MINI REVIEW

TRKing Down an Old Oncogene in a New Era of Targeted Therapy

Aria Vaishnavi, Anh T. Le, and Robert C. Doebele

ABSTRACT

The use of high-throughput next-generation sequencing techniques in multiple tumor types during the last few years has identified NTRK1, 2, and 3 gene rearrangements encoding novel oncogenic fusions in 19 different tumor types to date. These recent developments have led us to revisit an old oncogene, Trk (originally identified as OncD), which encodes the TPM3–NTRK1 gene fusion and was one of the first transforming chromosomal rearrangements identified 32 years ago. However, no drug has yet been approved by the FDA for cancers harboring this oncogene. This review will discuss the biology of the TRK family of receptors, their role in human cancer, the types of oncogenic alterations, and drugs that are currently in development for this family of oncogene targets.

Significance: Precision oncology approaches have accelerated recently due to advancements in our ability to detect oncogenic mutations in tumor samples. Oncogenic alterations, most commonly gene fusions, have now been detected for the genes encoding the TRKA, TRKB, and TRKC receptor tyrosine kinases across multiple tumor types. The scientific rationale for the targeting of the TRK oncogene family will be discussed here. Cancer Discov; 5(1); 25–34. ©2014 AACR.

INTRODUCTION

The identification of dominant oncogenic mutations and our ability to specifically inhibit these genetic abnormalities with targeted inhibitors have altered the therapeutic approach for many patients with cancer, particularly those with non–small cell lung cancer (NSCLC). Activating point mutations, in-frame insertions/deletions, gene amplification, and gene rearrangements can serve as predictive biomarkers for oncogene-targeted therapies and thus help select patients that have a high likelihood of benefiting from a particular therapy. There are currently two well-established paradigms of this targeted therapy approach in NSCLC, both of which highlight the potential success of this strategy for other oncogene targets. Epidermal growth factor receptor (EGFR) mutation–positive patients who are treated with an EGFR tyrosine kinase inhibitor (TKI) have an objective response rate (ORR) of about 70% and a progression-free survival (PFS) time of approximately 10 months, both of which are superior to chemotherapy (2). ALK gene rearrangement–positive patients showed a response rate of approximately 65% and a PFS of approximately 8 months when treated with crizotinib, also superior to chemotherapy (3).

The paradigm of cancer treatment is shifting toward precision oncology. In this model, patients are selected for therapy using predictive biomarkers, such as oncogenic mutations, rather than using empiric chemotherapy. Many of the actionable or potentially actionable oncogenes that represent molecular subtypes in NSCLC involve genomic rearrangements with genes encoding receptor tyrosine kinases (RTK), such as ALK, ROS1, RET, and most recently NTRK1 (4–7). The unprecedented improvement in patient outcomes with oncogene-targeted therapies suggests that even rare oncogenes, such as ROS1 gene rearrangements (which occur at a frequency of ~1%–2%), should be investigated as therapeutic targets, as this molecular subset represents approximately 2,500 patients in the United States each year (8, 9). Indeed, a recent study of crizotinib in patients with ROS1-positive NSCLC highlights the ability to successfully accrue rare oncogene subtypes (10). The study of these low-frequency oncogenes not only applies to NSCLC, but also is directly relevant to the treatment of numerous other cancer types: ALK, ROS1, RET, and NTRK1 gene rearrangements have also been observed in other malignancies.
expanding the relevance of this work to colorectal cancer, thyroid cancer, cholangiocarcinoma, glioblastoma, inflammatory myofibroblastic tumors (IMT), ovarian cancer, bladder cancer, sarcomas, and others (11–17). Indeed, isolated reports show the success of targeting oncogenes across multiple tumor types (15, 18). It was estimated in 2007 that gene fusions were reported in approximately 20% of all cancers, accounting for a significant proportion of cancer morbidity and mortality (19). The emergence of high-throughput genomic technologies and programmatic sequencing efforts, such as the NCI/National Human Genome Research Institute Cancer Genome Atlas Network and the Sanger Cancer Genome Project, have generated the molecular profiles of numerous cancers, and this emergent technology has enabled the identification of many additional gene fusions that are putative oncogenes and predicted to be conserved as drivers across breast cancer, glioblastoma, lung cancer, colorectal cancer, and other tumors (16, 17, 20–22). This review describes the emergence of an increasingly described class of potential oncogenic targets in cancer, the TRK family of kinases.

TRK FAMILY BIOLOGY

The NTRK1 gene encodes TRKA, which is a member of the TRK (tropomyosin-receptor kinase) family of RTKs that includes TRKB (encoded by NTRK2) and TRKC (encoded by NTRK3) (12, 23). TRKA, TRKB, and TRKC play important roles in nervous system development through their regulation of cell proliferation, differentiation, apoptosis, and survival of neurons in both the central and peripheral nervous systems. The TRK receptors are expressed abundantly in the nervous system, as well as in many other nonneuronal cell types and tissues, including monocytes, the lung, bone, and pancreatic beta cells (24). TRKA, TRKB, and TRKC are most frequently activated by their primary ligands nerve growth factor (NGF), brain-derived neurotrophic factor (BDNF), and neurotrophin 3 (NT-3), respectively (25, 26). However, overexpression studies in cell lines suggest the possibility of promiscuity among these neurotrophin ligands and all three receptors that may be cell-type and neurotrophin concentration dependent (23). Additional studies have shown that NT-3 may activate TRKA and TRKB, and NT-4/5 may activate TRKB (27). The binding of each of these ligands to its cognate receptor, such as the binding of NGF to TRKA, induces receptor homodimerization and trans phosphorylation of five critical tyrosine (Y) residues (Y496, Y676, Y680, Y681, and Y791). Y496 and Y791 serve as phosphorylation-dependent binding sites for various adaptor proteins that contain SH2 or PTB domains, primarily SHC1, PLCγ, and GAB1, but others include FRS2, GRB2, IRS1, IRS2, and SH2B (Fig. 1; refs. 12, 28–30). Evidence from several studies points to activation of the PI3K signaling pathway by RAS or GAB1, although it may also be activated from other mechanisms (29, 31–33). Once activated, the three wild-type TRK family members most frequently signal through several downstream signaling pathways, including SHC-RAS-MAPK, PI3K-AKT, or PLCγ-PKC, depending on which docking protein(s) bind to the critical phosphorylated tyrosines Y496 and Y791 (34). Activation of these signaling cascades results in transcriptional and other cell programs that mediate cellular proliferation, synaptic plasticity, neurite outgrowth and repair, prevention or repair of neurodegeneration, sensory neuron maintenance, or apoptosis (12, 34–37).

It is expected that most TRK fusions would use many or all of the same downstream signaling cascades as the full-length receptors, given the preservation of the kinase domain and the critical tyrosine docking sites; however, this is a relatively unexplored area compared with decades of detailed studies on the signaling mechanisms used by the full-length receptors, particularly in the rat pheochromocytoma cell line PC12 (Fig. 1). The ETV6–NTRK3 fusion might be an exception, because it lacks the critical Y485 docking site for the preferential adaptor SHC1 due to the location of the breakpoint in the fusion, and evidence points to the use of an alternate adaptor, IRS-1 (38). Cell-type context and differential subcellular localization of fusions might alter the signaling program of the oncogenic fusion kinases.

Studies of TRKA fusions in thyroid cancer have revealed the TRK oncogenes (TRK, TRK-T1-T3) are capable of binding a number of different adaptor molecules, similar to full-length TRKA, but are predominantly engaged in signaling through the RAS–RAF–MAPK pathway (Fig. 1; refs. 39–41). The STAT3 signaling pathway was identified as a role in NIH-3T3 transformation by TRK oncogenes (42). Interestingly, the constitutive signaling induced by TRK oncogenes has also been shown to result in neuronal differentiation of PC12 cells (43). It was also elegantly demonstrated that the TRK oncogenes are capable of transforming not just NIH-3T3 fibroblasts, the commonly used model system for studies of oncogenic transformation, but also a more relevant in vivo model of cellular transformation, thyroid epithelial cells (44). Similarly, in vivo transformation of mammary epithelia was shown using the ETV6–NTRK3 fusion, clearly demonstrating the potency of these oncogenes in multiple model systems (45). Studies of TRKA fusion signaling in endogenous colorectal (KM12) and lung cancer (CUTO-3) cells have been conducted recently by our laboratory. The TPM3–NTRK1, MPRIP–NTRK1, and CD74–NTRK1 fusions seem to signal predominantly through the SHC–RAS–MAPK pathway in endogenous colorectal and lung cancer cell lines, but can engage PI3K–AKT or STAT3 signaling in certain cell types (4). Studies of the ETV6–NTRK3 fusion have demonstrated that oncogenic signaling is engaged through IRS-1, but due to the limited availability of cell lines expressing the ETV6–NTRK3 fusion, most studies were conducted using
Targeting TRK Oncogenes in Cancer

Autocrine and paracrine signaling by TRK receptors have been implicated as protumorigenic in several different tumor types. An autocrine loop involving TRKA and NGF is associated with protumorigenic activity in both breast and prostate carcinomas; similarly, TRKB and BDNF have been shown to play a protumorigenic role in several malignancies, including both breast and prostate cancers (59, 60). TRKB signaling has also been shown to promote anoikis resistance and induce metastatic programs in numerous cancers (61). Expression of TRKA and TRKC wild-type receptors is associated with a positive prognosis in patients with neuroblastoma (excluding expression of the splice variant TRKAlIII), whereas TRKB expression is correlated with a poorer prognosis (62, 63).

TRK Family Oncogenic Fusions

The typical gene structure for an oncogenic fusion is that the 3′ region of a proto-oncogene (encoding the kinase domain for upstream RTK signaling, through the insulin-like growth factor receptor (IGF1R) in ETV6–NTRK3 fusion-driven tumorigenesis (38). Studies in mice in selected NTRK1 and NTRK3 fusions have suggested these fusions likely play an important, early role in tumor progression (45, 47). Although P75NTR can modulate the activity and signaling of the full-length TRK receptors, its interaction with oncogenic TRK fusions has not been studied to date (23).

TRK Family in Cancer

Mutations in TRK family members have been reported in numerous malignancies, including ovarian cancer, colorectal cancer, melanoma, and lung cancer, but among NTRK1 alterations other than gene fusions, only an in-frame deletion of NTRK1 (ΔTRKA) in acute myeloid leukemia (AML) and a splice variant of NTRK1 (TRKAIII) in neuroblastoma have been functionally characterized as oncogenic to date (Fig. 2A; refs. 48–54). The deletion in ΔTRKA results in the loss of 75 amino acids in the extracellular domain of TRKA, removes four glycosylation sites adjacent to the transmembrane domain, and transforms both fibroblasts and epithelial cells (53). The TRKAIII splice variant, which was identified in a neuroblastoma cell line, results in the loss of exons 6, 7, and 9, and the corresponding loss of the extracellular domain Ig-like C2-type 1 (IG-C2) as well as multiple glycosylation sites (51). TRKAIII is constitutively active (ligand-independent), and its expression is promoted by hypoxic conditions (51). Although not yet identified in human tumor samples to date, mutations in the extracellular domain of TRKA, P203A and C345S, have both been characterized as transforming (55, 56). These studies may point to regions of interest where mutations have been identified in human tumors; for example, a relative cluster of mutations occurs in NTRK1 at the R342 position in close proximity to the C345 site identified by mutagenesis (57). The most common mechanism of oncogenic activation of TRKA is through genomic rearrangement and the creation of a gene fusion (12). Interestingly, all of these different mechanisms of oncogenic activation of TRKA (gene rearrangements, deletion, and splice variant) contain the loss of some of the extracellular domain of TRKA. The loss of these common sequences suggests the presence of critical regulatory domains in the extracellular domain of TRKA (and potentially B and C) that, when lost, results in constitutive activation of the kinase domain and thus its oncogenic capacity and is supported by mutagenesis studies in which Ig-like domains in the extracellular region of TRKA were deleted (58).

Figure 1. TRK fusion signaling. Schematic showing common signaling mechanisms for an example of a cytoplasmic (nonmembrane bound) chimeric TRK gene fusion is shown. Gene fusions are constitutively activated, or phosphorylated, often as a result of dimerization mediated by sequences in the 5′ gene. SH2 and PTB domain containing adaptors compete for binding at specific tyrosine residues, which most frequently results in propagation of the downstream signaling pathways shown. DD, dimerization domain; KD, kinase domain.
Figure 2. TRKA oncogenic variants and TRK gene fusion partners. A, schematic of TRKA isoforms, deletions, and mutations are shown. Mutations are shown in the TRKA isoform. Amino acid position numbers are shown in black. B, domains are shown (gray), and 3 domains shown in blue (green), fusions and the tumor types in which they have been identified. It is important to note that not all of these gene fusions have yet been characterized functionally, but each one occurred in-frame with an intact TRK kinase domain and are thus potentially oncogenic. Known or potential 5' dimerization domains are shown (gray), and 3' domains shown in blue (NTRK1), red (NTRK2), or green (NTRK3). No protein domains are shown for fusions that lack a reported breakpoint. Fusion proteins are not drawn to scale. ADC, adenocarcinoma; PTC, papillary thyroid cancer; AML, acute myeloid leukemia; CMN, congenital mesoblastic nephroma; MASC, mammary analogue secretory carcinoma; HNSCC, head and neck squamous cell cancer; CCD, coiled-coil domain; TD, trimerization domain; IG-C2, Immunoglobulin-like C2-Type domain; IG-V, Immunoglobulin-like V domain; OD, oligomerization domain; ZF QUA1, Quaking 1 domain; BTB, bric-a-brac, tramtrack, and broad complex domain; ETS, E26 transformation-specific domain.
Chromosomal rearrangements have been observed between the paradigm and contain a 5′ dimerization domain from ETV6 and the kinase domain of TRKC. ETV6–NTRK3 fusions can vary slightly with regard to the breakpoint in different cancer types, but always retain the SAM dimerization domain from ETV6 and the kinase domain of TRKC. Chromosomal rearrangements have been observed between NTRK1 and TFG, TPM3, or TPR in PTC, the most common malignancy of the thyroid (12). Interestingly, many of these activating 5′ gene fusion partners are promiscuous among various kinase fusion classes (12, 16). Although most of the NTRK1, NTRK2, and NTRK3 fusions identified thus far fit the paradigm and contain a 5′ gene partner with a dimerization domain, several of the partners do not contain clearly identifiable dimerization domains (Fig. 2B). 5′ Gene partners often contain one or more dimerization domains, such as the prototypical coiled-coil domain(s), and the corresponding constitutive tyrosine kinase activity that occurs results in uninterrupted downstream signaling messages for the cell to proliferate aberrantly and survive (12). Oncogenic gene rearrangements involving ROS1 may be an exception to this paradigm, as many of the 5′ gene partners have known dimerization domains, but have still been shown to possess transforming properties (16). One can speculate based on this that activation of ROS1 may only require loss of 5′ sequences that act as an autoinhibitory signal in the full-length RTK. A similar mechanism may be worth investigating in TRK family fusions. For example, VCL–NTRK2 has not been functionally characterized for transforming properties, but may be activated without a 5′ dimerization domain through the loss of a regulatory domain or by a different unknown mechanism, similar to many ROS1 fusions.

NGS Identification of NTRK1, 2, and 3 Fusions

In the last year, many next-generation sequencing (NGS) efforts, including programmatic, disease-oriented whole-genome, and/or transcriptome projects and also targeted clinical NGS platforms have resulted in the identification of NTRK family fusions in numerous tumor types. NTRK1 fusions were recently identified in lung adenocarcinoma, intrahepatic cholangiocarcinoma, spitzoid neoplasms, glioblastoma, and pontine glioma (4, 75–79). These findings were further validated in lung adenocarcinoma, as well as the discovery of novel fusions in PTC, and glioblastoma using a novel, targeted technique known as anchored multiplex PCR (80). It is also important to note that although TRK fusions were not detected initially by The Cancer Genome Atlas (TCGA), revisiting these data in 20 different cancers with a more efficient computational pipeline for the detection of gene fusions identified TRK fusions in eight additional tumor types (Table 1; refs. 9, 17). The first evidence of gene fusions involving the NTRK2 gene came in pilocytic astrocytoma and very soon afterward in pontine glioma (66, 74, 75). New tumor types with NTRK3 fusions were also identified, including PTC, pontine glioma, and Philadelphia chromosome-like acute lymphoblastic leukemia (Ph-ALL; refs. 68, 75, 81). Each of the three NTRK family genes can rearrange with multiple 5′ gene partners (Fig. 2).

A unique biologic aspect of the ETV6–NTRK3 fusion is that it was the first oncogenic gene fusion to be identified in numerous different cancer tumor tissues. In each of those different tumor types, all of which are relatively rare malignancies, ETV6–NTRK3 is the dominant oncogene. For example, 100% of MASC of salivary glands and 93% of secretory breast cancers harbor ETV6–NTRK3 fusions (45, 70). This observation is similar to CML, where BCR–ABL is found in the vast majority of cases. However, in most tumors in which TRK fusions are identified, they represent only a small proportion of patients (Table 1). Collectively, the TRK family represents a sizeable number of cases distributed across multiple tumor types.

TRK INHIBITORS

Given the long history of oncogenic TRK alterations, one might ask why it has taken so long to develop drugs for this target in cancer. Several reasons likely contribute to the slow development of this target, including the lack of selective inhibitors and the relative difficulty in screening large tumor cohorts when this oncogene was first identified in the early 1980s. Similar to TRK family alterations, oncogenic ALK gene rearrangements were found to be important in cancer long before the first ALK inhibitor was FDA approved. The first ALK gene rearrangement was identified in anaplastic large cell lymphoma in 1994, but no ALK-targeted therapies were developed in this disease until many years later. The critical moment for ALK inhibitor development came in 2007 with the discovery of ALK gene rearrangements in NSCLC (5). The corresponding FDA approval of crizotinib for ALK-positive metastatic NSCLC was exceedingly fast, taking only 4 years from the time of first identification of ALK rearrangements in this patient population (5). This rapid approval highlights the successful strategy of precision oncology by matching targeted therapies with biomarker-selected patients. Neurotrophins and TRK receptors, particularly TRKA, have been pursued in the past as drug targets for the treatment of chronic pain (35), and a few studies have pursued the...
TRK family as a therapeutic target in cancer (60, 82, 83). High levels of homology between TRKA, TRKB, and TRKC within the intracellular kinase domains have resulted in the synthesis of small-molecule inhibitors that target all three TRK family members (pan–TRK inhibitors; Table 2).

Clinical trials of TRK inhibitors will need to investigate potential side effects that may arise from inhibition of the full-length TRK receptors in normal tissues. Loss of normal regulation of TRKA, TRKB, or TRKC receptor activity can result in numerous human diseases. TRK receptors are known for mediating pain sensation and can play a role in chronic pain (35, 84). TRKA loss-of-function mutations are seen in class IV hereditary sensory and autonomic neuropathies (HSAN), such as the genetic disorder congenital insensitivity to pain with anhidrosis (CIPA; refs. 36, 84). Loss-of-function mutations in TRKB result in energy imbalances, the loss of appetite control and obesity, and neuronal defects such as memory impairment (37). Similarly, loss of BDNF expression in the cerebellum of the mutant stargazer mouse is associated with a severe ataxia phenotype (85), and Ntrk2 homozygous mutant mice have severe neurologic deficits (37), suggesting a critical role for the BDNF–TRKB signaling axis in normal neurologic development. However, it remains unclear whether inhibition of the full-length TRK receptors will produce symptoms that mimic developmental loss of signaling in this receptor family. A more detailed evaluation

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<th>Frequency</th>
<th>Detection method(s)</th>
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<td>Lung adenocarcinoma</td>
<td>3/91 (3.3%)</td>
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<td>NTRK1</td>
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<td>28/228 (12.3%)</td>
<td>PCR</td>
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<tr>
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<td>Spitzoid neoplasms</td>
<td>23/140 (16.4%)</td>
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<td>2/157 (1.1%)</td>
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<td>Pediatric gliomas</td>
<td>8/112 (7.1%)</td>
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NOTE: The frequency of NTRK1 (blue), NTRK2 (red), and NTRK3 (green) gene fusions indicating the tumor type and the detection method that was used in each study. Only positive studies are listed, and thus the actual prevalence may be lower than reported.

Post-Chernobyl.

Sporadic.

Abbreviations: FMI, Foundation Medicine, Incorporated; TCGA, The Cancer Genome Atlas.
of TRK receptors in non–cancer-related diseases is beyond the scope of this review, but can be found elsewhere (86, 87). Interestingly, one of the potential beneficial side effects of targeting TRK receptors in cancer might be a decrease in pain sensation, a frequent symptom among patients with cancer. Conversely, it will be important to monitor for potential neurologic side effects in clinical trials, given the expression pattern of the TRK family of receptors. Currently, little data exist on the toxicities of the more selective TRK inhibitors. A phase 1 study of PHA-848125AC with significant blood–brain penetration produced dose-limiting (grade 3) axatia and tremors, but as this drug inhibits cyclin-dependent kinases in addition to TRKA, it is unclear which drug target was responsible for these side effects (88). One of the largest reported studies of a drug with TRKA inhibition was a randomized study of lestaurtinib in FLT3-mutant AML (89). Only one neurologic adverse event was noted, a death due to cerebellar toxicity; however, given the multiple kinase targets of this drug, no conclusions can be drawn about the relationship of this toxicity to TRKA inhibition. Monoclonal antibodies against TRKA or NGF have been developed for the treatment of pain (35); however, antibodies to TRKA or other TRK family members would not be effective against TRK fusions, as the extracellular domains for these fusions are routinely lost in the gene rearrangement. Currently, several TKIs with activity against the TRK family are being explored in clinical trials (Table 2). Two patients with identified NTRK1 fusions were recently treated with inhibitors that demonstrated the potential clinical benefit of targeting this family of oncogenes. The first was a patient with lung cancer harboring the MPRIP–NTRK1 fusion, who was treated off-label with the multikinase inhibitor crizotinib (4). Crizotinib has only modest activity against TRKA and produced only a proportionally transient, minor radiographic response, emphasizing the need for more potent TRK inhibitors in the clinic. More recently, a patient with colorectal cancer with a TPM3–NTRK1 gene fusion was treated in the phase I portion of a clinical trial investigating an interrupted dosing schedule of RXDX-101 (Ignyta; ref. 90). RXDX-101 is a pan–TRK inhibitor that also has activity against two other gene fusion targets, ALK and ROS1. The TRKA-positive (TPM3–NTRK1) patient experienced a partial response, providing the first evidence of clinical activity of a TRK inhibitor in a patient with an oncogenic TRK alteration (90). A phase I/II study of RXDX-101 called STAR-TRK-1 is currently accruing patients with TRK alterations (NCT02097810). LOXO-101 (Loxo Oncology) is a selective pan–TRK inhibitor that has no significant activity outside of the TRK family and is currently being investigated in a phase Ia/ib trial across multiple tumor types (NCT02122913). TSR-011 (Tesaro) is a TRKA and ALK inhibitor that is currently in a phase I study (NCT02048488). PLX-7486 (Plexxikon) is a pan–TRK inhibitor that also targets FMS (McDonough Feline Sarcoma Viral). It is currently being investigated as monotherapy or in combination with nab-paclitaxel in pancreatic cancer, but there are plans to explore activity in patients with oncogenic TRK alterations in the future (NCT01804530). DCC-701 (Deciphera), XL-184 (Exelexis), and MGCD516 (Mirati) are all multikinase inhibitors that are currently in clinical trials that allow multiple different molecular subtypes, including the TRK family. Lestaurtinib (CEP-701; Cephalon) showed promising preclinical activity in NTRK1 fusion models, but its clinical development remains unclear (4).

**CONCLUSIONS**

TRK was one of the first oncogenes identified, more than three decades ago. The TRK oncogenes occur across a broad array of...
tumor types. Oncogenic fusions involving NTRK1, NTRK2, and NTRK3 and in-frame deletions or splice variants of NTRK1 are likely to be actionable oncogenes based on preclinical data. The first clinical evidence of tumor response to TRK-targeted therapy in a patient with an NTRK1 fusion suggests that this family of oncogenes will represent a new valid drug target in cancer.

Disclosure of Potential Conflicts of Interest

A.T. Le has received licensing fees from Abbott Molecular. R.C. Doebele reports receiving a commercial research grant from Mirati Therapeutics; has received honoraria from the speakers’ bureau of OxoOnc; is a consultant/advisory board member for Loxo Oncology and OxoOnc; and has received licensing fees from Abbott Molecular. No potential conflicts of interest were disclosed by the other author.

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