, EWSR1 and TAF15) and the structurally similar MATR3. Here, we characterized the interactomes of these four proteins, revealing that they largely have unique interactors, but share in common an association with U1 snRNP. The latter observation led us to analyze the interactome of the U1 snRNP machinery. Surprisingly, this analysis revealed the interactome contains ~220 components, and of these, >200 are shared with the RNA polymerase II (RNAP II) machinery. Among the shared components are multiple ALS and Spinal muscular Atrophy (SMA)-causative proteins and numerous discrete complexes, including the SMN complex, transcription factor complexes, and RNA processing complexes. Together, our data indicate that the RNAP II/U1 snRNP machinery functions in a wide variety of molecular pathways, and these pathways are candidates for playing roles in ALS/SMA pathogenesis.

The neurodegenerative disease Amyotrophic Lateral Sclerosis (ALS) has no known treatment, and elucidation of disease mechanisms is urgently needed. This problem has been especially daunting, as mutations in greater than 30 genes are ALS-causative, and these genes function in numerous cellular pathways¹. These include mitophagy, autophagy, cytoskeletal dynamics, vesicle transport, DNA damage repair, RNA dysfunction, apoptosis, and protein aggregation^{2–6}. The discovery that mutations in two RNA/DNA binding proteins, FUS and TARDBP, are ALS-causative first raised the possibility that dysfunction of RNA-related processes plays a role in the disease^{7–11}. This hypothesis gained traction when additional ALS-causative RNA/DNA binding proteins (EWSR1, TAF15, HNRNPA1, HNRNPA2B1, MATR3 and TIA1) were identified^{12–16}. At present, however, the roles of these proteins in ALS pathogenesis are not known.

FUS, EWSR1 and TAF15 constitute the FET family of structurally related proteins^{17,18}. They share in common RNA binding motifs and low complexity domains. Similar to the FET family members, MATR3 also contains both types of domains¹⁹. Although ample evidence exists that all four of these ALS-causative proteins function in transcription and splicing, much less is known about how their functions are distinguished from one another in these processes. We recently found that the four ALS-causative proteins associate with the RNAP II machinery and that several other ALS-causative proteins, including HNRNPA1²⁰, HNRNPA2B1²⁰, TIA1¹⁶ and VCP²¹, do as well (BC *et al.*, submitted). Moreover, multiple proteins that are mutated in the childhood motor neuron disease cause Spinal Muscular Atrophy (SMA) associate with the RNAP II machinery, including SMN1, EXOSC8²², HSPB1^{23,24} and two components (ASCC1 and TRIP4)^{25,26} of the ASC-1 transcriptional co-activator (BC *et al.*, submitted). To investigate the roles of ALS-causative proteins within the RNAP II machinery, we used CRISPR to knock out the 3 FET family members or MATR3 in HeLa cells and then characterized the RNAP machinery isolated from these cell lines. One of the notable conclusions from this study was that all four ALS-causative

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proteins are required for interaction of the SMA-causative ASC-1 complex with RNAP II (BC *et al.*, submitted). The observation that two different components of the ASC-1 complex are mutated to cause SMA and that the ALS-causative proteins mediate the association of the ASC-1 complex with RNAP II provide excellent examples of the importance of identifying interaction partners of ALS/SMA-causative proteins, as these interaction partners themselves are candidates for causing the diseases. In addition, identification of their interaction partners will assist in identifying molecular pathways involved in the pathogenesis of motor neuron disease.

In the present study, we report the interactomes of FUS, EWSR1, TAF15 and MATR3, and show that all four of these proteins associate with U1 snRNP. Unexpectedly, comparison of the interactome of the U1 snRNP machinery with that of the RNAP II machinery shows that virtually the entire U1 snRNP machinery overlaps with the RNAP II machinery. Among the proteins present in the U1 snRNP/RNAP II machinery are multiple ALS/SMA-causative proteins. These data raise the possibility that the RNAP II/U1 snRNP machinery and the pathways in which it functions may underlie the pathogenesis caused by a host of motor neuron disease-causative proteins.

Results and Discussion

FUS, EWSR1, TAF15 and MATR3 associate with U1 snRNP. To characterize the interactomes of FUS, EWSR1, TAF15 and MATR3 (hereafter referred to as ALS proteins) we immunopurified (IP'd) these proteins from HeLa cell nuclear extracts. To identify the highly abundant interactors, we excised individual bands from a Coomassie-stained gel and carried out mass spectrometry. This analysis revealed that U1 snRNP components are enriched in the FUS, EWSR1 and TAF15 IPs. These components include all of the U1 snRNP-specific proteins (SNRNP70, SNRPA, SNRPC) as well as the snRNP core proteins (SNRP proteins) (Fig. 1a, lanes 1–3). U1 snRNP components were not observed in the MATR3 IP (Fig. 1a, lane 4). We next carried out reciprocal IP/westerns using an antibody against the SNRPC core component of U1 snRNP. As shown in Fig. 1b, the three FET family members and MATR3 co-IP'd with U1 snRNP, but not with the negative control nuclear protein EIF4A3. Although U1 components were not detected on the Coomassie gel in the MATR3 IP, this may be due to a buried epitope (see below for mass spectrometry data of the U1 snRNP machinery that support this conclusion).

To determine whether the association between the ALS proteins and U1 snRNP was specific, we treated nuclear extracts with an anti-sense morpholino (AMO) that binds to the 5' end of U1 snRNA and blocks splicing²⁷. This U1 AMO also disrupted the association of FUS with U1 snRNP²⁸. We obtained the same results in the present study (Fig. 1c, lanes 5–8). In addition, the U1 AMO disrupted the interactions between U1 snRNP and TAF15, EWSR1 and MATR3 (Fig. 1c, lanes 9–14). We further confirmed these associations by carrying out IPs and analyzing total RNA on an ethidium bromide stained gel. As shown in Fig. 1d, all of the ALS proteins co-IP'd with U1 snRNA, and the interaction was specific as it was disrupted by the U1 AMO. We conclude that FUS, TAF15, EWSR1 and MATR3 associate with U1 snRNP.

FUS, EWSR1, TAF15 and MATR3 interactomes. To gain further insight into the interactomes of the four ALS-causative proteins, we carried out shotgun mass spectrometry of each IP. These data revealed 156, 68, 132 and 91 interactors for FUS, EWSR1, TAF15 and MATR3, respectively (Table S1). We listed the well-known functions and/or functions potentially relevant to motor neuron disease in the table for all of the interactors (color coded in Table S1). The top 15 hits in each interactome are shown in Fig. 2. Consistent with the Coomassie gel, canonical U1 snRNP components are among the top hits in the FUS, EWSR1 and TAF15 interactomes (marked by stars). In the EWSR1 interactome, multiple ALS-causative proteins are present (color coded red, Fig. 2). A top interactor of TAF15 is PABPC1, which is known to be mislocalized in ALS patient motor neurons²⁹. A top hit in both the FUS and TAF15 interactomes is HNRNPR, which interacts with SMN1 in the axons of motor neurons^{30,31}. HNRNPR is also found in the EWSR1 and MATR3 interactomes (ranked 34 and 19, respectively in Table S1). The observation that HNRNPR is a common interactor of ALS proteins and SMN1 reveals a new molecular link between ALS and SMA. Among the top hits in the MATR3 interactome are numerous proteins that function in the DNA damage response, including NUMA1, CAD, RUVBL1, RUVBL2, HNRNPK and DDB1. Consistent with these results, MATR3 itself is involved in the DNA damage response³², which has emerged as a pathway disrupted in multiple types of ALS and SMA^{33–39}. Moreover, both RUVBL1 and RUVBL2 are components of the HSP90/R2TP chaperone complex, which interacts with the SMN complex and functions in facilitating snRNP assembly^{40,41}, suggesting an involvement of MATR3 in snRNP assembly.

To identify complexes in each of the interactomes, we analyzed the data in Table S1 using the STRING database (<https://string-db.org>). This analysis showed that each of the interactomes contain numerous distinct complexes. Several well-known complexes were not separated into clusters by STRING. Thus, we manually clustered these proteins (Figs 3–6). These data revealed complexes in common among the ALS protein interactomes so we next analyzed the proteins shared by all four ALS interactomes (Fig. S1). These interactomes share three dead box helicases (DHX9, DDX5 and DDX17), which, similar to the ALS proteins, are DNA/RNA binding proteins with roles in transcription and splicing. The DBIRD complex, reported to function in coupling transcription to alternative splicing⁴², as well as hnRNP proteins, are also shared by the four interactomes. The factors that are shared by the 4 ALS protein interactomes are good candidates for being disease-relevant. Consistent with this possibility, several ALS-causative proteins are also shared among the 4 interactomes, including HNRNPA1, HNRNPA2B1, FUS and MATR3.

The data in Figs 3–6 reveal complexes/factors unique to one or more of the ALS protein interactomes. FUS and TAF15 interactomes contain the SMN complex, thereby linking both of these ALS proteins to the SMA-causative SMN1 protein (Figs 3 and 5). The FUS and TAF15 interactomes also contain the transcription elongation factor P-TEFb, and the FUS interactome uniquely contains many other factors/complexes that function in transcription, including subunits of RNAP II, and BAF, PAF and integrator complex components (Fig. 3). The TAF15 interactome also contains the TREX mRNA export complex, which has been tied to ALS previously^{43–46}. In addition, ASAP RNA processing/apoptosis complex is present in the TAF15 interactome, and apoptosis is a pathway

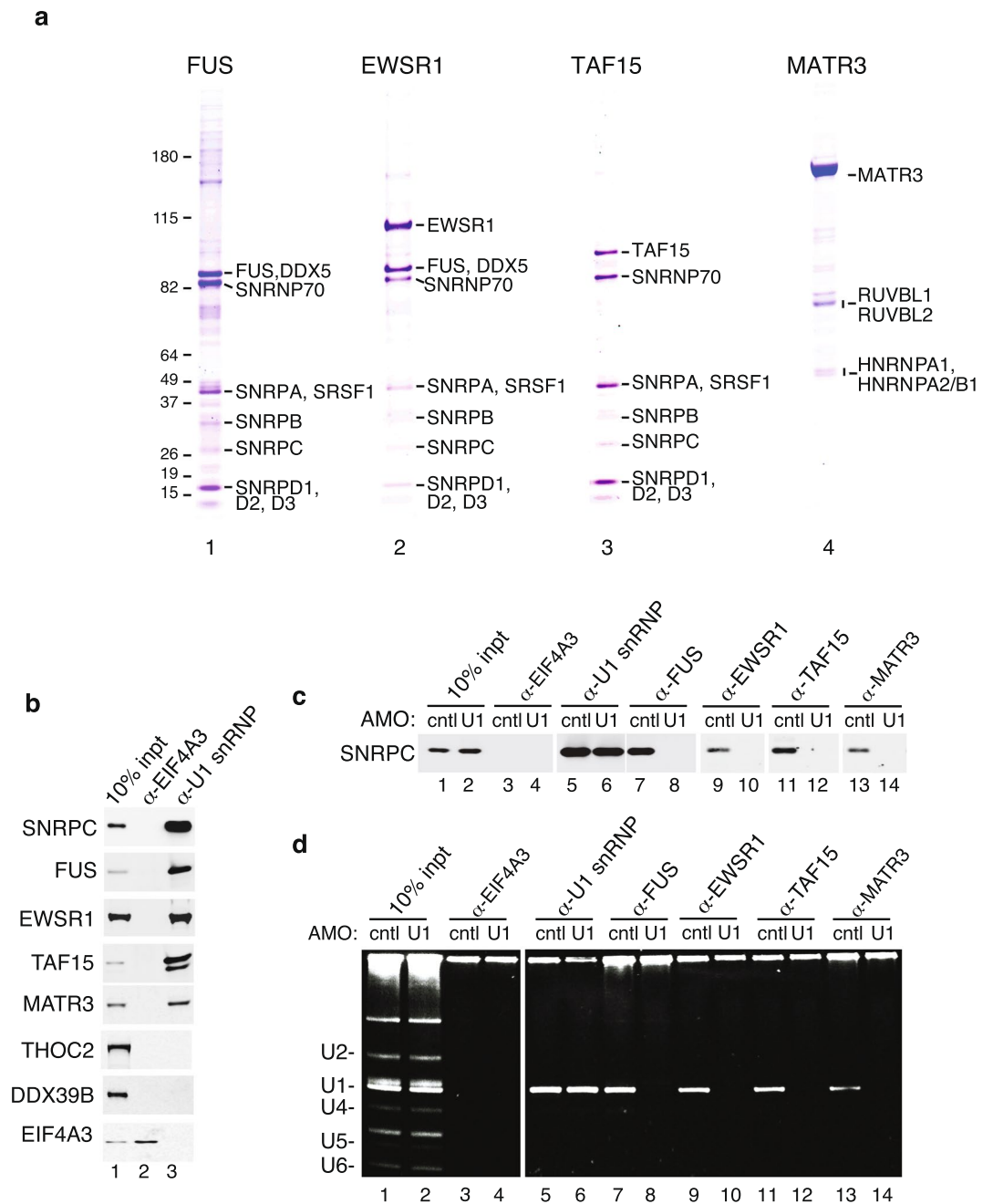


Figure 1. FET proteins and MATR3 associate with U1 snRNP. **(a)** Immunoprecipitations (IPs) were carried out with antibodies to FET proteins or MATR3 followed by analysis on a Coomassie-stained gel. Molecular weight markers and protein identified by mass spectrometry are indicated. **(b)** IPs were carried out from nuclear extract using a negative control antibody (EIF4A3) or an antibody to the SNRPC subunit of the U1 snRNP followed by Westerns with the indicated antibodies. **(c)** IPs were carried out with the indicated antibodies from nuclear extract treated with a U1 snRNA AMO or a negative control AMO followed by Western using the SNRPC antibody. **(d)** Same as (c) except that total RNAs from the IPs were examined on a denaturing gel stained with ethidium bromide.

associated with ALS (Fig. 5)^{47,48}. Finally, the MATR3 interactome contains CUL1 and CUL2, factors that are components of the ubiquitin proteasome pathway. This pathway is known to be important in ALS via genes such as UBQLN2, which is mutated to cause the disease (Fig. 6)^{49,50}. We conclude that the four ALS-causative proteins have multiple interaction partners, many of which are linked to different pathways involved in ALS/SMA, and these interaction partners are new candidates for factors involved in pathogenesis via these known pathways. Moreover, on a more basic science note, our data reveal that, despite the structural similarities and their common association with U1 snRNP, the four ALS proteins have many unique interaction partners that likely explain the distinct roles that these proteins have been reported to play in such processes as transcription and splicing.

Top FUS interactors

Rank	Symbol	kD	Function	Total	Unique
1	FUS	58	Txn, splicing	100	15
2	SRSF1	27	SR protein family member SF2	89	28
3	TRIM28	92	Mediates gene silencing by recruiting CHD3	81	33
4	HNRNPA2B1	39	Txn, splicing, neuronal transport of specific mRNAs to cytoplasm	74	20
5	SNRPD2	13	snRNP Core Protein SmD2	72	11
6	SNRNP70	48	U1 snRNP component U170K	70	39
7	SNRPA	31	U1 snRNP component U1A	69	22
8	SNRNPB	26	snRNP core protein B, B'	63	13
9	HNRNPR	70	Splicing, interaction partner of SMN in axons of MNS	59	41
10	PPP1R10	103	Component of PTW/PP1 phosphatase complex, control chromatin structure	48	33
11	ILF2	43	Txn factor associates with ILF3	48	17
12	DHX9	140	Splicing, txn activator	43	39
13	PABPC1	70	PolyA binding protein mislocalized in motor neurons in ALS	43	33
14	DDX3X	73	Splicing, txn, translation initiation	43	31
15	HNRNPU	91	Txn, splicing	43	31

Top EWSR1 interactors

Rank	Symbol	kD	Function	Total	Unique
1	RBMX	43	Txn, splicing	113	21
2	EWSR1	72	Txn, splicing	100	29
3	HNRNPUL1	94	Txn, splicing	96	33
4	HNRNPM	80	Txn, splicing	92	92
5	SNRNP70	48	U1 snRNP component U170K	75	38
6	HNRNPA2B1	39	Txn, splicing, neuronal transport of specific mRNAs to cytoplasm	75	25
7	TAF15	65	Txn, splicing	63	17
8	DDX3X	73	Splicing, txn, translation initiation	58	29
9	TARDBP	46	Txn, splicing	58	25
10	SRSF1	27	SR protein family member SF2	50	38
11	FUS	58	Txn, splicing	50	29
12	CLINT1	69	Transport via clathrin-coated vesicles	42	33
13	AKAP8	76	Nuclear A-kinase anchor protein that binds to PKA	38	25
14	DDX5	68	Txn, splicing	33	17
15	SNRPA	31	U1 snRNP component U1A	33	17

Top TAF15 interactors

Rank	Symbol	kD	Function	Total	Unique
1	SNRPA	31	U1 snRNP component U1A	164	17
2	TAF15	65	Txn, splicing	100	13
3	SNRNPB	26	snRNP core protein B, B'	80	14
4	SNRPD2	13	snRNP core protein SmD2	80	12
5	SNRPF	9	snRNP core protein SmF	74	3
6	SNRNP70	48	U1 snRNP component U170K	68	24
7	SNRNP200	235	U5 snRNP component	58	55
8	SRSF1	27	SR protein family member SF2	54	17
9	PABPC1	70	PolyA binding protein mislocalized in motor neurons in ALS	53	18
10	SNRPE	10	snRNP core protein SmE	42	8
11	HNRNPR	70	Splicing, interaction partner of SMN in axons of MNS	38	29
12	SNRPD3	14	snRNP Core Protein SmD3	36	5
13	HNRNPA1	41	Txn, splicing	33	12
14	SNRPC	17	U1 snRNP component U1C	33	4
15	ACIN1	148	ASAP complex component, EJC component and promotes apoptosis	30	29

Top MATR3 interactors

Rank	Symbol	kD	Function	Total	Unique
1	MATR3	93	Nuclear matrix protein, txn, splicing, DNA damage response	100	34
2	HNRNPM	80	Txn, splicing	54	41
3	NUMA1	233	DNA damage response; functions in mitotic spindle formation	38	36
4	CAD	245	Functions in pyrimidine biosynthesis; DNA damage response	31	30
5	RUVBL2	51	Txn and DNA damage response	30	22
6	DDX3X	73	Splicing, txn, translation initiation	25	18
7	RUVBL1	50	Txn and DNA damage response	22	18
8	HNRNPL	65	Splicing	22	14
9	HNRNPA1	41	Txn, splicing	22	11
10	HNRNPK	51	Txn, splicing, DNA damage response	21	13
11	COPA	135	Coatomer component	20	20
12	SKIV2L2	115	Splicing, associate with RNA exosome complex	20	19
13	HSPA8	71	Molecular chaperone	20	17
14	DDB1	125	Component of DNA damage (DDB) complex	19	19
15	DDX5	68	Coatomer component	19	16

Figure 2. Top hit interactors in the FET proteins and MATR3 interactomes. The top ranked (by total peptide number) proteins in each interactome are shown. The rank, HGNC official symbol, calculated molecular weight, best-known function, total and unique peptide counts are shown. Functions in splicing (pink), transcription (txn, orange), DNA damage response (green), neuronal (blue) and other (black) are indicated. The symbols of ALS-causative proteins are in red. The stars indicate U1 snRNP components.

The U1 snRNP machinery overlaps extensively with the RNAP II machinery. In light of the observation that FUS, EWSR1, TAF15 and MATR3 all associate with U1 snRNP, we next investigated the interactome of this machinery, identifying 226 proteins within it. These proteins and their functions are color coded in Table S2. As expected, the top two hits are core components (SNRNP70 and SNRPA) of U1 snRNP and the other

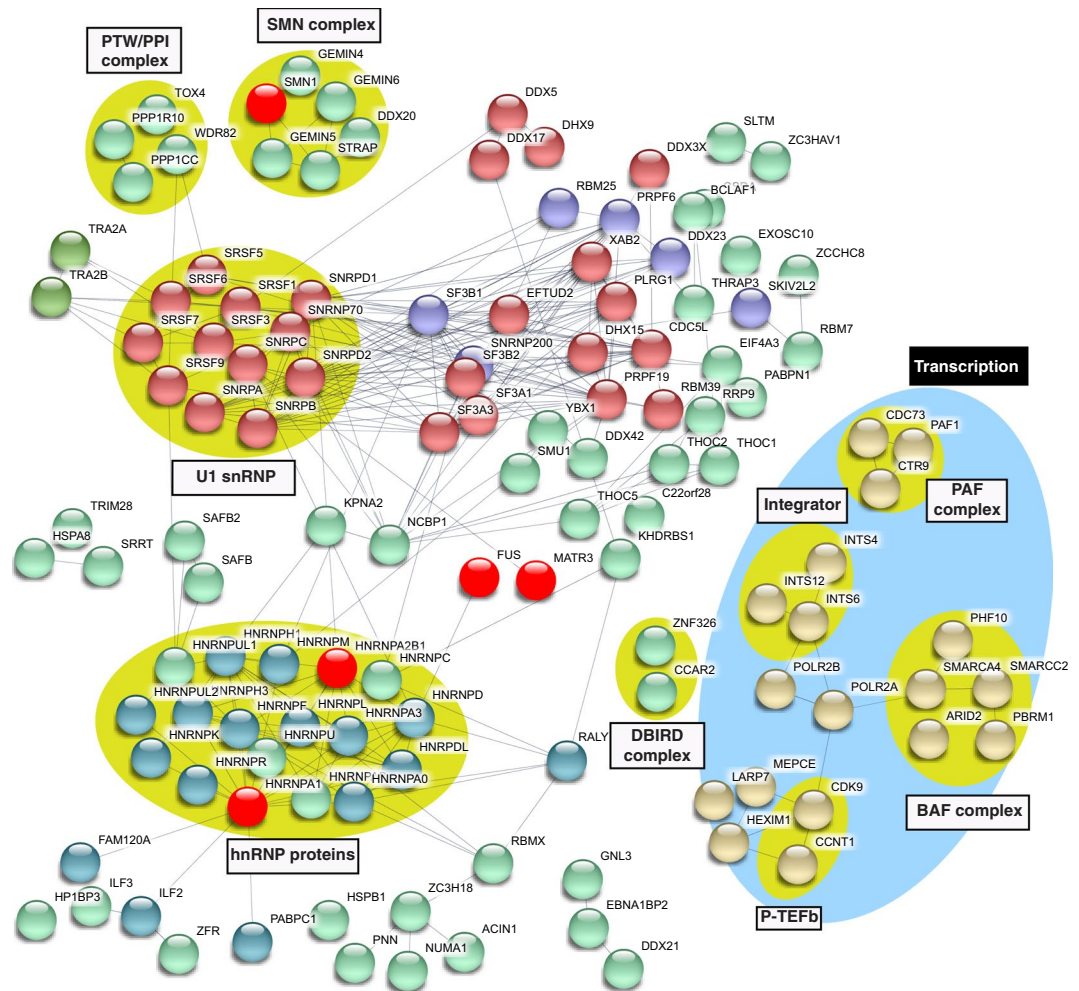


Figure 3. Protein-protein interaction network of the FUS interactome. The network of the FUS interactome constructed using STRING database (confidence score >0.7) is shown. Disconnected nodes are omitted. Protein complexes and clusters of functionally related proteins are indicated by yellow circles and blue circles, respectively. The ALS and SMA-causative proteins are in red.

core component (SNRPC), which is low molecular weight, is 48th on the list. Numerous SRSFs and the snRNP core proteins (SNRPs) that are known U1 snRNP components are also in the interactome. We next investigated the U1 interactome using STRING (Fig. 7). Unexpectedly, this analysis revealed numerous complexes not typically associated with the role of U1 snRNP as a canonical splicing factor. Indeed, the U1 snRNP interactome contained many complexes that we recently identified in the interactome of the RNAP II machinery. The latter machinery contains 274 proteins (BC *et al.*, submitted). Thus, we next directly compared the U1 snRNP and RNAP II machineries to one another. Remarkably, as shown in the Venn diagram, we found that virtually the entire U1 snRNP machinery interactome ($>90\%$) overlaps with the RNAP II machinery interactome (Fig. 8a). The extent of the overlap between the U1 snRNP and RNAP II machineries is exemplified by the observation that core U1 snRNP components (SNRNP70, SNRPC, SNRNA) and SNRP core proteins are among the most abundant components of both the U1 snRNP and RNAP II machineries (Table S2 and BC *et al.*, submitted). The abundance of the U1 snRNP components is readily apparent on a Coomassie stained gel in which high levels of these components can be seen in both the U1 snRNP and RNAP II machineries (Fig. S2). Moreover, consistent with our observation that the two machineries overlap, we found that RNAP II elutes in the same fractions as U1 snRNP components (SNRPA and SNRPC) in the high molecular weight region of a gel filtration column (Fig. 8b).

To validate the association of components of the U1 snRNP machinery with the RNAP II machinery, we carried out IP/Westerns. As shown in Fig. 8c, three DEAD box helicases, DHX9, DDX5, and DDX17, which are shared by both machineries all co-IP with both RNAP II and U1 snRNP, but not with the negative control EIF4A3. In addition, reciprocal IPs showed that all three proteins co-IP with U1 snRNP, and this association is specific as it is completely disrupted by the U1 AMO (Fig. 8d). Although the U1 snRNP machinery is highly abundant in RNAP II IPs, we do not observe reciprocal IPs of the RNAP II machinery using antibodies against U1 snRNP. One possible explanation for this is that the epitope on U1 snRNP that is recognized by the antibody is buried within the RNAP II machinery. We note that antibodies against the two other U1 snRNP core components also do not co-IP the RNAP machinery.

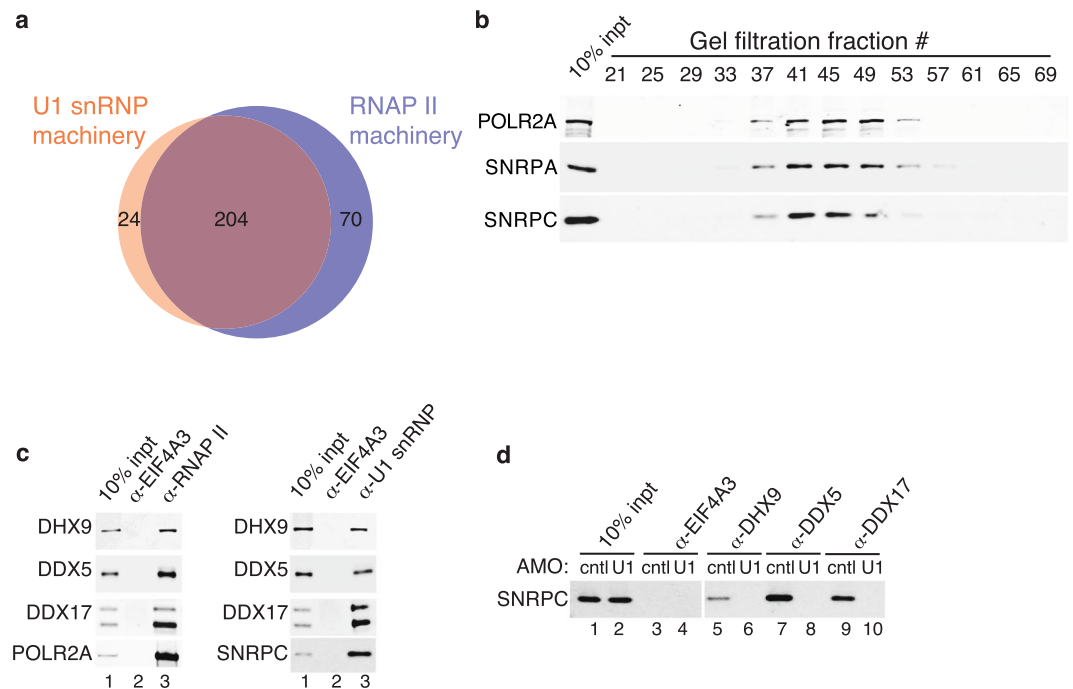


Figure 8. The U1 snRNP machinery overlaps with the RNAP II machinery. **(a)** Venn diagram showing overlap of the U1 snRNP and RNAP II machineries. **(b)** HeLa cell nuclear extract was separated on a Sephacryl-S500 column. The indicated fractions were used for Western analyses with antibodies against RNAP II and U1 snRNP components (SNRPA and SNRPC). Fraction 25 is the void volume and 69 is the included volume. **(c)** IPs were carried out from nuclear extract using an antibody to the POLR2A subunit of the RNAP II (left panel) or an antibody to the SNRPC subunit of the U1 snRNP (right panel) as well as a negative control antibody (EIF4A3) followed by Westerns with antibodies to the DEAD box helicases (DHX9, DDX5 and DDX17). **(d)** IPs were carried out with the indicated antibodies from nuclear extract treated with a U1 snRNA AMO or a negative control AMO followed by Western using the SNRPC antibody.

After elution, DTT was added to a final concentration of 40 mM, and 15 μ l of each eluate was analyzed on a 4–12% SDS-PAGE gradient gel (Life technologies). AMO treatment was performed by adding control AMO (5'-CCTCTTACCTCAGTTACAATTTATA-3') or U1 AMO (5'-GGTATCTCCCCTGCCAGGTAAGTAT-3')^{27,28} to HeLa nuclear extract to a final concentration of 12 μ M before IP. For analysis of total RNAs in the IPs, beads were treated with proteinase K for 10 min at 37 °C, and RNAs were recovered by phenol/chloroform extraction and ethanol precipitation. RNAs were run on 8% denaturing polyacrylamide gels and stained with Ethidium Bromide.

Mass Spectrometry. To identify the interactomes of FUS, EWSR1, TAF15 and MATR3, the IP samples were trichloroacetic acid (TCA) precipitated and subjected to shotgun mass spectrometry. The total peptide number of the antigen in each IP was set as 100 and the relative peptide numbers of each interactors are shown in Table S1. Abundant cytoplasmic proteins, ribosomal proteins, proteins greater than 250 kDa, and proteins for which the relative total peptide number is smaller than 5 were omitted. For mass spectrometry of the U1 snRNP machinery, the IP was TCA precipitated and the digested peptides were labeled by tandem mass tag⁶¹ for MS3 analysis on an Orbitrap Fusion mass spectrometer coupled to a Proxeon EASY-nLC 1000 liquid chromatography (LC) pump (Thermo Scientific). Abundant cytoplasmic proteins, ribosomal proteins, proteins greater than 200 kDa with less than 10 spectral counts, proteins greater than 70 kDa with less than 4 spectral counts, and proteins with one spectral count were not included in Table S2. The proteins in Tables S1 and S2 were annotated with functions using the Gene Cards database (www.genecards.org)⁶² and/or searching the literature. To compare the U1 snRNP machinery and the RNAP II machinery, the quantitative mass spectrometry data of the WT RNAP II machinery (BC *et al.*, submitted) was filtered using the same criteria used for the U1 snRNP machinery as mentioned above.

Gel filtration. A reaction mixture containing 300 μ l of HeLa nuclear extract⁶⁰, 300 μ l of SDB (20 mM HEPES, pH 7.9, 100 mM KCl), 500 μ M ATP, 3.2 mM MgCl₂ and 20 mM creatine phosphate was incubated for 30 min at 30 °C. After incubation, the mixture was separated on a Sephacryl S500 (GE Healthcare) gel filtration column. The gel filtration column buffer contains 20 mM HEPES, 60 mM KCl, 2.5 mM EDTA and 0.1% Triton X-100.

Data availability statement. The materials and datasets generated during and/or analyzed during the current study are available from the corresponding author upon request.

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Acknowledgements

We are grateful to lab members for useful discussions and critical reading of the manuscript. This work was supported by NIH grants R01GM043375 and R35GM122524 to R.R.

Author Contributions

B.C. and R.R. conceived the project. The experiments were carried out by B.C. and T.Y. Mass spectrometry was performed by J.D.O. The data were analyzed by B.C., J.D.O., S.P.G. and R.R. with assistance from J.G. The manuscript was written by B.C. and R.R. with input from all authors.

Additional Information

Supplementary information accompanies this paper at <https://doi.org/10.1038/s41598-018-27136-3>.

Competing Interests: The authors declare no competing interests.

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