Mutation Profiling and Microsatellite Instability in Stage II and III Colon Cancer: An Assessment of Their Prognostic and Oxaliplatin Predictive Value

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Introduction

Mutation profiling has proven to be a useful tool for predicting response to targeted therapies in colon cancer, but the clinical impact of mutation profiling for prognosis and for prediction of standard chemotherapies has yielded little clinical use. PIK3CA mutations have been shown to be associated with a poor prognosis in stage II and III colon cancer, but these results have not been confirmed in a randomized clinical trial (1–3). BRAF mutations have been shown to be associated with poor prognosis in many colon cancer studies including randomized clinical trials (4–9), but not in all studies (10, 11). Likewise, results from studies evaluating KRAS mutations in early-stage colon cancer have been contradictory (6, 10, 12–16).

As a first step in identifying mutations as potential biomarkers, we identified the common colon cancer mutations by profiling 187 different cancer mutations in 19 genes in a cohort of 235 cases from the NSABP C-07 trial, using Type Plex chemistry, mass spectrometry, and the OncoCarta Panel v1.0 (Sequenom). Twenty-four hot spot mutations in 5 genes (BRAF, KRAS, MET, NRAS, and PIK3CA) were found to occur in more than 1% of stage II and III colon cancer. These mutations were re-plexed into 6 new pools referred to as ColoCarta (Supplementary Table S1). This technology...
Translational Relevance

The prognostic and oxaliplatin predictive value of mismatch repair (MMR) and common hot spot mutations in stage II and III colon cancer using National Surgical Adjuvant Breast and Bowel Project clinical trials C-07 \( (n = 1,836) \) and C-08 \( (n = 463) \) was assessed. The findings of several other studies showing that \( BRAF \) mutations were associated with MMR and poor overall survival were validated and show that this is at least in part due to the association of \( BRAF \) with poor survival after recurrence. \( KRAS \), \( PIK3CA \), \( NRAS \), and \( MET \) mutations were not significantly associated with prognosis \( (N = 2,299) \). None of the mutations was shown to be predictive for oxaliplatin benefit. Future novel clinical trials targeting \( BRAF \) are warranted because of its association with poor prognosis and resistance to anti-EGF receptor therapies, and profiling of all of these mutations will be necessary in future clinical trials using targeted therapies that inhibit RAS/RAF and AKT pathways.

provided a cost-effective and sensitive method for the detection of hot spot mutations in routinely processed formalin-fixed, paraffin-embedded (FFPE) samples \( (17) \).

MMR status and mutations in \( BRAF \), \( KRAS \), \( MET \), \( NRAS \), or \( PIK3CA \) in C0-7 and C-08 samples were tested for their prognostic value in stage II and III colon cancer. The predictive value of mutations and MMR status for oxaliplatin benefit in C-07 were also tested.

Patients and Methods

Patient selection clinical samples

The National Surgical Adjuvant Breast and Bowel Project (NSABP) C-07 trial showed that the addition of oxaliplatin to 5-fluorouracil + leucovorin (5-FU + LV) improved survival of patients with resected stage II and III colon cancer \( (18, 19) \). Patients who participated in that study provided written informed consent to participate, and the study was approved by Institutional Review Boards at participating NSABP sites. All cases with available tumor blocks, consented for research, and with follow-up information from the NSABP C-07 \( (n = 1,836) \) were used in the current study (REMARK Fig. 1). In addition, we conducted gene mutation profiling on a representative cohort of 500 cases from the NSABP C-08 trial. This cohort was selected using stratified random sampling with strata for treatment and N-stage (N0, N1, N2) so that the proportion of patients in each stratum of the sample was the same as the proportion of eligible patients with tissue in each stratum of the parent C-08 trial. C-08 tested the worth of adding bevacizumab to 5-FU + LV and oxaliplatin (mFOLFOX6) in the treatment of patients with resectable stage II and III colon cancer \( (20) \). The original purpose of profiling C-08 was to identify predictive markers for bevacizumab benefit. However, there was no benefit from bevacizumab overall so we elected to add the mutation profiles from C-08 to the C-07 cases to add to the prognostic power of our study.
This correlative science study was approved by an institutional review board, and written informed consent was obtained from each patient for biomedical research.

DNA isolation and mutation detection
DNA from FFPE tumor blocks was prepared using an Ambion Recover-All kit or with the E.Z.N.A. FFPE DNA Isolation Kit from Omega Bio-Tek in a semi-automated method using the King Fisher Flex Instrument (ThermoFisher; ref. 17). DNAs were quantified with fluorosence, using the Quant-iT PicoGreen dsDNA Assay Kit (Invitrogen) and the InfiniteF200 fluorometer (Tecan).

MassSpec type plex technology and mutation panels
Mutation profiling with OncoCarta and ColoCarta and the running of samples on the MassSpec platform have been described previously (17). All mutations were reviewed independently by 3 investigators, and all inconsistencies were reexamined and a consensus was reached. Reactions with more than 20% unextended primer were excluded from analysis. Mutation at any position was considered evidence of mutation for that gene. A failed reaction resulted in missing data for that gene only if the other reactions were wild-type (wt). OncoCarta interrogated 187 mutations in 19 genes and was used to interrogate 235 C-07 cases (17). Twenty-four colon cancer mutations in BRAF, NRAS, KRAS, MET, and PIK3CA were reconfigured into ColoCarta, which was used to profile all of the remaining C-07 (n = 1,601) cases and the cases from the C-08 (n = 463) randomly selected cohort. OncoCarta interrogated 187 mutations in 19 genes and was used to interrogate 235 C-07 cases (17). Twenty-four colon cancer mutations in BRAF, NRAS, KRAS, MET, and PIK3CA were reconfigured into ColoCarta, which was used to profile all of the remaining C-07 (n = 1,601) cases and the cases from the C-08 (n = 463) randomly selected cohort. On the basis of the Catalogue of Somatic Mutation in Cancer (http://www.sanger.ac.uk/genetics/CGP/cosmic/; COSMIC) database, the ColoCarta panel included assays that captured 99%, 98%, and 79% of the known colon cancer mutations in BRAF, KRAS, and PIK3CA, respectively. COSMIC mutation frequencies are based on the sequence of 4,628, 858, and 203 samples for BRAF, KRAS, and PIK3CA, respectively. Roughly 20% of the PIK3CA mutations in the COSMIC database were the result of 8 mutations in PIK3CA that occurred only once. These 8 mutations were not represented in either the OncoCarta or the ColoCarta assays.

Immunohistochemistry
Antibodies for immunohistochemistry included anti-MSH2 (clone FE-11; 1:200; Calbiochem) and anti-MLH1 (clone G168-15; 1:30; BD Biosciences). Sections were incubated with normal goat serum for 30 minutes and then overnight at 4°C with specific mouse monoclonal antibodies and stained with DAKO EnVision+ System Kit (DAKO) according to the manufacturer’s instructions. Mismatch repair (MMR) status was determined by staining results of MSH2 and MLH1. Tumors that showed no staining with anti-MSH2 or anti-MLH1 or both in the tumor cells were considered MMR deficient or unstable. Only tumors that showed staining for both were considered MMR proficient or stable. Positive staining in nontumor cells was used as a control for assay success.

Statistical analysis
Time to recurrence and time to death (overall survival, OS) were measured from random assignment. Survival after recurrence (SAR) was the time from recurrence to death in the set of patients with recurrence. For all 3 endpoints, patients without an event were censored at last follow-up.

Mutations in BRAF, KRAS, KRASG12V, NRAS, MET, and PIK3CA were analyzed as dichotomous variables in which all mutations for a particular gene were combined so that each gene within each case was scored as 0 to indicate no mutation and 1 to indicate the presence of a mutation. In addition, the BRAFV600E mutation was tested as a categorical variable using the frequency data for alleles. In this case, BRAFV600E mutations were split into 2 groups at a median cutoff with a frequency of mutant alleles of 0.16. Thus, cases were split into 3 groups: BRAFV600E wild-type, BRAFV600E low-frequency allele, and BRAFV600E high-frequency allele.

Mutations were tested for their association with age (<65, ≥65), gender, MMR status, T stage (T1 or T2, T3, T4), and nodal status (N0 = 0, N1 = 1–3, and N2 = 4 or more invaded lymph nodes). Associations were evaluated by Fisher exact test for tables with less than 5 patients in any category and the χ² test for other covariates. Two-sided P values <0.05 were considered significant.

The association of mutations and MMR status with the endpoints of recurrence, OS, and SAR were tested in Cox proportional hazard models controlling for treatment and the combination of nodal status and T stage (8 categories: N0 T3, N0 T4, N1 T1 or T2, N1 T3, N1 T4, N2 T1 or T2, N2 T3, and N2 T4). To control for multiple testing of 7 explanatory variables and 3 endpoints, a significant P value was considered less than 0.05/21 = 0.00238 according to the method of Bonferroni.

Data from C-07 and C-08 were combined for all analyses with the exception of interaction treatment tests for the prediction of oxaliplatin benefit, which was restricted to cases from C-07. The mutation-by-treatment interaction or the MMR-by-treatment interaction was tested by adding a cross-product term of indicator variables for oxaliplatin treatment and mutation status to the Cox models described in the previous paragraph. Statistical significance was corrected for multiple tests via the method of Bonferroni.

Our study had more than 80% power to detect a prognostic effect of mutant KRAS (35% in population) and mutant BRAF (12% in population) using recurrence as the endpoint and assuming a significance level of 0.05 if the corresponding HR was more than 1.4. For rare mutations such as NRAS (3% in population), our study had more than 70% power to detect an HR of more than 1.8. The estimated power to detect an HR of 1.5 for each mutation and each endpoint is summarized in Supplementary Table S2.

Our study for oxaliplatin prediction had more than 80% power to detect a prognostic effect of mutant KRAS (35% in population) and mutant BRAF (12% in population) using recurrence as the endpoint and assuming a significance level of 0.05 if the corresponding HR was more than 1.4. For rare mutations such as NRAS (3% in population), our study had more than 70% power to detect an HR of more than 1.8. The estimated power to detect an HR of 1.5 for each mutation and each endpoint is summarized in Supplementary Table S2.

Our study for oxaliplatin prediction had more than 80% power to detect an interaction effect of KRAS mutations and oxaliplatin treatment for recurrence if the corresponding HR was more than 2.0. However, for NRAS mutations, there was only a 30% power to detect a predictive effect if the corresponding HR was more than 2.
Results

Frequency and association of mutations with each other

The frequencies for the well-known colon mutations were 38.11% for KRAS, 20.18% for PIK3CA, and 14.20% for BRAF and were mostly similar to those seen in the COSMIC database (35.3% for KRAS, 12.4% for PIK3CA, and 14.3% for BRAF; ref. 21). Other infrequent mutations including NRAS (2.9%) and MET (3.7%) have also been described previously (Supplementary Table S3). While the sequence alterations in MET were listed as somatic mutations in COSMIC, they are actually single-nucleotide polymorphisms. Sequence alterations responsible for MET R970 and T992I were present in both normal and tumor tissues and are listed in the SNP database (data not shown).

The pairwise distribution of the multiple mutations in tumors differed from what would be expected under statistical independence for several pairs of mutations in our study. Similar to previous results, we found that BRAF and KRAS mutations were almost mutually exclusive (P < 0.0001; refs. 22, 23). Only 4 cases of 2,226 had mutations in both KRAS and BRAF. In Fig. 2, only 3 cases overlap because this figure includes only cases for which all mutations for all 4 genes were available. One of the cases with both NRAS and BRAF mutations had an assay failure for one of the other mutations and was eliminated from the figure. Likewise, only one tumor with an NRAS mutation had a BRAF mutation, which is similar to other reports that have found them to be mutually exclusive (24). Conversely, PIK3CA mutations were significantly associated with KRAS mutations (P < 0.0001) but PIK3CA did not show any significant association with BRAF. The overlap of the mutations in these 4 different genes is shown in Fig. 2.

Association of mutations and MMR status with clinical variables

In agreement with previous observations, BRAF mutations were significantly more prevalent in older-aged individuals (P < 0.0001), in females (P < 0.0001), and in MMR-deficient tumors (P < 0.0001; Table 1; refs. 6, 25–28). MMR status was associated with KRAS (P = 0.001) and KRASG12V (P < 0.0001), as expected, as BRAF and KRAS were mutually exclusive (6, 26). No mutations were associated with T stage or nodal status when corrected for multiple comparisons via Bonferroni, but BRAF mutations showed a trend toward significance for association with higher T stage (P = 0.01) and nodal status (P = 0.02). MMR-deficient tumors were significantly associated with higher T stage (P = 0.0005; tumors with a greater depth of invasion) and with lower N stage (P < 0.0001), as has been previously been observed (Table 1; ref. 29).

Association of mutations and MMR status with prognosis

MMR status and mutations in BRAF, KRAS, KRASG12V, MET, NRAS, and PIK3CA were examined for prognostic value by evaluation of time to recurrence, OS, and SAR
MMR-deficient tumors were positively associated with good prognosis for recurrence [HR, 0.48; 95% confidence interval (CI), 0.33–0.70; P < 0.0001] and showed a trend for association with OS (HR, 0.63; 95% CI, 0.46–0.89; P = 0.02) but the trend for SAR was in the opposite direction. Conversely, BRAF mutations were associated with poor OS (HR, 1.46; 95% CI, 1.20–1.79; P = 0.0002) and SAR (HR, 2.3; 95% CI, 1.83–2.95; P < 0.0001) but not for recurrence (HR, 1.02; 95% CI, 0.82–1.28; P = 0.86). The association of BRAF with poor SAR may help explain why BRAF mutations were not prognostic for recurrence but were for OS. The Kaplan–Meier plot in Fig. 4A clearly shows that patients with BRAF mutations have a much shorter survival time after recurrence than do patients whose tumors are wild-type for BRAF. KRAS, KRASG12V, MET, NRAS, and PIK3CA mutations were not associated with recurrence, OS, or SAR. NRAS mutations showed a trend for an association with recurrence but were not significant when corrected for multiple comparisons (HR, 1.53; 95% CI, 1.01–2.31; P = 0.04).

### Association of combined effect of MMR and BRAF with prognosis

It seems counterintuitive that BRAF mutations were associated with poor OS, SAR, and MMR-deficient tumors, even though MMR-deficient tumors were associated with a good prognosis based on recurrence and OS. To determine whether MMR status and BRAF mutation effects were additive or interactive, Kaplan–Meier plots for...
tions were re-analyzed based on the amount of mutant

\[ P = 0.88 \text{–} 3.49; \]

in MMR-proficient tumors (HR, 1.58; 95% CI, 1.23–2.04; 

The sensitivity of mutation detection provided a potentially meaningful clinical assessment of tumors. Therefore, we tested the 6 mutations and MMR status for interaction with oxaliplatin treatment in C-07 (Table 2). Mutations and MMR status did not come close to reaching significance for interaction with oxaliplatin. The power to detect an interaction HR of 2.0 for mutations in BRAFV600E alleles within a tumor. All C-07 and C-08 cases were split into 3 groups: BRAFV600E wt, BRAFV600E-low-frequency allele, and BRAFV600E high-frequency allele.

(Prepared for publication by the Sequenom platform allows for the sensitive quantification of tumor cells. Therefore, as part of an exploratory analysis, we analyzed BRAF mutations to determine whether the sensitivity of mutation detection provided a potentially meaningful clinical assessment of tumors. BRAF mutations were re-analyzed based on the amount of mutant

<table>
<thead>
<tr>
<th>Time to recurrence</th>
<th>P</th>
<th>HR</th>
<th>95% Lower</th>
<th>95% Upper</th>
</tr>
</thead>
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<td>0.86</td>
<td>1.02</td>
<td>0.82</td>
<td>1.28</td>
</tr>
<tr>
<td>KRAS_G12V</td>
<td>0.16</td>
<td>1.22</td>
<td>0.93</td>
<td>1.60</td>
</tr>
<tr>
<td>KRAS</td>
<td>0.21</td>
<td>1.12</td>
<td>0.94</td>
<td>1.32</td>
</tr>
<tr>
<td>MET</td>
<td>0.64</td>
<td>1.11</td>
<td>0.73</td>
<td>1.68</td>
</tr>
<tr>
<td>NRAS</td>
<td>0.04</td>
<td>1.53</td>
<td>1.01</td>
<td>2.31</td>
</tr>
<tr>
<td>PIK3CA</td>
<td>0.25</td>
<td>0.88</td>
<td>0.71</td>
<td>1.09</td>
</tr>
<tr>
<td>MMR status</td>
<td></td>
<td>0.0001</td>
<td>0.48</td>
<td>0.70</td>
</tr>
</tbody>
</table>

OS

| BRAF              | 0.0002| 1.46 | 1.20     | 1.79     |
| KRAS_G12V         | 0.49  | 1.11 | 0.83     | 1.47     |
| KRAS              | 0.33  | 1.09 | 0.92     | 1.29     |
| MET               | 0.40  | 1.19 | 0.79     | 1.80     |
| NRAS              | 0.34  | 1.25 | 0.80     | 1.95     |
| PIK3CA            | 0.32  | 0.90 | 0.72     | 1.11     |
| MMR status        | 0.0084| 0.64 | 0.46     | 0.89     |

SAR

| BRAF              | <0.0001| 2.31 | 1.83     | 2.95     |
| KRAS_G12V         | 0.55  | 0.91 | 0.66     | 1.25     |
| KRAS              | 0.30  | 1.11 | 0.92     | 1.34     |
| MET               | 0.27  | 1.31 | 0.81     | 2.12     |
| NRAS              | 0.11  | 0.67 | 0.40     | 1.10     |
| PIK3CA            | 0.10  | 1.23 | 0.96     | 1.57     |
| MMR status        | 0.02  | 1.60 | 1.07     | 2.41     |

Figure 3. Forest plot of mutations and MMR status and their association with recurrence, OS, and SAR. HR > 1 indicates detrimental.

Association of mutations and MMR with oxaliplatin benefit

Mutations have been identified as sensitivity and resistance markers to cancer therapies. Therefore, we tested the 6 mutations and MMR status for interaction with oxaliplatin benefit in C-07 on the 3 outcomes (recurrence, OS, and SAR). No significant interactions were seen between mutations (BRAF, KRAS, KRASG12V, MET, NRAS, and PIK3CA) and MMR status with oxaliplatin treatment in C-07 (Table 2). Mutations and MMR status did not come close to reaching significance for interaction with oxaliplatin. The power to detect an interaction HR of 2.0 for mutations in BRAF, KRAS, and PIK3CA was 71%, 96%, and 87%, respectively, for recurrence and OS. We found no significant interaction for these mutations and MMR status in this analysis and conclude that these common mutations are
Discussion

We conducted this study to evaluate the potential prognostic value and oxaliplatin predictive value of common hot spot mutations in patients with stage II and III colon cancer in a large cohort consisting of all available and consented tissues from NSABP clinical trial C-07 and an additional 463 cases from a representative cohort from NSABP clinical trial C-08.

This study represents one of the largest analyses of common hot spot mutations of prospective randomized clinical trial samples of stage II and III colon cancer. We used Type Plex chemistry and mass spectrometry, which we have previously shown to be sensitive, reproducible, and cost-effective for mutation detection of DNAs isolated from FFPE (17). The mutation frequencies in this study (KRAS, 38.1%; PIK3CA, 20.2%; NRAS, 2.9%; and BRAF, 14.2%) were comparable with other studies for stage II and III colon cancer (1, 6, 10, 21, 32). Lower frequencies for PIK3CA (14%) and BRAF (7%) mutations have been reported previously (6, 21). This could be due to differences in the population or to the greater sensitivity of the mass spec platform, which has been shown to be more sensitive than the methods used in the other studies (30, 31, 32).

No significant interactions were seen between mutations (BRAF, KRAS, KRASG12V, MET, NRAS, and PIK3CA) or MMR status with oxaliplatin treatment in C-07. We can conclude that these common mutations and MMR do not render tumors resistant to benefit from oxaliplatin within the limitations of detection based on sample size.

FOLFOX has become the standard of care for patients with resected stage III and most stage II colon cancer based on NSABP trial C-07 and the MOSAIC trial (19, 33, 34). However, in some studies, 5-fluorouracil has been shown to render no benefit to MMR-deficient tumors, but because no clinical trial has shown that there was no benefit from treatment of this group with FOLFOX, FOLFOX remains the standard of care (34). However, mechanistic arguments suggest that oxaliplatin would be particularly beneficial to patients with MMR-deficient tumors because oxaliplatin forms platinum adducts with DNA, which cannot be repaired in MMR-deficient tumors. One study has shown that stage III patients with deficient MMR had improved outcomes with FOLFOX over 5-fluorouracil; however, these were not randomized controlled trials, and we are unaware of any data that support this mechanistic argument (35). In our study, oxaliplatin did not interact with MMR status.

As in previous studies, we showed that MMR-deficient tumors and BRAF mutations were associated with each other and with prognosis (4, 6, 8). MMR-deficient tumors were associated with a longer recurrence-free interval but showed a trend for poor survival after recurrence. The seeming reversal of MMR as a good prognostic factor based on recurrence to a bad prognostic factor based on SAR maybe the result of the association of BRAF mutations with MMR tumors because BRAF-mutant tumors were associated with a shorter SAR. These observations seem confusing but can be explained by speculating that MMR-deficient tumors are held in check by a strong immunologic reaction associated with MMR-deficient tumors but are overcome by BRAF mutations, which may allow for immune evasion as discussed below (36).

We and others have previously reported that BRAF and KRAS were largely mutually exclusive and PIK3CA mutations were largely mutually exclusive and MMR-deficient tumors were associated with a longer recurrence-free interval but showed a trend for poor survival after recurrence.
mutations were significantly associated with KRAS mutations (17, 24, 37). The overrepresentation of KRAS-mutant tumors suggests that PIK3CA mutations may occur after KRAS mutations and therefore later in the etiology of the tumor, which has been discussed previously (17).

Early research using institution-based studies and meta-analyses have reported that KRAS and KRASG12V mutations were prognostic for colon cancer, respectively (12–14, 16, 38). In agreement with these early studies are the results from 2 large clinical trials: the Quasar study (n = 1,583) and the MRC study, both of which reported significant association with KRAS for recurrence and OS, respectively. However, not all of these early studies found KRAS mutations to be prognostic (15). More recently, the PETACC trial, another large study using tissue collected as part of a randomized clinical trial of stage II and III colon cancer, also did not find any prognostic significance for KRAS mutations when relapse-free survival and OS were used as endpoints (6). What accounts for these differences in the results of these well-powered clinical trials? One possible explanation is that the MRC focus study evaluated metastatic tumors, and it is possible that KRAS mutations have a different impact on the survival of metastatic patients than on stage II and III patients, which has been reported previously (6, 39). The Quasar study consisted largely of patients with stage II colon cancer (91%) and included rectal cancers (28%), unlike our study and the PETACC study, which included a substantial number of stage III patients and did not include rectal cancers (16, 6). Thus it seems likely that KRAS mutations are not prognostic in stage II and III colon cancer. However, it will be of interest to determine whether KRAS mutations are associated with prognosis in rectal cancer.

We also did not find any prognostic value for PIK3CA mutations in stage II and III colon cancer in contrast to findings in other earlier studies (1–3). Reasons for the differences in the results between our study and these other studies are differences in the patient population, covariates included in the multivariate Cox model, and differences in the methodologies used to detect mutations. In addition, our study included mutations in PIK3CA in exons 1, 7, and 13, which were not included in the other studies and constituted 14.4% of the total PIK3CA mutations. A study published during the review of this article has reported that concomitant PIK3CA mutations in exons 9 and 20 were associated with bad prognosis, but this analysis, as the author points out, should be viewed with caution because there were only 7 patients with this genotype (40) of a total of more than 1,170 colorectal cancers. We did not detect any double mutations of exons 9 and 20 in PIK3CA in our 2,299 samples of colon cancer. The distinction between these 2 samples sets may be the presence of rectal cancer in the tumors in the study of Liao and colleagues, whereas our study included only colon cancer. It should not be surprising that the mutation spectrum varies between colon and rectal cancers because the frequency of BRAF mutations varies within the colon depending whether the tumor is on the right or left side of the colon.

This study validates the results from previous studies that associated BRAF mutations with OS (4–9) and shows that BRAF is associated with poor SAR in patients first diagnosed as stage II or III and is, at least in part, responsible for poor OS. The association of BRAF mutations with poor SAR is consistent with previous observations that have associated it with poor OS in metastatic patients (39). Further confirmation of the association of BRAF with OS and SAR was recently published during the review of the manuscript (8, 41). BRAF tumors showed no significant relationship with recurrence even though they were associated with OS and SAR. Thus, we could conclude that BRAF-mutant tumors do not readily metastasize, but once they have metastasized, they rapidly lead to the death of the patient. This may help explain the differences observed in the frequency of BRAF mutations found in metastatic patients compared with our study. Patients who have BRAF-mutant tumors have such a short survival after recurrence that few of these patients survive long enough to be recruited into metastatic studies. This would help explain the lower frequency of BRAF mutations (4.7%) in the De Rook study, which profiled tumors from chemorefractory metastatic patients (23). However, if BRAF-mutant tumors are unlikely to become metastatic, what accounts for the very poor SAR of these tumors? BRAF mutations may associate with poor SAR due to resistance to systemic anti-EGFR therapies that may have been given after recurrence. However, we would

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Table 2. Interaction of mutations and MMR status with oxaliplatin treatment

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<tr>
<th>Variable</th>
<th>Recurrence logHR</th>
<th>stderr</th>
<th>P</th>
<th>OS logHR</th>
<th>stderr</th>
<th>P</th>
<th>SAR logHR</th>
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</tbody>
</table>
35% to 40% of all stage II and III colon tumors did not have BRAF-mutant tumors may have altered immune response. MMR-deficient tumors have been shown to be associated with a high density of cytotoxic (CD8^+ T) and memory (CD45RO^+ T) cells and may be responsible for the good prognosis associated with MMR-deficient tumors (42–44). One of the roles of the activated BRAF/MAPK pathway is immune evasion by the suppression of immunosuppressive factors and inflammatory cytokines, such as interleukin (IL)-10 (45). IL-10 has been shown to be required for optimal promotion and sustainment of T-cell memory in a mouse model with IL-10 knockout mice (42, 45). However, if BRAF-mutant tumors have an altered interaction with memory T cell, it is not likely to be the result of a decrease in the density of these cells in the primary tumor because higher density of memory T cells (CD45RO) are also associated with BRAF-mutant tumors (43).

All of the mutations screened in this study are possible resistance or sensitivity biomarkers that could aid in the selection of patients for clinically approved targeted therapies. Recent evidence suggests that KRAS, BRAF, PIK3CA, and NRAS may render tumors nonresponsive to anti-EGFR therapies. Currently, patients with metastatic colon cancer with KRAS- or BRAF-mutant tumors are not recommended for treatment with cetuximab due to their inherent resistance (23). In melanoma, BRAF mutations appear to be sensitivity markers for the BRAF inhibitor PLX4032, which has been shown to give a significant survival benefit in untreated BRAF/V600E mutation–positive patients with metastatic melanoma, but results in colon cancer have not been as promising. However, given that BRAF mutations are associated with poor post-recurrence survival and may confer resistance to EGFR-targeted agents, there is a strong rationale to design colon cancer clinical trials that use new BRAF-targeted therapies (46).

New clinical trials are being developed to correlate the mutation status of tumors and their response to targeted therapies, in an effort to develop biomarkers that will identify those tumors that are sensitive or resistant to treatment. It is important to remember that approximately 35% to 40% of all stage II and III colon tumors did not have mutations in any of the 5 genes profiled here and may be good candidates for targeted therapies such as cetuximab. Conversely, mutations in these genes may also act as sensitivity markers for targeted therapies such as vemurafenib, PLX4032, and others that block the signaling pathways for which these genes are a part. Therefore, at a minimum, the mutation status of BRAF, KRAS, NRAS, and PIK3CA will need to be determined in clinical trials assessing targeted therapies that block the RAS/RAF/MAPK and PI3K/PTEN/AKT pathways. Such clinical trials are under development at NSABP.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

Disclaimer
The Pennsylvania Department of Health specifically disclaims responsibility for any analysis, interpretations or conclusions. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. K.L. Pogue-Geile had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Authors' Contributions

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References


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