Genomic Landscape of Malignant Mesotheliomas
Shumei Kato1, Brett N. Tomson2, Timon P.H. Buys2, Sheryl K. Elkin2, Jennifer L. Carter2, and Razelle Kurzrock1

Abstract
Understanding the genomic landscape of malignant mesothelioma may identify novel molecular drivers of this ultra-rare disease, which can lead to an expanded roster of targeted therapies and clinical trial options for patients with mesothelioma. We examined the molecular profiles of 42 patients with malignant mesothelioma (including pleural, peritoneal, and pericardial) that were referred by clinicians to be tested in a Clinical Laboratory Improvement Amendments (CLIA) laboratory using next-generation sequencing (NGS; 182 or 236 genes). Among 42 patients, there were 116 alterations, with 92 being distinct. The number of genomic alterations per patient ranged from 1 to 5 (median = 3). No two patients had identical molecular portfolios. The most common aberrations were in BAP1 (BRCA1-associated protein 1; 47.6% [20/42]), NF2 (38.1% [16/42]), and CDKN2A/B (loss) (35.7% [15/42]). BAP1 alterations and CDKN2A/B loss were associated with pleural mesothelioma (OR 3.4, P = 0.059 [BAP1] [trend]; OR 5.8, P = 0.01 [CDKN2A/B]). All 42 patients had a molecular abnormality that was potentially actionable (median = three actionable alterations per patient; range, 1 to 5), and, in 40 patients (95.2%), a drug approved by the FDA was applicable. In conclusion, each individual with malignant mesothelioma harbored a unique set of genomic aberrations, suggesting that NGS-based profiling of patients will be needed if patients are to be optimally matched to cognate treatments. All 42 patients had at least one alteration that was, in theory, pharmaceutically tractable. Mol Cancer Ther; 15(10); 2498–507. ©2016 AACR.

Introduction
Malignant mesothelioma is an aggressive, ultra-rare tumor (defined as prevalence of less than 20 per million individuals; ref. 1) arising from mesothelial surfaces. The majority of mesotheliomas derive from pleura (83%) followed by peritoneum (11%; ref. 2). In rare cases, mesotheliomas arise from tunica vaginalis testis and pericardium (1%–2%; ref. 3). Mesotheliomas are associated with poor clinical outcome, with a median survival of 12 to 16 months for advanced stage malignant pleural mesothelioma (4), and 12.5 to 31 months for peritoneal mesothelioma (5). Exposure to asbestos is implicated as a risk factor, and about 50% of patients with malignant pleural mesothelioma were reported to have such exposure (4). Asbestos causes chronic irritation of the mesothelial surface, which leads to local inflammation, scarring, and ultimately development of mesothelioma (6).

For selected patients who can be predicted to achieve complete resection, a combined modality approach with surgery, chemotherapy, and/or radiation therapy has been used, with the literature suggesting clinical improvement when compared to historic controls (7). However, due to the rarity of this cancer type (2) there are no adequately powered trials to evaluate the benefit of combined modality approaches.

For patients with advanced or recurrent disease, chemotherapy with platinum-based doublets has been widely applied. For example, cisplatin plus pemetrexed has been shown to improve clinical outcome in malignant pleural mesothelioma when compared to cisplatin alone, with OS of 12.1 months versus 9.3 months (P = 0.02), progression-free survival (PFS) of 5.7 months versus 3.9 months (P = 0.001), and a response rate of 41.3% versus 16.7% (P < 0.0001; ref. 8). Addition of bevacizumab to cisplatin plus pemetrexed is also associated with better clinical outcome when compared to cisplatin plus pemetrexed alone [OS of 18.8 months versus 16.1 months (P = 0.0167), PFS 9.2 months versus 7.3 months (P < 0.0001); ref. 9]. Although chemotherapy has shown some salutary effects, prognosis remains poor; thus, targeted therapies such as sunitinib [partial response (PR): 12%; ref. 10], sorafenib (PR: 6%; ref. 11), and imatinib (PR: 0%; ref. 12), have been tried, although with minimal clinical efficacy, perhaps because they were given to patients without genomic selection (13, 14). Because patients with mesothelioma uniformly have high expression of mesothelin (15), clinical trials targeting mesothelin are ongoing [e.g., BAY 94-9343, an anti-mesothelin antibody conjugated to the maytansinoid tubulin inhibitor DM4 (NCT01439152); amatuximab (MORAb-009), an anti-mesothelin antibody (NCT02357147); and CRS-207, mesothelin-expressing Listeria cancer vaccine (NCT01675765)]. Immunotherapy approaches are under investigation and early-phase clinical trials in patients who failed standard therapy showed moderate responses with tremelimumab (anti-CTLA4 monoclonal antibody; PR: 7%; ref. 16) and pembrolizumab (anti-PD-1 antibody; PR: 24%; ref. 17).

In several refractory malignancies, such as lung cancer and melanoma, elucidation of the molecular defects and prosecution...
of the tumor with matched targeted therapy has proved effective (18, 19). A deeper understanding of the underlying alterations in various types of mesothelioma may also prove worthwhile. Previous studies show that BRCA1-associated protein-1 (BAP1: 21%–63%; refs. 20–25), TP53 (57%; ref. 25), CDKN2A/B (45%–75%; refs. 22 and 24), and NF2 (14%–50%; refs. 20–22, 24, and 25) are frequently abnormal in pleural mesothelioma and that Hippo, mTOR, histone methylation, RNA helicases, and p53 signaling pathways are most often affected (21). Here we examined the genomic portfolios of 42 patients with diverse types of mesothelioma (including pleural, peritoneal, and pericardial) interrogated by clinical-grade NGS, and assessed the resulting implications for potential targeted therapy options.

Materials and Methods

Patients

We investigated the genetic aberration status of 42 patients with mesothelioma (pleural: n = 23, peritoneal: n = 11, pericardial: n = 2, subtype unknown: n = 6) referred to Foundation Medicine for NGS from December 2011 through November 2013. Tumor types were provided by the submitting physicians. The database was de-identified. Next-generation sequencing data were collected and interpreted by N-of-One, Inc.

Tissue samples and mutational analysis

We collected sequencing data from 42 mesothelioma patients whose formalin-fixed, paraffin-embedded (FFPE) tumor samples were submitted to a clinical laboratory improvement amendments (CLIA)-certified lab for genetic profiling (Foundation Medicine). Samples required surface area >25 mm², volume ≥1 mm³, nucleated cellularity ≥80%, and tumor content ≥20% (26). The methods used in this assay have been previously reported and validated (26–28). In short, 50 to 200 ng of genomic DNA was extracted and purified from the submitted FFPE tumor samples. This whole-genome DNA was subjected to shotgun library construction and hybridization-based capture before paired-end sequencing on the Illumina HiSeq2000 platform. Hybridization selection is performed using individually synthesized baits targeting the exons of 182 or 236 cancer-related genes and the introns of 14 or 19 genes frequently rearranged in cancer (29). Sequence data were processed using a customized analysis pipeline (26).

Sequencing was performed with an average sequencing depth of coverage greater than ×250, with ×100 at >99% of exons. This method of sequencing allows for detection of copy number alterations, gene rearrangements, and somatic mutations with >99% specificity and >95% sensitivity for base substitutions at ≥5 mutant allele frequency and >95% sensitivity for copy number alterations. A threshold of ≥8 copies for gene amplification with ≥6 copies considered equivocal (except for ERRB2, which is considered equivocally amplified with ≥5 copies) was used. All aberrations were analyzed based on American College of Medical Genetics guidelines to evaluate whether alterations were pathogenic. This study and data analysis was performed in accordance with UCSD IRB guidelines.

Endpoints and statistical methods

Descriptive statistics were used to summarize the baseline patient characteristics. Fisher exact test was used to assess the association between categorical variables in univariate analysis. All tests were two-sided. Statistical analyses were carried out using GraphPad Prism version 6.0.

Results

Genetic aberrations in mesotheliomas

Among all mesotheliomas (N = 42), the most common histologic diagnosis was pleural mesothelioma (55% [23/42]) followed by peritoneal mesothelioma (26% [11/42]). Pericardial mesothelioma was the least common subtype (5% [2/42]), and 14% (6/42) of mesothelioma samples had unknown subtype (Figs. 1–4 and Supplementary Tables S1 and S2).

The number of molecular aberrations reported per patient ranged from one to five, with a median of three per patient (Supplementary Fig. S1). The most common genetic aberrations among all mesotheliomas occurred in the BAP1 gene (47.6% [20/42]), followed by NF2 (38.1% [16/42]), CDKN2A/B loss (35.7% [15/42]), and TP53 aberrations (16.7% [7/42]; Figs. 1 and 2 and Supplementary Table S1). Among pleural mesothelioma patients (n = 23), BAP1 was the most common gene altered (60.9% [14/23]) followed by CDKN2A/B loss (52.2% [12/23]), NF2 (34.8% [8/23]), and TP53 (17.4% [4/23]; Fig. 3 and Supplementary Table S1). Among peritoneal mesothelioma (n = 11), the most common alteration was in NF2 (36.4% [4/11]), followed by BAP1 (27.3% [3/11]; Fig. 4 and Supplementary Table S1). BAP1 aberrations (n = 20) consisted of mutation (50% [10/20]), loss (25% [5/20]), rearrangement (5% [1/20]), and cases with multiple aberrations (20% [4/20]). Among individual with NF2 aberrations (n = 16), 81.3% (13/16) had a mutation, 12.5% (2/16) had loss, and 6.3% (1/16) had multiple alterations (Fig. 2).

Association between histologic subtypes of mesothelioma and coexisting molecular alterations

Among BAP1, NF2, CDKN2A/B, and TP53 aberrations, there were no statistically significant associations in terms of coexisting genetic aberrations (Supplementary Tables S3–S5). However, a trend toward less common association between BAP1 aberration and TP53 (OR 0.14; P = 0.096) or NF2 aberrations (OR 0.33; P = 0.12) was noted (Supplementary Tables S3 and S4). When focusing on the association between histologic diagnosis and molecular aberrations, pleural mesothelioma was significantly associated with loss of CDKN2A/B (OR 5.8; P = 0.011) and a trend toward association with BAP1 aberration was noted (OR 3.4; P = 0.059). However, there was no association between pleural mesothelioma and NF2 aberration (OR 0.73; P = 0.63; Supplementary Tables S3–S5). However, peritoneal mesothelioma was significantly less associated with CDKN2A/B loss (OR 0.12; P = 0.032) and a trend suggests less common association with BAP1 aberration (OR 0.31; P = 0.12; Supplementary Tables S3 and S5).

Number of genetic aberrations and possible cognate targeted therapies in patients with mesothelioma

Among 42 mesothelioma cases, a total of 116 aberrations were identified. Among all aberrations, 112 aberrations were potentially actionable either with therapies approved by FDA for other types of malignancies or with therapies currently in clinical trials (112/116 [96.6%]). Among 112 actionable aberrations, 97 (86.6%) were targetable with FDA-approved agents (off label), and an additional 15 (13.4%) were targetable with investigational agents (Table 1 and Supplementary Tables S2 and S6).

Among 116 aberrations, there were 92 distinct aberrations. For example, BAP1 and NF2 aberrations were considered distinct; BAP1 S460* and BAP1 S63C mutations were also considered to be distinct aberrations. However there were n = 15 with CDKN2A/B loss and those were counted as a
Nearly all of the distinct aberrations (88/92 [95.7%]) were potentially actionable, including 77 (87.5% [77/88]) that were theoretically targetable by an FDA-approved drug. An additional 11 aberrations (12.5% [11/88]) were theoretically targetable by an experimental drug in a clinical trial (Table 1 and Supplementary Tables S2 and 6). The median number of potentially actionable aberrations per patient was 3 (range, 1 to 5; Supplementary Fig. S1). All 42 patients with mesothelioma had theoretically actionable aberrations. Of the 42 patients, 40 (95.2%) had an aberration targetable by an FDA-approved drug and an additional two (4.8%) had an aberration targetable by an investigational drug in a clinical trial (Table 1 and Supplementary Tables S2 and S6 and Supplementary S1).

Distinctness of the genomic aberrations among 42 mesothelioma patients

As noted, 92 distinct genetic aberrations were detected. Among 42 patients, no two patients had an identical molecular portfolio. If we considered the genetic aberrations at the level of the gene, rather than the specific aberration (for example, different aberrations in same gene would be considered as identical), then there were 40 genetic aberrations and four patients had genomic portfolios identical to at least one other patient. Those include one patient with pleural (BAP1 loss and CTNNB1 Q280/C3) and one with pericardial mesothelioma (BAP1 loss and CTNNB1 splice site 1955-2_1955-1ins16) and two patients with pleural mesothelioma (one with a BAP1 rearrangement and the other with BAP1 truncation and R610fs7 mutations. Both also had CDKN2A/B loss; Supplementary Table S2).

Discussion

Malignant mesothelioma is an uncommon cancer (2) with limited therapeutic options (8, 10–12) and poor clinical outcomes (4, 5). Thus, we investigated the genomic landscape of this tumor by targeted NGS. In our current study of 42 patients, 55%
(23/42) had pleural mesothelioma; 26% (11/42), peritoneal mesothelioma; and 5% (2/42), pericardial mesothelioma. Previous literature from the Surveillance Epidemiology and End Results (SEER) database suggests that the majority (83%) of mesothelioma cases are from pleura and 11% are from peritoneum (2).

The most frequent genetic aberrations were in BAP1 (47.6% [20/42]; Figs. 1 and 2 and Supplementary Table S1). Our observation is in agreement with previous studies demonstrating that 21% to 63% of malignant mesothelioma tumors harbored BAP1 abnormalities (20–25). BAP1 aberrations showed a trend to be more commonly associated with pleural mesothelioma (OR 3.4; P = 0.059) and less often with peritoneal mesothelioma (OR 0.31; P = 0.12). Moreover, BAP1 aberrations showed a trend to be less likely to be associated with NF2 (OR 0.33; P = 0.12) or TP53 (OR 0.14; P = 0.096) aberrations, but no difference was observed for CDKN2A/B loss among patients with or without BAP1 aberration (OR 0.94; P = 1.0; Supplementary Table S3). These associations must, however, be viewed with significant caution, as the total number of patients is small.

BAP1 is a tumor suppressor gene that encodes a deubiquitinating enzyme BAP1 that binds to BRCA1 and regulates key cellular pathways including cellular differentiation, cell cycle, and DNA damage response (30). Because a functional defect in the BRCA1-mediated DNA repair pathway confers synthetic lethality to PARP inhibition (31), the association between BAP1 mutation and efficacy of PARP inhibitors has been investigated. Pena-Llopis and colleagues showed that clear cell renal cell carcinoma cell
lines with BAP1 loss were associated with higher sensitivity to olaparib (a PARP inhibitor) when compared to cell lines with intact BAP1 (32). However, another study using mesothelioma cell lines showed no difference between BAP1-mutant and wild-type cells in terms of sensitivity to PARP inhibitors (20). BRCA1 mutation is also associated with increased sensitivity to platinum (33); thus, mesothelioma patients with BAP1 aberrations may benefit from agents such as cisplatin or carboplatin when compared to patients without these alterations, and this may explain the responses to platinum-based regimens (8, 9). Of note, germline mutations in BAP1 have been associated with familial cancer syndromes, with an increased risk of malignancies including mesothelioma and uveal melanoma (30). However, BAP1 germline mutations are rare among sporadic malignant mesothelioma (34). The genomic sequencing performed in this study did not distinguish germline from somatic alterations.

The second most common aberration was in the NF2 gene (38.1% [16/42]; Figs. 1 and 2 and Supplementary Table S1). Our observation is in agreement with previous studies where 14% to 50% of patients with mesothelioma were found to have aberrations in NF2 (20–22, 24, 25). As mentioned, NF2 aberrations tended to be less commonly associated with BAP1 aberrations (OR 0.33; P = 0.12; Supplementary Table S4). NF2 (neurofibromin 2) is a tumor suppressor gene that encodes the protein merlin, which affects multiple signaling pathways (35). Among multiple cancer types, mesothelioma is one of the most common cancers that harbor NF2 aberrations (35). In a preclinical model with malignant mesothelioma cell lines, inactivation of NF2 led to enhanced cell spreading and invasion through activation of FAK (36). Interestingly, mouse models with hemizygous NF2 that were exposed to asbestos had markedly accelerated formation of malignant mesothelioma when compared to asbestos-exposed wild-type mice. In the same study, further molecular profiling of these mesothelioma samples showed frequent deletion of CDKN2A and inactivation of TP53, suggesting that mesothelioma develops along with the accumulation of additional genetic aberrations (37). Moreover,
conditional mouse models showed that loss of all three genes (NF2, CDKN2A, and TP53) was associated with an increased risk of mesothelioma formation and a significant decrease in survival when compared to the mice with loss of two genes (NF2 and CDKN2A or NF2 and TP53), suggesting that aberrations in all three genes enhances tumorigenesis and cancer aggressiveness (38). However, in our current study, only one patient (1/42) was found to have an aberration in all three genes (NF2, CDKN2A, and TP53) (Fig. 1). Of interest in this regard, patients with neurofibromatosis type 2, which is an autosomal-dominant disorder associated with germline mutations in NF2, do not have an increased risk of mesothelioma (35). It is unclear why such a dichotomy exists. Because NF2 is a negative regulator of mTOR, it is potentially targetable with mTOR inhibitors, and cases of metaplastic breast cancer and of patients with neurofibromatosis that have achieved response (complete remission for 3+ years for the breast cancer) to a temsirolimus (mTOR inhibitor)-containing regimen have been reported (39, 40). Moreover, in preclinical models, lack of NF2 was associated with increased sensitivity to FAK inhibitors (41); trials of FAK inhibitors VS-6063 (defactinib) (NCT02004028) and GSK2256098 (NCT01938443) in patients with mesothelioma are ongoing.

Loss of CDKN2A/B was the third most common aberration among patients with malignant mesothelioma (35.7% [15/42]; Figs. 1 and 2 and Supplementary Table S1). Interestingly, CDKN2A/B loss was significantly more common in pleural mesothelioma (OR 5.8; P = 0.01) and less associated with peritoneal histology (OR 0.12; P = 0.032; though number of patients are small, suggesting that these correlations require
Table 1. Summary of examples of theoretically matched therapies

<table>
<thead>
<tr>
<th>Gene aberration</th>
<th>Mechanism of action</th>
<th>Examples of theoretical therapies</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABL1 mutation</td>
<td>ABL1 is a nonreceptor tyrosine kinase that transduces diverse extracellular signaling</td>
<td>ABL kinase inhibitors, such as imatinib, nilotinib or dasatinib (S1)</td>
</tr>
<tr>
<td>AKT2 amplification</td>
<td>AKT is downstream of activated tyrosine kinases leading to mTOR signaling</td>
<td>mTOR inhibitors, such as everolimus or temsirolimus (S2, S3)</td>
</tr>
<tr>
<td>ALK fusion</td>
<td>ALK fusion leads to ligand-independent activation of the tyrosine kinase (S4)</td>
<td>ALK inhibitors, such as crizotinib (S4, S5)</td>
</tr>
<tr>
<td>ARID1A mutation</td>
<td>ARID1A is a component of the SWI/SNF chromatin remodeling complex and its aberration is thought to drive tumorigenesis by altering gene expression (S6)</td>
<td>EZH2 inhibitor (EPZ-6438) (NCT01897571)(^b)</td>
</tr>
<tr>
<td>ARID2 mutation</td>
<td>ARID2 is a subunit of the polybromo- and BRG1-associated factor (PBAF) chromatin remodeling complex, which facilitates transcriptional activation (S7)</td>
<td>Unclear</td>
</tr>
<tr>
<td>ATM mutation</td>
<td>ATM tumor suppressor gene encodes DNA damage-signaling protein</td>
<td>PARP inhibitors, such as olaparib (S8)</td>
</tr>
<tr>
<td>BAP1 aberration</td>
<td>BAP1 (BRCA1 associated protein-1) is a deubiquitinating enzyme (S9)</td>
<td>PARP inhibitors, such as olaparib (S10) Platinum such as cisplatin or carboplatin (S11, S12) EZH2 inhibitor, such as EPZ01989(^9) (S13).</td>
</tr>
<tr>
<td>BCL2 mutation</td>
<td>BCL2 encodes protein that regulates cell death and inhibits apoptosis</td>
<td>Bcl-2 inhibitors, such as ABT-199 or ABT-263(^3) (S14, S15).</td>
</tr>
<tr>
<td>BRCA2 mutation</td>
<td>BRCA2 are important for DNA double-strand break repair by homologous recombination (S16)</td>
<td>PARP inhibitors, such as olaparib (S17) Platinum such as cisplatin or carboplatin (S11, S12) Unclear</td>
</tr>
<tr>
<td>CBL mutation</td>
<td>CBL (casitas B-lineage lymphoma) is an E3 ubiquitin-protein ligase for tyrosine kinase receptors</td>
<td>Unclear</td>
</tr>
<tr>
<td>CCNE1 amplification</td>
<td>CCNE1 (Cyclin E1) forms a complex with cyclin-dependent kinase 2 (CDK2) to regulate G1/S transition (S18)</td>
<td>Possibly with CKD2 inhibitors such as dinaciclib (CDK1/2/5/9 inhibitor(^3)) (S19). Possibly with bortezomib (S20)</td>
</tr>
<tr>
<td>CDH1 mutation</td>
<td>CDH1 (cadherin 1, type 1, E-cadherin) is important for cell-cell adhesion and plays fundamental role in the maintenance of cell differentiation and the normal structure of epithelial cells (S21)</td>
<td>CDK4/6 inhibitors, such as palbociclib (S22)</td>
</tr>
<tr>
<td>CDKN2A/B loss and mutation</td>
<td>CDKN2A/B are tumor suppressor genes that inhibit cyclin D-cyclin-dependent kinase (CDK) 4/6 complex, which regulates G1 cell-cycle progression</td>
<td>CDK4/6 inhibitors, such as palbociclib (S22)</td>
</tr>
<tr>
<td>CTNNB1 mutation</td>
<td>CTNNB1 (β-catenin) is part of Wnt signaling pathway associated with tumorigenesis (S23)</td>
<td>β-Catenin antagonist(^8) (S24)</td>
</tr>
<tr>
<td>DNMT3A mutation</td>
<td>DNMT3A is a tumor suppressor and its mutation disrupts DNA methylation (S25)</td>
<td>DNA methyltransferase inhibitors such as decitabine or azacitidine (S26)</td>
</tr>
<tr>
<td>EMSY amplification</td>
<td>EMSY is BRCA2 binding partner and capable of silencing the activity of BRCA2, leading to chromosomal instability (S27)</td>
<td>Possibly with PARP inhibitors such as olaparib. Platinum such as cisplatin or carboplatin (S11, S12). Anti-EphA5 antibody(^9)</td>
</tr>
<tr>
<td>EPHA3 amplification</td>
<td>EphA3 is highly expressed on the tumor-initiating cell and involved in maintaining tumor cells in a less differentiated state (S28)</td>
<td>Unclear</td>
</tr>
<tr>
<td>FBXW7 mutation</td>
<td>F-box and WD40 repeat domain-containing 7 (FBXW7) is involved in ubiquitination and turnover of several oncoproteins (S29)</td>
<td>Possibly with mTOR inhibitors, such as everolimus or temsirolimus (S30)</td>
</tr>
<tr>
<td>FGFR3 amplification</td>
<td>FGFRs (fibroblast growth factor receptors) are transmembrane tyrosine kinase receptor (S31)</td>
<td>Tyrosine kinase inhibitors that target FGFR3, such as dovitinib or ponatinib (S4)</td>
</tr>
<tr>
<td>IGF-IR amplification</td>
<td>IGF-IR (insulin-like growth factor) signaling is associated with transformation of cells, cancer cell proliferation, and metastasis (S32)</td>
<td>IGF-IR inhibitor(^9) (S32, S33)</td>
</tr>
<tr>
<td>KDR mutation</td>
<td>KDR (kinase insert domain receptor, also known as VEGFR-2) regulates VEGF-induced endothelial proliferation, survival, and migration (S33)</td>
<td>Tyrosine kinase inhibitors that target VEGFR-2, such as caboazantinib (S34)</td>
</tr>
<tr>
<td>KMT2A mutation</td>
<td>KMT2 (histone-lysine N-methyltransferase 2) family protein is methyltransferase (S35)</td>
<td>EPZ-5676 (DOTTIL inhibitor: NCT02141828)(^b) Flavopiridol (NCT00012818)(^b)</td>
</tr>
<tr>
<td>MAP2K1 mutation</td>
<td>MAP2K1 (mitogen-activated protein kinase kinase 1), also known as MEK1, is involved in MAP kinase signal transduction signaling (S36)</td>
<td>MEK inhibitors, such as trametinib</td>
</tr>
<tr>
<td>MCL1 amplification</td>
<td>MCL1 is an antiapoptotic protein (S36)</td>
<td>Possibly with sorafenib (S37)</td>
</tr>
<tr>
<td>MDM2 amplification</td>
<td>MDM2 is E3 ubiquitin protein ligase that suppresses p53 activity (S38)</td>
<td>MDM2 inhibitors (DS-3032b; NCT01877382, RO6839921; NCT02098967)(^5) (S38)</td>
</tr>
<tr>
<td>MYC amplification</td>
<td>MYC is pleiotropic transcription factor (S39)</td>
<td>Possibly with aurora kinase inhibitors such as MLN8237(^2) (S40) Possibly with CDK1 inhibitor such as dinaciclib (CDK1/2/5/9 inhibitor(^3)) (S41)</td>
</tr>
<tr>
<td>NF1 mutation</td>
<td>NF1 encodes protein neurofibromin that affects RAS activation (S42)</td>
<td>mTOR inhibitors, such as everolimus or temsirolimus (S42, S43) MEK inhibitors, such as trametinib (S44)</td>
</tr>
</tbody>
</table>

(Continued on the following page)
Dulate G1 cell-cycle progression. Thus, CDKN2A/B mutation SUFU (SMO released suppressor of fused) negatively regulates SMO. SUFU protein functions as ubiquitin ligase which ubiquitylates TSC2, which inactivates mTOR (S45).

Table 1. Summary of examples of theoretically matched therapies (Cont’d)

<table>
<thead>
<tr>
<th>Gene alteration</th>
<th>Mechanism of action</th>
<th>Examples of theoretical therapies</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF2 aberration</td>
<td>Neurofibromin 2 (NF2) is a tumor suppressor that affects RAS, Src/FAK, and PI3K pathway (S45)</td>
<td>mTOR inhibitors, such as everolimus or temsirolimus (S45)</td>
</tr>
<tr>
<td>PIK3R2 mutation</td>
<td>PIK3R2 aberration leads to the activation PI3K pathway (S47)</td>
<td>mTOR inhibitors, such as everolimus or temsirolimus (S47)</td>
</tr>
<tr>
<td>PTCH1 mutation</td>
<td>PTCH1 receptor is involved in Hedgehog signaling pathway (S48)</td>
<td>SMO inhibitors, such as vismodegib (S48)</td>
</tr>
<tr>
<td>RAS mutations</td>
<td>RAS mutations lead to constitutive activation of RAS (S49)</td>
<td>MEK inhibitors, such as trametinib (S50)</td>
</tr>
<tr>
<td>RICTOR amplification</td>
<td>RICTOR is component of mTORC2 complex, which is required for AKT phosphorylation (S51)</td>
<td>mTORC1/2 inhibitors (AZD2014, MLN0128)</td>
</tr>
<tr>
<td>SOX2 amplification</td>
<td>SOX2 is a transcription factor that is essential for maintaining self-renewal or pluripotency (S52)</td>
<td>Unclear</td>
</tr>
<tr>
<td>STK11 mutation</td>
<td>STK11 (serine/threonine-protein kinase 11) inactivates mTORC1 and FAK signaling (S53, S54)</td>
<td>mTOR1 inhibitor, such as everolimus or temsirolimus (S55, S55)</td>
</tr>
<tr>
<td>SUFU mutation</td>
<td>SUFU (SMO released suppressor of fused) negatively regulates the Hedgehog pathway (S58)</td>
<td>FAK inhibitors such as dasatinib (S56) or bosutinib (S57)</td>
</tr>
<tr>
<td>TPS3 mutation</td>
<td>TPS3 is a tumor suppressor gene (S59)</td>
<td>Possibly with arsenic trioxide or bortezomib (S58)</td>
</tr>
<tr>
<td>TSC2 aberration</td>
<td>Tuberous sclerosis complex 2 (TSC2) is a negative regulator of mTOR</td>
<td>Bevacizumab (pilot retrospective data; S60)</td>
</tr>
<tr>
<td>VHL mutation</td>
<td>VHL protein functions as ubiquitin ligase which ubiquitylates hypoxia inducible factors (HIF) leading to degradation by proteasome (SE2)</td>
<td>mTOR inhibitors, such as everolimus or temsirolimus (S61)</td>
</tr>
</tbody>
</table>

NOTE: For references in Table 1, please see supplemental references.

*See Supplementary Table S6 for the additional comments for the examples of theoretical therapies.

**Therapies currently in clinical trial. All other drugs are FDA approved for other types of cancer treatment.

verification in larger cohorts (Supplementary Table S5). CDKN2A/B are tumor suppressor genes that suppress cyclin D–cyclin-dependent kinase (CDK) 4/6 complexes, which regulate G1 cell-cycle progression. Thus, CDKN2A/B loss facilitates G1 cell-cycle progression, leading to cancer aggressiveness, and has been associated with poor clinical outcome (42). As mentioned earlier, CDKN2A aberrations in mouse models increase the risk of the development of mesothelioma along with NF2 and TPS3 anomalies, and thus, this mutation likely has an important role for tumor initiation (38). Abnormalities in CDKN2A/B are potentially targetable with CDK4/6 inhibitors such as palbociclib (42), although some studies suggest that aberrations in the CDK pathway may not be a predictive biomarker for response (43).

Although chromatin-modifying genes including SETD2 and SETDB1 aberrations were previously reported in a portion of malignant pleural mesothelioma patients (8% and 3%, respectively; ref. 21), we only evaluated SETD2 aberration, which was negative in current report. Thus, further investigation with a larger panel of patients is required.

Among 42 patients with mesothelioma, there were 92 distinct aberrations. Eighty-eight alterations (95.7%) were potentially targetable with either an FDA-approved drug (87.5% [77/88]) or with an experimental drug in a clinical trial (12.5% [11/88]) (Table 1 and Supplementary Tables S2 and S6). Of note, all 42 mesothelioma patients had theoretically actionable alterations; in 40 (95.2%), at least one alteration was potentially targetable by an FDA-approved drug and an additional 2 (4.8%) by an investigational drug in a clinical trial (Table 1 and Supplementary Tables S2 and S6).

Interestingly, among 42 patients, there were no patients who had identical genomic portfolios (Supplementary Table S2). Molecular singletons as the norm are commonly reported in cancers as well (44–48). Considering that effective therapies for mesothelioma are lacking (8–12), clinical trials for mesothelioma that incorporate molecular profiling for patient selection and appropriately customized therapy are warranted (49).

There are several limitations to current data. First, the dataset was not clinically annotated. Thus, correlation between genomic aberrations and clinical outcomes were not feasible. Second, because we have not evaluated normal tissues, the possibility of underlying germline mutations is not addressed. Third, cancer diagnoses were submitted by referring physicians, which can potentially introduce the sample size bias. Related in this regard, because current data were derived from a de-identified database, we were not able to confirm the histologic subtypes of mesothelioma (epithelioid, biphasic, and sarcomatoid), which are known to have different genomic aberration patterns (e.g., CDKN2A aberrations are more often seen in epithelioid than sarcomatoid subtypes; ref. 21). In addition, we were not able to review the pathology slide for histological confirmation. Despite these limitations, this study provides comprehensive analysis of genomic landscape of malignant mesothelioma patients using clinical grade NGS.

In conclusion, among 42 patients with mesothelioma, 116 aberrations were identified (median = 3 per patient), 92 of which were distinct. The most common alterations were in BAP1 (47.6% [20/42]), NF2 (38.1% [16/42]), and CDKN2A/B (loss, 35.7% [15/42]). All patients had at least one aberration that was possibly targetable with either an FDA approved or an investigational drug (Table 1 and Figure 1 and Supplementary Tables S2 and S6). Of interest in this regard, previous studies have shown that targeted drugs are most effective when matched by biomarkers to the tumor, and that use of targeted therapies in unselected patient populations is often ineffective (13, 14). Understanding the landscape of genomic alterations in patients with mesothelioma may therefore assist in informing next generation clinical trials.
Disclosure of Potential Conflicts of Interest

S.K. Elkin has ownership interest (including patents) in N-of-One, Inc. J.L. Carter has ownership interest (including patents) in N-of-One Inc. R. Kurzrock has ownership interest in Novena, Inc. and Curematch, Inc.; reports receiving commercial research grants from Genentech, Merck Serono, Pfizer, Sequenom Foundation Medicine, and Guardant; has ownership interest (including patents) in Novena, Inc. and Curematch, Inc.; and is a consultant/advisory board member for Sequenom, Actuate Therapeutics, and Xhoschot. No potential conflicts of interest were disclosed by the other authors.

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Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): B. N. Tomson

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