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NSD3–NUT Fusion Oncoprotein in NUT Midline Carcinoma: Implications for a Novel Oncogenic Mechanism

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INTRODUCTION

Hematopoietic and mesenchymal malignancies are often characterized by translocation-associated fusion oncoproteins that block differentiation. In 1973, several epithelial cancers were discovered to harbor multiple sequential mutations that contribute to their progression, leading to a multistep pathway to carcinogenesis. One exception of that paradigm is a fusion oncogene that is driven by a translocation: NUT midline carcinoma (NMC). NMC is defined by the presence of the NUT (aka NUTM1) gene that is most commonly fused to the BET family gene BRD4 and BRD3 (1, 2), which are part of a multistep pathway, leading to a poorly differentiated state. NMCs are more aggressive than even small cell carcinoma of the lung, with a median survival of 6.7 months (3), and there exist no effective treatment options.

Recent excitement in small-molecule BET inhibitors arose from the demonstration of therapeutic targeting of BRD–NUT oncoproteins in NMC in vitro and in preclinical models. This has led to clinical trials using the GSK BET inhibitor drug, GSK-525762A, and the Tenshla Therapeutics BET inhibitor, TEN-010, now enrolling patients with NMC and other solid tumors (NCT01587703) (4). BET inhibitors are acetyl-histone mimetics that target the acetyl-histone binding pocket of BET protein chromatin-reading bromodomains, such as those of BRD2, 3, 4, and T (4, 5). BET inhibitors induce differentiation and proliferation arrest of NMC and are a potential form of differentiation therapy in this disease. It is not clear how interference with chromatin binding leads to inhibition of the blockade of differentiation by BRD–NUT oncoproteins, because the mechanism by which BRD–NUT blocks differentiation is unclear. Evidence suggests that deregulation of MYC expression by BRD–NUT may be key to the blockade of differentiation (6), but it remains to be determined whether BRD–NUT acts directly or indirectly.

Known functional domains of BRD4 that are present in BRD–NUT fusions may give clues to its function. Wild-type BRD4 binds to acetylated histones and the positive transcriptional elongation factor, P-TEFb with its bromodomains (7), and is associated with transcriptional activation of target genes (7, 8). Although the function of NUT, an entirely unstructured protein, is unknown, it binds to and activates the histone acetyltransferase (HAT) p300 (9). Both of the bromodomains and the p300-binding domain are present in BRD–NUT oncoproteins. This has led to the hypothesis that BRD–NUT fusion oncoproteins tether HATs and transcriptional cofactors to chromatin via their bromodomains, leading to a feed-forward process of acetylation and recruitment that results in sequestration of these factors away from pro-differentiation genes to progrowth genes, such as MYC (2, 9).

The role of the ET domain and its binding proteins has not been investigated in the context of BRD–NUT oncoproteins. Here, we describe a novel fusion in a NUT-variant NMC that results in sequestration of these factors away from pro-differentiation genes to progrowth genes, such as MYC (2, 9).

ABSTRACT

NUT midline carcinoma (NMC) is an aggressive subtype of squamous cell carcinoma that typically harbors BRD4/3–NUT fusion oncoproteins that block differentiation and maintain tumor growth. In 20% of cases, NUT is fused to uncharacterized non-BRD gene(s). We established a new patient-derived NMC cell line (1221) and demonstrated that it harbors a novel NSD3–NUT fusion oncogene. We find that NSD3–NUT is both necessary and sufficient for the blockade of differentiation and maintenance of proliferation in NMC cells. NSD3–NUT binds to BRD4, and BRD bromodomains induce differentiation and arrest proliferation of 1221 cells. We find further that NSD3 is required for the blockade of differentiation in BRD4–NUT-expressing NMCs. These findings identify NSD3 as a novel critical oncogenic component and potential therapeutic target in NMC.

SIGNIFICANCE: The existence of a family of fusion oncoproteins in squamous cell carcinoma is unprecedented, and should lead to key insights into aberrant differentiation in NMC and possibly other squamous cell carcinomas. The involvement of the NSD3 methyltransferase as a component of the NUT fusion protein oncogenic complex identifies a new potential therapeutic target. Cancer Discov; 4(8): 928–41. ©2014 AACR.
be a key component of the BRD–NUT oncogenic complex. Thus, we investigated the oncogenic role of NSD3 in this NUT-variant NMC as well as more typical BRD4–NUT NMCs.

RESULTS

A Novel NSD3–NUT Fusion in NMC

A poorly differentiated squamous cell carcinoma of the mediastinum (Fig. 1A) metastatic to the femur of a 13-year-old girl was referred to us for molecular diagnostic testing for NMC. Immunohistochemical analysis revealed diffuse nuclear expression of the NUT protein, a feature that is diagnostic of NMC (Fig. 1B; ref. 10). FISH demonstrated rearrangement of the NUT gene locus on chromosome 15q14; however, neither BRD4 nor BRD3 rearrangement was detected. Discarded live tumor tissue from a metastatic focus in the patient’s lung was collected under Institutional Review Board approval through the NMC registry (www.NMCRегистry.org). From this tissue, the first known NUT-variant cell line, 1221, was established. To determine the putative partner gene to NUT, we performed comprehensive RNA sequencing on RNA purified from 1221 cells. We identified an in-frame transcript fusing the 5′ coding sequence of NSD3 (exons 1–7) to exons 2–7 of NUT (Fig. 1C). Expression of the NSD3–NUT fusion oncprotein was verified by immunoblotting with an antibody to NUT, revealing an approximately 200-kDa band that is similar in size to BRD3–NUT, but smaller than BRD4–NUT (Fig. 1D). Knockdown using siRNAs targeting NSD3 led to the disappearance of the putative NSD3–NUT band, as did siRNAs targeting NUT, confirming the identity of the NSD3 and NUT portions of the NSD3–NUT fusion protein (Fig. 1E). Genomic fusion of the NSD3 and NUT genes was confirmed by FISH, demonstrating bring-together of NUT and NSD3 probes (Fig. 1F). Likewise, the expression of an NSD3–NUT mRNA was demonstrated by reverse transcriptase PCR (RT-PCR; Fig. 1G). Cytogenetic analysis of the 1221 cell line was consistent with an NSD3–NUT fusion, revealing a t(8;15)(p12;q15) translocation, and metaphase FISH demonstrated localization of the NUT probe near the NSD3 chromosomal region (8p11.23; Supplementary Figs. S1–S2). Several additional aberrations of unknown significance were also present.

The fusion sequence is predicted to encode a 1694 amino acid protein containing amino acids 1–569 of NSD3, and 8–1132 of NUT. Interestingly, the NSD3 portion of the fusion protein lacks the Su(var)3–9, Enhancer-of-zeste and Trithorax (SET) domain and contains only its Pro–Trp–Trp–Pro motif (PWPW) domain, whereas nearly all of NUT is included in the fusion, as is typical in NMC (Fig. 1H; refs. 1, 11, 12). The NSD3–NUT fusion bears no resemblance to NUP98–NSD3/NSD1 fusion oncogenes that have been previously described in leukemia (13, 14), all of which fuse NUP98 to the 3′ end of NSD3/NSD1 containing their SET, PHD (Plant Homeo Domain), and C/H (Cys–His)-rich domains.

NSD3–NUT Is a Recurrent Form of NMC

We next sought to determine whether NSD3 is a recurrent NUT fusion partner in NMCs; thus, we performed a dual-color NSD3 split-apart FISH assay on several NUT-variant cases. Four of eight non-BRD3/BRD4–NUT NMC cases (including the index case) demonstrated rearrangement of NSD3 and NUT, suggesting a frequent incidence of NSD3–NUT among NUT-variant cases (Fig. II).

NSD3–NUT Is Required for the Blockade of Differentiation and Maintenance of Proliferation in 1221 NMC Cells

The recurrent existence of NSD3–NUT in NMCs suggested that it may function similarly to BRD–NUT by blocking differentiation and maintaining proliferation of NMC cells (2). We thus knocked down endogenous expression of NSD3–NUT in 1221 cells to determine its effect on growth and differentiation. Seventy-two hours following knockdown, 1221 cells exhibited differentiation as evidenced by increased keratin expression, an epithelial differentiation marker, by immunofluorescence (Fig. 2A and B), and decreased proliferation as measured by Ki-67 fraction (Fig. 2C) and cell number (Fig. 2D). Notably, knockdown of wild-type NSD3 using siRNAs directed toward the 3′ end of NSD3 that is not included in the NSD3–NUT fusion gene had no effect on differentiation (Fig. 2B). These findings indicate that NSD3–NUT serves to block differentiation and maintain proliferation of 1221 cells.

Wild-Type NSD3 Is Required for the Blockade of Differentiation in BRD4–NUT-Expressing NMC Cells

NSD3 is one of several proteins that have been shown to bind to the ET domain of BET proteins (8). Thus, we hypothesized that NSD3 may have an oncogenic role in NMC through its interaction with BRD4–NUT’s retained ET domain. It is noted that the BRD3 and BRD4 fusions with NUT in the BRD–NUT NMCs occur 3′ to the ET domain; thus, the ET domain is always included as part of the fusion protein (1, 2). We therefore tested whether NSD3 is required for the blockade of differentiation in BRD4–NUT-expressing NMC cells. In three different patient-derived BRD4–NUT NMC cell lines, TC-797 (15), PER-403 (16), and B645 (17), siRNA knockdown of NSD3 resulted in differentiation, as measured by increased expression of the terminal squamous differentiation marker involucrin (Fig. 3A–C). This was accompanied by morphologic differentiation, as evidenced by flattening and enlargement of cells (Fig. 3B and Supplementary Fig. S3), as well as mild-to-moderate decreased proliferation quantified by Ki-67 staining (Fig. 3D) in all cell lines. Moreover, induced expression of the ET domain fused to a nuclear localization sequence (NLS) in a tet-inducible NMC derivative cell line, 797TRex, exhibited a dominant negative effect on BRD4–NUT function, inducing differentiation morphologically and immunophenotypically (Fig. 3E). In addition, induction of ET domain expression also negatively affected the proliferation rate of TC-797 cells, whereas the growth of heterologous, non-NMC cells, U2OS, or 293T, was unaffected (Fig. 3F). The findings indicate that expression of wild-type NSD3 protein and the ET domain of BRD4–NUT are required for the blockade of differentiation in BRD4–NUT NMC. The specific requirement of the ET domain for the oncogenic function of BRD4–NUT is evidenced by its conservation in all characterized BRD–NUT fusions (1, 2, 12, 18, 19), including uncommon splice variants (16, 18), and by...
A novel NSD3–NUT fusion is identified in NMC. A, histology of the NMC from which the 1221 cell line was derived reveals a very poorly differentiated tumor (magnification, ×400). B, IHC of the tumor using the anti-NUT monoclonal antibody C52 (magnification, ×400). C, RNA-sequencing reads spanning the junction of NSD3 and NUT. D, immunoblot of three NMC cell lines and 293T control cells stained with AX.1 polyclonal antibody to NUT. E, immunoblot of the 1221 cell line 48 hours following transfection with control (CTRL), NSD3, and NUT siRNAs stained with the AX.1 antibody to NUT. F, NSD3–NUT dual-color bring-together FISH assay (magnification, ×1,000) using bacterial artificial chromosome (BAC) probes telomeric (3′) to NUT (green), and BAC probes centromeric (5′) to NSD3 (red) as depicted in the chromosomes 8 and 15 ideograms. Yellow arrows, NSD3–NUT fusions. G, gel electrophoresis of PCR of TC-797 and 1221 cell lines with (+) and without (−) reverse transcriptase reaction. H, schematic of the NSD3–NUT predicted encoded protein in comparison with NSD3, NUT, and BRD4–NUT. PWWP, Pro–Trp–Trp–Pro motif; PHD, plant homeo domain; SET, Drosophila Su(var)3-9 and 'Enhancer of zeste'; C/H, Cys-His; NES, nuclear export signal sequence; Bromo, bromodomain. Arrows, breakpoints. I, NSD3 dual-color split-apart FISH assay using BAC probes flanking NSD3, as depicted in the chromosome 8 ideogram, depicted in three NMCs, not including 1221, designated cases 1–3. All photomicrographs are of identical magnification (×1,000).
the lack of growth inhibition induced by ET domain expression in non-BRD–NUT-expressing cell lines (Fig. 3F).

The N-Terminus of NSD3 Associates with BRD4 and BRD4–NUT

Because the ET domain is retained in BRD–NUT oncoproteins, we predicted that the interaction of NSD3 with BRD4 would be preserved when coexpressed with BRD4–NUT. BRD4–NUT normally localizes to discrete nuclear foci by immunofluorescence and IHC. We found that the HA-tagged portion of NSD3 present in NSD3–NUT (NSD3Tr, corresponding to amino acids 1–569 of NSD3) colocalized with BRD4–NUT foci (Fig. 4A). Moreover, HA-tagged NSD3, NSD3–NUT, and NSD3Tr (Fig. 4B) coimmunoprecipitated BRD4 in C33A cervical carcinoma cells. In reciprocal experiments, HA-tagged constructs of BRD4 and BRD4–NUT, but not NUT, were coimmunoprecipitated NSD3 (Fig. 4C). Of note, all the multiple NSD3 isoforms seen in this blot contain the N-terminal domain of NSD3 (NSD3Tr) that is present in the NSD3–NUT fusion protein that interacts with BRD4 (Fig. 4B). The findings indicate that NSD3 does associate with BRD4–NUT. To determine the role of the association of NSD3 with BRD4–NUT in the blockade of differentiation, NSD3Tr was expressed in 797TRex cells, and was found to induce differentiation (Fig. 4D). The findings, coupled with the dominant-negative effects of ET domain expression (Fig. 3E and F), suggest that the interaction of NSD3 with BRD4–NUT may be required for the blockade of differentiation. In support of this, other known interactors of the ET domain, including CHD4, ATAD5, GLTSCR1, and JMJD6 (MCB), were knocked down in TC-797 cells, but failed to induce differentiation (Supplementary Fig. S4A and S4B). Although the findings suggest that NSD3–ET domain interaction is required for the blockade of differentiation in NMC, they are not conclusive, because other unknown interactors with either of these domains may be critical.
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**Figure 3.** Wild-type NSD3 is required for the blockade of differentiation in BRD4-NUT-expressing NMC cells. A, immunoblots of BRD4-NUT-positive NMC cell lines TC-797, PER-403, and 8645 120 hours following transfection with control and NSD3 siRNAs stained with the terminal squamous differentiation marker involucrin, using GAPDH as loading control. B, representative photomicrographs of TC-797s 120 hours following transfection with either control or NSD3 siRNAs stained with H&E for morphology, or involucrin IHC. All photographs are of identical magnification (×400). C, qRT-PCR of NSD3 levels 24 hours following transfection of control or NSD3 siRNAs. Primers were either 5′ of the breakpoint (NSD3-5′ primers), or 3′ of the breakpoint (NSD3-3′ primers) with NUT. Results are of a single biologic replicate performed in triplicate. Error bars, the mean ± SD of the triplicate wells. D, proliferation assay (Ki-67 fraction) comparing BRD4-NUT-positive TC-797, 8645, and PER-403 NMC cells transfected with control and NSD3 siRNAs. Three hundred cells were counted per cell block. E, 797TRex cells induced to express FLAG-tagged NLS-ET domain for 120 hours. Immunoblot was performed with anti-involucrin (Inv), anti-FLAG, or anti-GAPDH (left). Cell block preparations were H&E stained, or subjected to involucrin IHC (right). All photographs are of identical magnification (×400). F, cell viability assay (CellTiter-Glo) of 797TRex, 293TRex, and U2OSTRex cells induced to express FLAG-tagged NLS-ET domain for 120 hours. Results are the average of three biologic replicates, each performed in quadruplicate and normalized to the negative control (ethanol vehicle control) for each cell line. Error bars, the mean ± SD of the three biologic replicates. Immunoblot demonstrating NLS-FLAG-ET expression was stained with anti-FLAG or anti-GAPDH (right).
Figure 4. The N-terminus of NSD3 associates with BRD4 and BRD4–NUT. **A,** immunofluorescence microscopy of 797TRex cells induced to express the HA-tagged portion of NSD3 included in NSD3–NUT (NSD3Tr) for 24 hours stained with anti-NUT monoclonal antibody (red), and anti-HA monoclonal antibody (green). **B,** immunoblot of anti-HA immunoprecipitations (IP) of tet-repressor–positive C33A cell (C33A-6TR) lysates following induction of expression of HA-tagged NSD3 variants: HA-NSD3 (full-length), HA-NSD3–NUT, and HA-NSD3-tr (NSD3 portion of the NSD3–NUT fusion protein). Indicated proteins were detected using anti-HA and anti-Brd4 antibodies. The smaller bands are degraded protein. **C,** immunoblot of anti-HA immunoprecipitations of C33A-6TR lysates following induction of expression of HA-tagged NUT, BRD4, and BRD4–NUT constructs stained with anti-HA, anti-NSD3, anti-p300, and anti-actin antibodies. To identify the NSD3-specific bands, lysates from TC-797s subjected to siRNA knockdown of NSD3 are shown. **D,** immunoblot of 797TRex lysates 120 hours following induction of expression of BioTAP-tagged NLS fusion construct of NSD3Tr stained with anti-involucrin, anti-PAP (recognizes the protein A moiety of the BioTAP tag), and anti-GAPDH antibodies.
NSD3 Is Required for BRD4–NUT Foci Formation

The function of BRD4–NUT foci is unknown; however, it has been demonstrated that they are intensively enriched with BRD4–NUT and factors associated with transcription, including RNA polymerase II, the HAT, p300, the transcriptional elongation complex P-TEFb, and active histone marks (9, 20). On the basis of these observations, it is believed that BRD4–NUT foci are important to the function of BRD4–NUT in transcriptional regulation (9, 20), though this has not been tested directly. To determine what role, if any, NSD3 has in the formation of BRD4–NUT foci, we knocked it down in TC-797 cells and quantified foci number as compared with control siRNA-transfected cells. We found that the reduction of BRD4–NUT foci after NSD3 knockdown was not accompanied by a reduction of total BRD4–NUT protein levels (Fig. 5C), indicating that the effect is not due to loss of BRD4–NUT. Thus, the findings indicate that NSD3 is required for BRD4–NUT focus formation, suggesting a key role in BRD4–NUT complex or aggregate formation.

NSD3–NUT Can Replace BRD4–NUT in the Blockade of Differentiation

Because NSD3 is critical for BRD4–NUT function, we investigated whether NSD3–NUT was functionally equival-
existence of NSD3–NUT speaks to the importance of NSD3 and its association with BRD4–NUT. NSD3, also known as WHSC1L1, is a histone methyltransferase that belongs to the mammalian nuclear SET domain-containing (NSD) protein family of SET domain-containing methyltransferases, which also includes NSD1 and NSD2 (WHSC1/MMSET). Both NSD3 and NSD2 are known to bind the ET domain of BRD4; thus, the dominant-negative phenotype of ET and NSD3Tr expression in NMC cells is evidence that this interaction of BRD4 with NSD3 may be critical to BRD4–NUT function. However, it is not clear that the methyltransferase activity of NSD3 is needed for BRD4–NUT function as it is for NUP98–NSD3 fusions (14), because the NSD3 portion of NSD3–NUT lacks the SET domain. Moreover, knockdown of full-length NSD3 in the 1221 cells (Fig. 2B) does not induce differentiation, again suggesting that NSD3’s SET domain is not required for the differentiation blockade. Thus, it appears that the critical portion of NSD3 is its N-terminal, ET-binding domain in NSD3–NUT-expressing NMC. Combining these data with the fact that BRD4 expression and interaction with chromatin is required for NSD3–NUT function (Fig. 7), we have devised a model whereby the NSD3 portion links NSD3–NUT to BRD4, which tethers NSD3–NUT to chromatin, forming a complex that functions similarly to BRD4–NUT. In future studies, we plan to test this model by examining whether the interaction of NSD3–NUT with BRD4 is required for the oncogenic function of NSD3–NUT. In the context of BRD4–NUT-expressing NMC, we have shown that NSD3 is required for BRD4–NUT foci formation (Fig. 5A), suggesting a role in the aggregation of large BRD4–NUT-containing foci.

**Figure 6.** NSD3–NUT can replace the function of BRD4–NUT to block differentiation. A, H&E and anti-involucrin IHC micrographs of 797TReX cells with tetracycline (ON), or treated with vehicle (OFF) to express NSD3–NUT 120 hours following transfection with either control or NUT 3′-UTR siRNA. All photographs are of identical magnification (×400). B, immunoblots using lysates corresponding to the experiment in A were performed for the differentiation marker, involucrin, NSD3–NUT, and BRD4–NUT using antibodies to NUT. C, quantification of immunohistochernical Ki-67 proliferation fraction of 797TReX cells induced to express NSD3–NUT 120 hours following transfection with either control or NUT 3′-UTR siRNA as in A. Results are the average of three biologic replicates performed using the 384-well high-throughput assay as in Fig. 2A, each performed in triplicate. Error bars, the mean ± SD of the three biologic replicates. *, P < 0.0001.
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Although its importance is not known in NSD3–NUT+ NMCs, NSD3 methyltransferase activity may be important to the function of BRD4–NUT NMC. The SET domain of NSD proteins is homologous to the *Saccharomyces cerevisiae* histone 3 lysine 36 (H3K36)–specific methyltransferase SET2 and is specific for H3K36 dimethylation (H3K36me2; ref. 25). NSD3 has been reported to regulate H3K36 methylation and thereby active gene expression (8, 26). It is possible that akin to the aberrant activation of HoxA1 expression by NUP98–NSD1-mediated methylation of H3K36 in acute leukemia (14), NSD3 may contribute to the transcriptional activation of key targets of BRD4–NUT. Although the NUP98–NSD3 fusion oncogene has been described in acute leukemia as well (13), it has not been further characterized mechanistically. Proteomic analysis of NSD3 suggested that the protein also interacts with the histone protein variant macroH2A1. MacroH2A1 replaces conventional H2A histones in a subset of nucleosomes, where it represses or activates transcription and participates in stable X chromosome inactivation (27–29). Moreover, macroH2A1 regulates cell growth and differentiation and is differentially expressed in cancer cells (30–32). Thus, NSD3 may regulate differentiation in BRD4–NUT-expressing NMCs by affecting differentiation-specific genes via alterations of H3K36 or macroH2A1 levels.

**BET and NSD3 Proteins in Cancer**

NSD family proteins have been associated with other cancers (reviewed in ref. 33). Chromosome translocation resulting in NSD2 (aka MMSET) overexpression leads to multiple myeloma, whereas reduction in NSD2 levels suppresses cancer growth (34–36). Moreover, NSD3 is amplified in breast cancer cell lines and primary breast carcinomas (37, 38). NSD3 has been reported to contribute to the transformed phenotype and invasiveness of these breast cancer cells (39, 40). Most recently, mutations in NSD3 have been identified in pancreatic adenocarcinoma (41). Despite these associations, the mechanism by which NSD3 contributes to oncogenesis in these cancers remains poorly understood.

A key to understanding the role of NSD3 in cancer may be through its association with BRD4. The indispensability of the BRD4 chromatin-binding bromodomains in NMC (4, 6) and
its ET domain’s role in recruiting NSD proteins demonstrates that BRD4 is a key player in BRD4-NUT chromatin-associated oncogenic complex formation. Moreover, recent studies with BET inhibitors have shown that BRD4 plays a role in other human cancers such as acute myeloid leukemia, multiple myeloma, and Burkitt lymphoma (42–44). In these cancers, as well as in NMC, BRD4 and BRD4-NUT, respectively, are required for the maintenance of MYC expression, and BET inhibitors repress expression of MYC, presumably through interference with BRD4-chromatin interaction (6, 43, 44). Our findings that siRNA knockdown or BET inhibitor blockade of BRD4 function induce differentiation in NSD3-NUT-expressing NMC cells indicate that NSD3 function depends on BRD4 and its interaction with chromatin (Fig. 7). If NSD function is dependent upon BRD4 in other cancers, these NSD-associated cancers may be responsive to BET inhibitor therapy. Thus, oncogenic NSD may be a biomarker of response to BET inhibitor therapy.

Drug Targeting of NSD3

Apart from BET inhibitors, this study highlights the importance of the therapeutic potential of targeting the NSD family of proteins. Histone-modifying enzymes, including the NSD family, are often deregulated in cancer, and aberrant histone modification profiles are intimately linked to carcinogenesis (45). Histone deacetylase (HDAC) inhibitors have been found to be effective in inhibiting NSD3-NUT-expressing NMC cells indicating that NSD3 function depends on BRD4 and its interaction with chromatin (42–44). HDAC inhibitors may be responsive to BET inhibitor therapy. Thus, oncogenic complex formation. Moreover, recent studies with BET inhibitors have shown that BRD4 plays a role in other human cancers such as acute myeloid leukemia, multiple myeloma, and Burkitt lymphoma (42–44). In these cancers, as well as in NMC, BRD4 and BRD4-NUT, respectively, are required for the maintenance of MYC expression, and BET inhibitors repress expression of MYC, presumably through interference with BRD4-chromatin interaction (6, 43, 44). Our findings that siRNA knockdown or BET inhibitor blockade of BRD4 function induce differentiation in NSD3-NUT-expressing NMC cells indicate that NSD3 function depends on BRD4 and its interaction with chromatin (Fig. 7). If NSD function is dependent upon BRD4 in other cancers, these NSD-associated cancers may be responsive to BET inhibitor therapy. Thus, oncogenic NSD may be a biomarker of response to BET inhibitor therapy.

METHODS

FISH

Dual-color FISH assays for NSD3 and NUT breakpoints were performed on formalin-fixed, paraffin-embedded, 4-μm tissue sections as described previously (20). Probes used for the 15q14 breakpoint flankning NUT included the telomeric bacterial artificial chromosome (BAC) clones RP11-11H8 and RP11-6403, and the centromeric clones RP11-1084A12 and RP11-368L15. Probes used for the chromosome 8p11.23 NSD3 breakpoint were the flanking 5’ centromeric BAC clones CTB-497A2 and RP11-9059P. Cytogenetic analysis and metaphase FISH was performed using standard methods (48, 49).

RNA Sequencing

RNA was extracted from live cultured 1221 cells using the RNeasy Mini Kit (Qiagen). Elim Biopharmaceuticals performed the library preparation and sequencing. RNA removal was performed using the Ribo-Zero Kit (Epicentre) following the manufacturer’s instructions. The library was prepared using standard Illumina protocols with proprietary modifications and sequenced using HiSeq2500 (Illumina). TopHat-Fusion (v2.0.8c bundled with TopHat2) was run with default parameters (as described at http://tophat.cchub.md/ top/hat/ tutorial.html#top but with t=50 and t-max-intron-length 1000000) to identify novel fusion transcripts from paired-end 50 base reads (50, 51).

RT-PCR

RT-PCR was as described (6) using the following primers: NSD3F1382 AAGAGGCCACCGCTCTTAA; NUTv388 GCTTCGA CAATGGAGGTGC; GAPDH254f TCAAGTGGGGCGATGCTGGC GCT; and GAPDH788r AGGGGGCCCTCCGACGCTCCT.

Plasmids

BRD4 ET domain containing fragment (BRD4 444–722) was cloned into pcDNAs FRT/TO-FLAG (Invitrogen) with an N-terminal SV40 NLS sequence to generate pcDNAs FRT/TO-Flag-NLS-BRD4-ET (p6894). MSCV-CMV-Flag-HA-NSD3 (p6351) has been described previously (8). To make tetracycline-inducible N- and C-terminal BioTAP-tagged constructs, we transferred the gateway destination cassette from pHAGE-TRE (gift of Steven Elledge, Harvard Medical School, Boston, MA) to the pcDNA5 frt/to mammalian expression vector with N-terminal BioTAP tandem tag to make pcDNA5 frt/to-DEST-NBioTap. NSD3-NUT was constructed by fusion PCR into pDONR223, then transferred into the pcDNAs frt/to-DEST-NBioTap vector by gateway cloning. Full-length NSD3, NSD3Tr encoding amino acids 1–569 of NSD3, full-length NUT, and BRD4-NUT (derived from pcDNAs frt/ to FLAG-BRD4-NUT; ref. 17) were PCR-cloned into pDONR223, then transferred by gateway cloning into the pHAGE-P CMV N-HA GAW expression vector derived from the PHAGE lentiviral vector (52).

A tetracycline-inducible HA-tagged NSD3Tr was gateway cloned from pDONR223 into the tetracycline-inducible pHAGE-P CMV N-HA GAW expression vector and into the tetracycline-inducible pHAGE-TRE-HA (gift of Steven Elledge).

Cell Culture

NMC cell lines, TC-797 (15), 10–15 (6), 8645 (17), 293T, U2OS, and C33A cells were maintained as monolayer cultures in DMEM (Invitrogen) supplemented with 10% (v/v) FBS (SH3008803; Hyclone) and 1% pen–streptomycin (GIBCO/Invitrogen). The 797Trex cell line was created using Flip-In technology as described previously (Invitrogen; ref. 6) and maintained as above, but with the addition of Hygromycin (150 μg/mL; Sigma-Aldrich) and Blasticidin (7.5 μg/mL; Life Technologies) to maintain selection of cDNA insert and repressor genes, respectively. 797Trex/Flag-NLS-ET and N-BioTAP-NSD3-NUT cell lines were generated by recombination with the plasmid pcDNA5 FRT/TO-FLAG-NLS-ET and N-BioTAP-NSD3-NUT (above) using Flip-In technology (Invitrogen). The resulting cell line was maintained in DMEM (Invitrogen) supplemented with 10% (v/v) FBS (SH3008803; Hyclone), 1% pen–streptomycin (GIBCO/Invitrogen), 7.5 μg Blasticidin/mL and 150 μg Hygromycin/mL. The 1221 cell line is derived from a lung metastasis from the index case of a 13-year-old female with NSD3-NUT-positive NMC. The 1221 cells were grown and maintained in WIT media as described previously (17, 53). Tet-inducible C33A cells (C33A-STR) were established by transfecting C33A cells with pcDNA/DE-253892 and RP11-957P17 and the 3′ telomeric BAC clones CTB-497A2 and RP11-9059P. Cytogenetic analysis and metaphase FISH was performed using standard methods (48, 49).

RNA Sequencing

RNA was extracted from live cultured 1221 cells using the RNeasy Mini Kit (Qiagen). Elim Biopharmaceuticals performed the library preparation and sequencing. RNA removal was performed using the Ribo-Zero Kit (Epicentre) following the manufacturer’s instructions. The library was prepared using standard illumina protocols with proprietary modifications and sequenced using HiSeq2500 (Illumina). TopHat-Fusion (v2.0.8c bundled with TopHat2) was run with default parameters (as described at http://tophat.cchub.md/ top/hat/ tutorial.html#top but with t=50 and t-max-intron-length 1000000) to identify novel fusion transcripts from paired-end 50 base reads (50, 51).

Luminescent Cell Viability Assay

Cells were plated at a density of 3,000 per well in a 96-well plate, and CellTiter-Glo (Promega) was used to determine cell viability as a measure of ATP content according to the manufacturer’s instructions.

siRNA Transfections

For TC-797, Per403, and 8645 cells, 7 × 10^6 cells were transfected with 50 nmol/L siRNA using Nucleofector II (Lonza) and Amaxa solution R and plated in 100-mm cell culture dishes. 1221 cells were transfected using RNAi-MAX (Invitrogen) using the manufacturer’s protocol. Briefly,
reverse transfection procedure was used to deliver 50 nmol/L siRNA to 33 × 10^6 cells in a 6-well plate. Cells were analyzed for mRNA levels 24 hours after transfection. Sequences of siRNA used were: a) Control, ON-TARGETplus siRNA #1 (Dharmacon; cat no. D-001810-01-20); siNUT-1 (targeting coding sequence), AAACUGAAGCAAUUCUUAUU; siNUT-2 (targeting the 3′-UTR), UAACCUUUGGAGGCGCCUA; siBRD4-1, 5′-cGUCCUGGUCCGAGAGGAGUUA; and siNSD3-6, ON-TARGETplus Human WHSC1L1 (5′-9404); (Dharmacon; cat no. J-012875-06-0020); siNSD3-7, ON-TARGETplus Human WHSC1L1 (5′-9404) siRNA (Dharmacon; cat no. J-012875-07); siNSD3, 3′-1 CUGUAAACCCUCUAAAGAAAUU; siNSD3, 3′-2 GAAAGGUGCCGAGAGGAGAUUU; siNSD3f, 5′-AGUGCGAAAGCAAGGAAAGAGA; and RPL13Ar, 5′-TCTTCTTCTCCAC; 5′-NSD3f GCCCCAGTGCCAGCATTACT; 5′-NSD3r ACCATACAAGGCCACACAGG; RPL13Af CCTGAGGAAGAGGAGAAAGAGA; and RPL13ar TTGGAGGACCCTGTTGATTGTCCAA, and using the TaqMan primers (Life Technologies), JMD56 (Hu00397095_m1), NSD3 (Hu00256555_m1), GLTSRC1 (Hu00185234_m1), and ATAD5 (Hu00227495_m1).

Immunofluorescence

Immunofluorescence on TC-797 cells was performed as described previously (55) and nuclei were counterstained with ProLong Gold antifade reagent with 4′,6-diamidino-2-phenylindole (DAPI; Life Technologies). Primary antibodies used were anti-NUT (1:1,000), rabbit anti-NUT (AX.1 rabbit polyclonal antibody; ref. 57), anti-GAPDH (1:5,000, mouse monoclonal 6C5; Life Technologies), anti-BRD4 (1:1,000; Bethyl Laboratories Inc.), anti-FLAG (1:1,000, mouse monoclonal; Sigma-Aldrich), anti-involucrin (1:1,000, mouse monoclonal; Sigma-Aldrich), anti-HA (1:1,000, mouse monoclonal; Sigma-Aldrich), anti-β-casein (1:1,000, mouse monoclonal clone 105; Abcam), anti-actin (1:1,000, mouse monoclonal clone 4; Millipore), and anti-p300 (1:1,000, mouse monoclonal clone RW128; EMD Millipore). Immunoblotting

For immunoblotting experiments of HA-tagged proteins, C33A-6TR cells stably expressing HA-tagged constructs under a tet-inducible promoter were used. Protein extracts were prepared 24 hours after transfection or induction with doxycycline (1 μg/mL). Cells were lysed in lysis buffer [50 mmol/L Tris–HCl (pH 7.5), 150 mmol/L NaCl, and 0.5% Nonidet P-40] with freshly added protease inhibitors (Roche Complete, EDTA-free protease inhibitor cocktail; Roche). Extracts were adjusted for protein concentration, and 10% of extracts were used as input. Immunoprecipitations were performed using 15 μL of HA-resin (Sigma A2095). Extracts were incubated overnight at 4°C, and precipitated proteins were detected by Western blot analysis.

IHC

Formalin-fixed, paraffin-embedded cell blocks of cultured cells were prepared using Histogel (Richard-Allan Scientific) as described previously (2). Sections were stained with hematoxylin and eosin (H&E) or by IHC, which was performed on 5-μm sections prepared from formalin-fixed, paraffin-embedded cell blocks. Immunohistochemical stains were performed using anti-NUT antibody (1:100, rabbit monoclonal clone C52; Cell Signaling Technology), anti-involucrin antibody (1:12,000; Sigma-Aldrich), and Ki-67 (MIB-1 clone; Dako; ref. 2). Three hundred cells were counted per sample for Ki-67 percentage. Standard deviations for triplicate counts are shown in figures.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors’ Contributions

Conception and design: C.A. French, S. Rahman, E.M. Walsh, A.R. Grayson, P.M. Howley

Gene Expression Analysis Using Quantitative Real-Time PCR

Total RNA was harvested at the indicated time points using TRIzol (Invitrogen) and the RNeasy Mini Kit (Qiagen), and RNA (1 μg) was reversed transcribed into cDNA using the iScript cDNA Synthesis Kit (Bio-Rad). Quantitative real-time PCR (qRT-PCR) was performed as described previously (6) using the reference gene ribosomal protein L13a (RPL13a) mRNA levels as normalizing control. All qRT-PCR experiments are representative of triplicate qRT-PCR reactions from one of three independent experiments. qRT-PCR was performed in triplicate on a Bio-Rad iCycler in 96-well plate format with iQ SYBR Green supermix (Bio-Rad) and 1 μL of cDNA template per reaction. Amplification curves and Cₜ values were generated using MyIQ Single-Color Real-Time software (Bio-Rad). Primers used were: 5′- NSD3 fwd TCTTCTTCTCCTCCTCCAC; 5′-NSD3r GCCCCAGTGCCAGCATTACT; 5′-NSD3r ACCATACAAGGCCACACAGG; RPL13Af CCTGAGGAAGAGGAGAAAGAGA; and RPL13ar TTGGAGGACCCTGTTGATTGTCCAA, and using the TaqMan primers (Life Technologies), JMD56 (Hu00397095_m1), NSD3 (Hu00256555_m1), GLTSRC1 (Hu00185234_m1), and ATAD5 (Hu00227495_m1).

High-Throughput Immunofluorescence Analysis of NMC cells

Cells were transplated in 384-well format using 50 nmol/L control siRNA (above), NSD3 siRNA (above), BRD4 siRNA, and NUT siRNA (above), as described previously (6), or a dose range of JQ1 treatment. Cells were stained with AE1/AE3 antibody (1:4; Dako) to measure keratin intensity, Ki-67 antibody (1:500; Cell Signaling Technology), and nuclei were stained with Hoechst 33342 (4 μg/mL; Molecular Probes). Imaging for keratin expression was performed using the ImageXpress high-throughput microscope with MetaXpress software (Molecular Devices) as described previously (56). Shown are representative images taken at ×400 magnification. Each condition was performed in triplicate in 384-well plate format in three separate experiments, where wells were analyzed using MetaXpress with Multi Wavelength Cell Scoring for cell number, average keratin fluorescence pixel intensity, and % Ki-67 per well. Statistics shown are from Student t tests.

RESEARCH ARTICLE

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