Colorectal cancer accounts for one million new cases and >500,000 deaths worldwide every year, and the treatment options available are far from optimal (1). Curative treatment of these patients involves surgery and/or chemotherapy. For patients with advanced disease, palliative chemotherapy is often administered and can significantly improve their quality of life and overall survival. For over four decades the pyrimidine analogue 5-fluorouracil (5-FU) has been the gold standard for the treatment of colorectal cancer. However, only about 20% to 30% of colorectal cancer patients benefit from the treatment with 5-FU, either in the adjuvant setting or for the treatment of advanced disease (2, 3). More recently, additional chemotherapeutic agents have been approved for the treatment of these patients and are now in common use. These include the topoisomerase I inhibitor irinotecan (CPT11), the platinum compound oxaliplatin, and monoclonal antibodies against the epidermal growth factor receptor (EGFR) and the vascular endothelial growth factor (VEGF). These new agents have increased the percentage of advanced-disease patients with an objective response to approximately 50% and the overall survival to almost 24 months (4–8).

The lack of response of approximately half of the patients treated highlights the need for new chemotherapeutic agents. In addition, because the different chemotherapeutic agents currently available are effective only in overlapping subsets of patients, it would be very useful to have markers capable of discriminating the patients who are likely to respond optimally to irinotecan-based therapy. The objective of this work was to identify new molecular markers capable of identifying the subset of patients who are unlikely to respond.

### Abstract

**Purpose:** Irinotecan (CPT11) treatment significantly improves the survival of colorectal cancer patients and is routinely used for the treatment of these patients, alone or in combination with other agents. However, only 20% to 30% of patients show an objective response to irinotecan, and there is great need for new molecular markers capable of identifying the subset of patients who are unlikely to respond.

**Experimental Design:** Here we used microarray analysis of a panel of 30 colorectal cancer cell lines and immunohistochemistry to identify and validate a new biomarker of response to irinotecan.

**Results:** A good correlation was observed between irinotecan sensitivity and the expression of aprataxin (APTX), a histidine triad domain superfamily protein involved in DNA repair. Moreover, using an isogenic in vitro system deficient in APTX, we show that aprataxin directly regulates the cellular sensitivity to camptothecin, suggesting that it could be used to predict patient response to irinotecan. We constructed a tissue microarray containing duplicate tumor samples from 135 patients that received irinotecan for the treatment of advanced colorectal cancer. Immunohistochemical assessment of the tumor levels of aprataxin showed a significant association with treatment response and patient survival. Patients with low aprataxin had longer progression-free (9.2 versus 5.5 months; \( P = 0.03 \)) and overall survival (36.7 versus 19.0 months; \( P = 0.008 \)) than patients with high tumor aprataxin. No associations were found between coding APTX variants and aprataxin levels or camptothecin sensitivity.

**Conclusions:** These results show that aprataxin tumor levels can be used to identify patients with low probability of response to irinotecan-based therapy who are ideal candidates to receive treatment with alternative agents in an attempt to improve patient survival.

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**Note:** Supplementary data for this article are available at Clinical Cancer Research Online (http://clincancerres.aacrjournals.org/).

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Irinotecan is commonly used for the treatment of advanced colorectal cancer. However, only 20% to 30% of these patients show an objective response to this topoisomerase I inhibitor and it is currently not possible to predict the probability of patient response. Here we show that aprataxin tumor levels can be used to separate two groups of colorectal cancer patients that show an overall survival difference of almost 1.5 years following irinotecan treatment. Aprataxin tumor levels can be used alone or in combination with other markers to make informed decisions regarding the type of treatment that is likely to be most effective for individual patients.

**Translational Relevance**

Irinotecan is commonly used for the treatment of advanced colorectal cancer. However, only 20% to 30% of these patients show an objective response to this topoisomerase I inhibitor and it is currently not possible to predict the probability of patient response. Here we show that aprataxin tumor levels can be used to separate two groups of colorectal cancer patients that show an overall survival difference of almost 1.5 years following irinotecan treatment. Aprataxin tumor levels can be used alone or in combination with other markers to make informed decisions regarding the type of treatment that is likely to be most effective for individual patients.

**Materials and Methods**

**Characterization of sensitivity to camptothecin.** The sensitivity to camptothecin was characterized in a panel of 30 colorectal cancer cell lines: Caco-2, Colo201, Colo205, Colo320, Dld-1, HCT116, HCT-15, HCT-8, HT29, LoVo, LS174T, RKO, SK-CO-1, SW1116, SW403, SW48, SW480, SW620, SW837, SW948, T84, WiDr, HT29-Cl.16E, HT29-Cl.19A, LIM1215 and LIM2405, HCC2998, KM12, RW2982, and RW7213. All cell lines were obtained and grown as reported before (18), and tested for mycoplasma contaminations using the PCR Mycoplasma Detection Set (Takara Bio). The dose resulting in 50% reduction in the growth of the cell line was calculated as previously reported using the sulforhodamine B method (18, 23). Cells were exposed for 72 h to the following concentrations of camptothecin: 0.001, 0.005, 0.0075, 0.01, 0.025, 0.05, 0.1, 0.25, 0.5, 1, and 2 μmol/L. The induction of apoptosis after 72 h exposure to the indicated concentrations of camptothecin was also measured to evaluate drug sensitivity using propidium iodide staining and flow cytometry as previously reported (24, 25). All experiments were carried out at least three times in triplicate. The unique peaks for 2n and 4n DNA content in these assays indicated the absence of cross-contamination between lines. We also used the parental chicken B-lymphocyte cell line DT40, a subline where APTX was reintroduced into the null cells (26). 

**RNA extraction and quantitative reverse transcription-PCR.** Total RNA of colorectal cancer cell lines was extracted with the RNeasy Midi Kit (Qiagen) and reverse transcribed using the cDNA Archive Kit (Applied Biosystems). Aprataxin levels were analyzed using SYBR Green.
Master Mix (Applied Biosystems) and the primers APTX-F: AAGCTGGACTTGAACCCCTA; APTX-R: CTGTCCTGTCTCACAAACCA. β-Actin was used as a standardization control: β-actin F: CACCTTCACCGTCCAGTTT; β-actin R: GATGAGATTGGCATGGCTTT. Relative mRNA levels were assessed using the $2^{-\Delta\Delta C_t}$ method as described before (17, 25).

**Patients.** A total of 135 colorectal cancer patients with metastatic disease receiving irinotecan-based chemotherapy at Vall d’Hebron University Hospital (Barcelona, Spain) were included in the study. Table 1 summarizes the clinicopathologic information of the patients. Response to the chemotherapeutic treatment was evaluated by computed tomography using response evaluation criteria in solid tumors (RECIST) criteria (27). The median follow-up time of the patients in this study was 4.6 y. The study was carried out according to Human Investigations and Ethical Committee–approved research protocols.

**Tissue microarrays and immunohistochemistry.** After histologic examination of H&E-stained sections of formalin-fixed, paraffin-embedded tumor samples, areas containing a high proportion of tumor cells were selected from all 135 patients. Duplicate 1.2-mm cores of tumor samples from every patient were arrayed in a fresh paraffin block using a Beecher Instruments tissue arrayer (Beecher Instruments). Unstained 4-μm sections from the tissue microarrays were mounted on slides coated with 3-aminopropyl-triethoxysilane (Sigma). Sections were deparaffinized in xylene, and rehydrated through a graded alcohol series and distilled water. Antigen retrieval was achieved with preheated citrate buffer 10 mmol/L (pH 6) for 20 min to 95°C. For immunohistochemical analysis, the commercial Novolink Polymer Detection System (Novocastra Laboratories) was used according to the manufacturer’s instructions. An aprataxin rabbit polyclonal antibody raised against the COOH-terminus of human aprataxin was used at a 1:100 dilution (4°C overnight; Aviva Systems Biology Corp). Staining was visualized using a 3,3-diaminobenzidine solution, and sections were counterstained with Mayer’s hematoxylin, rinsed in water, dehydrated through a series of ethanol solutions, cleared in xylene, and mounted. Aprataxin levels were evaluated blinded from the clinical data. A semiquantitative scale from 0 to 3 was used to measure the intensity of the staining. Absence of aprataxin immunostaining was scored as 0, and low, moderate, and high aprataxin levels were scored as 1, 2, and 3, respectively (Fig. 3A-D). The average score of duplicate samples was used in subsequent analyses. Aprataxin levels were considered low if average immunostaining score was <2 and high if it was ≥2.

**Table 1. Clinical features of the 135 patients in the series used in this study**

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Low aprataxin</th>
<th>High aprataxin</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sex, no. (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>50 (37.0)</td>
<td>20 (30.3)</td>
<td>30 (43.5)</td>
<td>0.15*</td>
</tr>
<tr>
<td>Male</td>
<td>85 (63.0)</td>
<td>46 (69.7)</td>
<td>39 (56.5)</td>
<td></td>
</tr>
<tr>
<td><strong>Age (y)</strong></td>
<td>62.4</td>
<td>63.0</td>
<td>61.9</td>
<td>0.78†</td>
</tr>
<tr>
<td><strong>Irinotecan regimen, no. (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irinotecan monotherapy</td>
<td>60 (46.9)</td>
<td>23 (37.1)</td>
<td>37 (56.1)</td>
<td>0.1‡</td>
</tr>
<tr>
<td>FOLFIRI</td>
<td>41 (32.0)</td>
<td>26 (41.9)</td>
<td>15 (22.7)</td>
<td></td>
</tr>
<tr>
<td>FOLFIRI + bevacizumab</td>
<td>8 (6.3)</td>
<td>4 (6.5)</td>
<td>4 (6.1)</td>
<td></td>
</tr>
<tr>
<td>FOLFIRI + cetuximab</td>
<td>19 (14.8)</td>
<td>9 (14.5)</td>
<td>10 (15.2)</td>
<td></td>
</tr>
<tr>
<td><strong>Degree of differentiation of tumor, no. (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>13 (10.4)</td>
<td>7 (11.7)</td>
<td>6 (9.2)</td>
<td>0.44‡</td>
</tr>
<tr>
<td>Moderate</td>
<td>74 (59.2)</td>
<td>38 (63.3)</td>
<td>36 (55.4)</td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>38 (30.4)</td>
<td>15 (25)</td>
<td>23 (35.4)</td>
<td></td>
</tr>
<tr>
<td><strong>Objective response</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete response</td>
<td>9 (7.7)</td>
<td>7 (11.9)</td>
<td>2 (3.5)</td>
<td>0.13‡</td>
</tr>
<tr>
<td>Partial response</td>
<td>30 (25.9)</td>
<td>17 (28.8)</td>
<td>13 (22.8)</td>
<td></td>
</tr>
<tr>
<td>Stable disease</td>
<td>29 (25)</td>
<td>16 (27.1)</td>
<td>13 (22.8)</td>
<td></td>
</tr>
<tr>
<td>Progressive disease</td>
<td>48 (41.4)</td>
<td>19 (32.2)</td>
<td>29 (50.9)</td>
<td></td>
</tr>
<tr>
<td>Median progression-free survival (mo)</td>
<td>6.7</td>
<td>9.2</td>
<td>5.5</td>
<td>0.03§</td>
</tr>
<tr>
<td>Median overall survival (mo)</td>
<td>26.3</td>
<td>36.7</td>
<td>19.0</td>
<td>0.008§</td>
</tr>
</tbody>
</table>

**NOTE:** P values calculated using Fisher’s exact test, Mann-Whitney test, $\chi^2$, or logrank test for the comparison of high and low Aprataxin. FOLFIRI: irinotecan with 5-FU and folinic acid.

*Calculated using Fisher’s exact test.
†Calculated using Mann-Whitney test.
‡Calculated using $\chi^2$.
§Calculated using Logrank test.
Transfections and Western blotting. pEGFP-C2 (BD Biosciences Clontech) or pEGFP-APTX (containing amino acids 2-342 of aprataxin and EGFP fused to the NH2-terminus, a kind gift from Professor Martin F. Lavin; Queensland Institute of Medical Research, Radiation Biology and Oncology, Brisbane, Australia) were transfected into HEK293T cells using the calcium phosphate precipitate method as previously reported (28). Briefly, 5 μg of plasmid DNA were resuspended in a total volume of 86 μL of HBS (280 mmol/L NaCl, 50 mmol/L HEPES, 1 mmol/L Na2HPO4, pH 7.12, at 25°C) and 5 μL of a 2.5 mol/L CaCl2 solution were added. This solution was pipetted dropwise to a 6-well plate containing 1.5 × 10⁶ HEK293T cells seeded 16 h earlier. Cells were harvested 48 h posttransfection and extracts of total protein (100 μg) in radioimmunoprecipitation assay buffer were loaded on a 10% acrylamide gel. After gel electrophoresis, proteins were transferred to a nitrocellulose membrane and probed with an anti-aprataxin (1:400; Aviva Systems Biology) or anti-GAPDH (1:2,000; clone 6C5; Santa Cruz Biotechnology) antibody as previously described (29). GAPDH served as a loading control.

Sequencing of coding APTX polymorphisms. The possible association between known (National Center for Biotechnology Information database) polymorphisms in the coding sequence of APTX were investigated by direct sequencing of 10 colon cancer cell lines that vary in their sensitivity to camptothecin. Briefly, the corresponding genomic DNA fragments were PCR amplified (See Supplementary Table S1).
Aprataxin Levels Predict Response to irinotecan

Results

Aprataxin levels inversely correlate with the sensitivity of colon cancer cell lines to camptothecin. We previously reported a profile of gene expression that is associated with the sensitivity of colon cancer cell lines to the irinotecan analog camptothecin. Microarray analysis of the levels of expression of >9,000 genes in a panel of 30 colorectal cancer cell lines identified a significant association between aprataxin expression levels and sensitivity to camptothecin (18). In good agreement, aprataxin has been recently shown to be involved in the repair of single-stranded DNA (22).

Expression values obtained by microarray analysis were independently validated using quantitative real-time reverse transcriptase-PCR in these 30 colorectal cancer cell lines. A good correlation was observed between expression values obtained with both techniques (Pearson $R = 0.5$; $P = 0.006$). Moreover, aprataxin mRNA levels showed excellent correlation with both camptothecin-induced growth inhibition (GI$_{50}$; Pearson $R = 0.4$; $P = 0.03$) and induction of apoptosis (Fig. 1; 0.1 and 1 $\mu$mol/L; $R < -0.51$; $P < 0.004$). In addition, we show that camptothecin treatment does not affect the expression of aprataxin in colon cancer cells (Supplementary Fig. S1).

Aprataxin regulates the sensitivity to camptothecin. To directly assess the role of aprataxin on camptothecin sensitivity we used an engineered in vitro system where both alleles of APTX were targeted by homologous recombination. Figure 2 shows that treatment of parental DT40 cells with 15 to 25 $\mu$mol/L camptothecin for 72 hours resulted in a modest induction of apoptosis. However, targeted inactivation of APTX significantly ($P < 0.004$) sensitized cells to camptothecin treatment. Moreover, reintroduction of APTX into APTX-null cells completely restored the camptothecin-resistant phenotype of the parental DT40 cells, further showing that aprataxin directly regulates the cellular sensitivity to camptothecin (Fig. 2).

Low aprataxin tumor levels are associated with good response to irinotecan. We next wanted to investigate the value of aprataxin tumor levels as a marker of response to irinotecan. For this purpose, we used a series of colorectal cancer patients with metastatic disease who received irinotecan-based treatment (see Table 1). A tissue microarray containing duplicate tumor samples from 135 patients was constructed. The levels of expression of aprataxin in these tumors were assessed by immunohistochemistry, and a gradient of expression was observed, ranging from complete absence (Fig. 3A) to high tumor levels of aprataxin (Fig. 3D). The specificity of the antibody was confirmed by Western blotting. A single band of the expected molecular weight was detected in HEK293T cells transiently transfected with an APTX-GFP fusion protein (Supplementary Fig. S2).

In good agreement with previous reports (4, 8), the overall response rate for this series of 135 irinotecan-treated patients with advanced colorectal cancer was 33.6% with a median progression-free survival of 6.7 and 26.3 months, respectively. Fifty-one percent of the cases studied showed low/absent aprataxin, whereas the remaining 49% were categorized as having moderate/high levels (Fig. 3). Aprataxin tumor levels could distinguish two groups of patients with significantly different responses to irinotecan-based treatment. A significantly higher proportion of patients with high aprataxin levels had progressive disease compared with patients with low aprataxin [29 of 57 (50.9%) versus 19 of 59 (32.2%); $\chi^2$ test $P = 0.04$]. The median progression-free survival of patients with high aprataxin tumor levels was 5.5 months whereas in the group of patients with low aprataxin levels it was 9.2 months (Logrank test $P = 0.03$; hazard ratio, 1.5; 95% confidence interval, 1.04-2.29; Fig. 3E). Moreover, the median overall survival of patients with absent/low aprataxin was 17.7 months longer than in the group of patients with moderate/high aprataxin (19.0 versus 36.7 months, respectively; Logrank test $P = 0.008$; hazard ratio, 2.1; 95% confidence interval, 1.21-3.63; Fig. 3F). In a multivariate analysis with sex, age, tumor grade, and aprataxin levels as covariates, low aprataxin remained a significant marker of better survival (Table 2).
overall survival in colorectal cancer patients treated with irinotecan (Cox regression; \( P = 0.04 \)), showing a strong association between low aprataxin levels and good response to irinotecan treatment.

**Coding polymorphisms in APTX.** The coding sequence of APTX has six reported polymorphisms (National Center for Biotechnology Information database, September 2009). Five of these are single nucleotide polymorphisms, and in addition, a deletion of 805 bp has been described (see Supplementary Table S2). To investigate the possible association between the sensitivity to camptothecin and the genotype of these APTX polymorphisms, we used direct sequencing of 10 different colon cancer cell lines that widely vary in their sensitivity to camptothecin (Supplementary Table S2). We found no variability in the genotype of these genomic regions in the tumor cell lines investigated. Therefore, variations in the coding sequence of APTX are not responsible for the expression and sensitivity differences observed in these cell lines, and are unlikely to underlie the differences in tumor response observed in colorectal cancer patients.

**Discussion**

The availability of molecular markers capable of predicting response to different chemotherapeutic agents used for the treatment of advanced colorectal cancer would constitute a significant step towards a more personalized treatment for these patients. For example, the realization that only patients with wild-type KRAS tumor cells are likely to respond to EGFR targeting agents such as cetuximab or panitumumab has significantly improved the management of these patients (9, 30). Patients with mutant KRAS tumors are spared from the treatment with EGFR targeting agents and can be treated with alternative agents that are more likely to elicit a positive response. Irinotecan is a TOP1 inhibitor that is frequently used for the treatment of advanced colorectal cancer patients. TOP1 is involved in
Aprataxin Levels Predict Response to Irinotecan

the relaxation of supercoiled DNA occurring during DNA replication or transcription, forming a covalent intermediate with the 3′-terminus of the nicked DNA that is normally released and religated to the adjacent 5′-end. However, treatment with TOP1 inhibitors, such as irinotecan, results in the stabilization of the TOP1-DNA complex that upon collision with the replication fork causes double-strand DNA breaks, cell cycle arrest and death (31). Treatment of advanced colorectal cancer patients with irinotecan as a single agent has shown response rates of approximately 30%, and these rates reach 50% when used in combination with other agents, resulting in significant improvements of progression-free and overall survival of irinotecan-treated patients (4, 8). However, the majority of patients do not show an objective response to irinotecan, and there is therefore an acute need for the identification of molecular markers capable of predicting the probability of response to this agent. Microarray analysis can simultaneously assess the levels of expression of thousands of genes and is therefore a useful tool to screen for potential new molecular markers of response to treatment with chemotherapeutic agents. The use of cell lines allows the rigorous assessment of sensitivity to chemotherapeutic agents individually in a controlled manner, and microarray analysis can then be used to identify genes with expression profiles across multiple tumor cell lines that closely correlate with drug sensitivity. Moreover, the expression profiles identified in vitro have been shown to be useful to predict patient response to these agents (16–18).

Here, we used microarray expression analysis to identify aprataxin (APTX) as a new molecular marker of response to irinotecan treatment. We found that the levels of aprataxin are significantly associated with camptothecin sensitivity in a panel of 30 colorectal cancer cell lines (P = 0.004). Aprataxin is a member of the histidine triad domain superfamily of nucleotide hydrolases and transferases, and participates in the repair of single- and double-strand DNA breaks (32). Using an in vitro cell system in which both copies of APTX have been inactivated by targeted recombination, we showed that low aprataxin levels significantly sensitize to camptothecin treatment in vitro.

Currently, the best-characterized marker capable of predicting response to irinotecan in patients with advanced colorectal cancer is the direct molecular target TOP1 (14). Irinotecan-treated patients with high TOP1 tumor levels have an overall survival of approximately 14.7 months compared with 17.4 months in patients with high TOP1 levels (14). In this study, we investigated the value of aprataxin as a new marker of response to irinotecan treatment. We found that patients with absent/low aprataxin tumor levels have better response rates (40.7% versus 26.3%) and longer progression-free (9.2 versus 5.5 months) and overall survival (36.7 versus 19.0 months) than patients with moderate/high aprataxin levels. Therefore, tumor levels of aprataxin can distinguish two subgroups of patients with advanced colorectal cancer that widely differ in their response to irinotecan treatment. If this result is independently confirmed, ideally on randomized trials, aprataxin could be used alone or in combination with other biomarkers to make informed decisions regarding the type of treatment that is likely to be most effective for individual patients. The identification of aprataxin as a new marker predicting the probability of response to irinotecan treatment constitutes a new step towards the goal a more individualized treatment for patients with advanced colorectal cancer. For example, a patient with advanced colon cancer with a tumor that has low levels of aprataxin, high topoisomerase I, and wild-type KRAS would be an ideal candidate to receive combined treatment with irinotecan and cetuximab/panitumumab.

Irinotecan treatment results in the accumulation of DNA strand breaks in tumor cells, and aprataxin has been shown to have an important role in the repair of DNA single- and double-strand breaks (12, 21, 22). Although the detailed mechanisms remain to be elucidated, tumors with elevated levels of aprataxin would be more resistant to irinotecan because the DNA damage caused by this agent would be repaired more efficiently, and therefore, these patients would have a poor response to this form of treatment. Although several polymorphisms have been reported in the coding sequence of APTX, no variants were observed in a series of colon cancer cells with significant differences in their sensitivity to camptothecin. Therefore, coding APTX variants are unlikely to play a major role in the response of colorectal tumors to irinotecan.

In conclusion, in this study we show that the histidine triad family protein aprataxin directly regulates the cellular sensitivity to camptothecin and the value of assessing aprataxin tumor levels as a biomarker capable of predicting response to irinotecan-based treatment in patients with advanced colorectal cancer. Aprataxin levels, combined with other markers such as TOP1, could allow identification of a large subset of patients with low probability of response to irinotecan. These patients would be ideal candidates to receive treatment with alternative agents available in an attempt to improve their survival and quality of life.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

We thank Dr. Keith W. Caldecott (Genome Damage and Stability Centre, University of Sussex, Falmer, Brighton) and Dr. Martin F. Lavin (Queensland Institute of Medical Research, Radiation Biology and Oncology, Brisbane, Australia) for kindly providing us with the DT40 APTX KO cell system and the pKGFP-APTX vector, respectively.

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Aprataxin Tumor Levels Predict Response of Colorectal Cancer Patients to Irinotecan-based Treatment

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