Copy number aberrations of \textit{BCL2} and \textit{CDKN2A/B} identified by array-CGH in thymic epithelial tumors

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The molecular pathology of thymic epithelial tumors (TETs) is largely unknown. Using array comparative genomic hybridization (CGH), we evaluated 59 TETs and identified recurrent patterns of copy number (CN) aberrations in different histotypes. GISTIC algorithm revealed the presence of 126 significant peaks of CN aberration, which included 13 cancer-related genes. Among these peaks, CN gain of \textit{BCL2} and CN loss of \textit{CDKN2A/B} were the only genes in the respective regions of CN aberration and were associated with poor outcome. TET cell lines were sensitive to siRNA knockdown of the anti-apoptotic molecules \textit{BCL2} and MCL1. Gx15-070, a pan-BCL2 inhibitor, induced autophagy-dependent necroptosis in TET cells via a mechanism involving mTOR pathways, and inhibited TET xenograft growth. ABT263, an inhibitor of BCL2/BCL-XL/BCL-W, reduced proliferation in TET cells when administered in combination with sorafenib, a tyrosine kinase inhibitor able to downregulate MCL1. Immunohistochemistry on 132 TETs demonstrated that CN loss of \textit{CDKN2A} correlated with lack of expression of its related protein p16INK4a and identified tumors with poor prognosis. The molecular markers \textit{BCL2} and \textit{CDKN2A} may be of potential value in diagnosis and prognosis of TETs. Our study provides the first preclinical evidence that deregulated anti-apoptotic \textit{BCL2} family proteins may represent suitable targets for TET treatment.

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Thymic epithelial tumors (TETs) are rare with an estimated incidence of 0.32/100,000 persons/year.\cite{1} According to the 2004 WHO classification, there are two major categories of TETs: thymomas and thymic carcinomas (TCs). Thymomas are further classified into A, AB, B1, B2, and B3 subtypes according to cancer cell features, degree of atypia and number of intratumoral thymocytes.\cite{2} Histology of TCs is similar to carcinomas originating in organs other than the thymus and displays the characteristics of aggressive epithelial tumors.\cite{2} Surgery represents the mainstay of TET treatment, and survival is strongly influenced by the stage of the disease and the completeness of tumor resection.\cite{2} Although chemotherapy is able to induce substantial tumor shrinkage of variable duration in metastatic and non-resectable TETs, it is not curative in patients with metastatic disease. Exploration of molecularly targeted drugs, which have become available for treatment of several cancer types, has so far been limited by the lack of understanding of the molecular changes of TETs.

Results

Correlation between chromosome arm-level aberrations and TET histotypes. A total of 59 tumors rich in cancer cells (>80%) were selected for array comparative genomic hybridization (CGH) evaluation from 132 formalin-fixed paraffin-embedded (FFPE) TET samples (Table 1). CGH revealed a total of 4300 copy number (CN) aberrations, ranging from large events involving an entire chromosome arm to only few kilobases. The length of each CN aberration was expressed as the percentage of a relative chromosome arm, and CN aberrations were divided into 10 groups according to the proportion of the chromosome affected (Figure 1a). Small CN aberrations (0–10% of a chromosome arm length) were the most common (Figure 1a; n = 3665). The number of CN aberrations progressively decreased in inverse proportion to their length up to 80% of their respective chromosome arms, and then rose again reaching a second peak at 90–100%. The number of expected

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Abbreviations: TET, thymic epithelial tumors; CGH, comparative genomic hybridization; TC, thymic carcinoma; CN, copy number; GISTIC, genomic identification of significant targets in cancer; WHO, World Health Organization; FFPE, formalin fixed paraffin embedded; MG, Myasthenia gravis; MMP, Matrix Metalloproteinase; TTP, Time To Progression; DRS, disease related survival; HR, hazard ratio; CI, confidence interval; siRNA, small interfering RNA; MTS, CellTiter 96 AQueous non-radioactive cell proliferation assay; Gx15-070, Oblatocia; BH3, BCL2 homology domain 3; IC50, inhibitory concentration 50; EM, electron microscopy; Nec1, Necrostatin 1; 3MA, 3-Methyladenine; CO, chloroquine; shRNA, short hairpin RNA; LOH, loss of heterozygosity; RNAi, inhibitory RNA; FDR, false discovery rate

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Table 1 Patient characteristics

|                         | Total (132) | CGH (59) |
|-------------------------|-------------|----------|
| Median age (range), years | 55 (20–86)  | 57 (20–86) |
| Sex                     |             |          |
| Male: Female            | 67: 65      | 28: 31   |
| Tumor sample            |             |          |
| Primary tumor           | 108 (82%)   | 46 (78%) |
| Relapsed                | 24 (18%)    | 13 (22%) |
| Stage                   |             |          |
| I                       | 35/114 (31%)| 15/49 (31%)|
| II A                    | 26/114 (23%)| 9/49 (18%)|
| II B                    | 17/114 (15%)| 5/49 (10%)|
| III A                   | 16/114 (14%)| 7/49 (14%)|
| III B                   | 3/114 (3%)  | 2/49 (4%) |
| IV A                    | 5/114 (4%)  | 3/49 (6%) |
| IV B                    | 12/114 (11%)| 8/49 (16%)|
| Na*                     | 18          | 10       |
| Completeness of resection |           |          |
| R0                      | 79/112 (71%)| 33/47 (70%)|
| R1                      | 23/112 (21%)| 7/47 (14%)|
| R2                      | 10/112 (9%) | 7/47 (14%)|
| Na*                     | 20          | 12       |
| WHO histotype           |             |          |
| A                       | 15/132 (11%)| 12/59 (20%)|
| AB                      | 28/132 (21%)| 14/59 (24%)|
| B1                      | 24/132 (18%)| 0        |
| B1/B2                   | 6/132 (5%)  | 0        |
| B2                      | 8/132 (6%)  | 1/59 (2%) |
| B2/B3                   | 11/132 (8%) | 5/59 (8%) |
| B3                      | 24/132 (18%)| 20/59 (34%)|
| C                       | 14/132 (11%)| 7/59 (12%)|
| Other#                  | 2/132 (2%)  | 0        |
| Paraneoplastic syndromes |           |          |
| MG                      | 32/125 (26%)| 17/58 (29%)|
| Other                   | 2/125 (2%)  | 1/58 (2%) |
| 10-Year DRS             | 87%         | 83%      |
| 10-Year TTP             | 69%         | 65%      |

Abbreviations: CGH, comparative genomic hybridization; DRS, disease-related survival; MG, myasthenia gravis; Na*, patients for whom data were not available at diagnosis; other#, one micronodular and one cystic thymoma; other+, one autoimmune glomerulonephritis (in the CGH analysis) and one autoimmune encephalopathy; TTP, Time to progression; WHO, World Health Organization.

90–100% arm-level aberrations was estimated interpolating the values up to 80% by the formula \( y = 6.5636x^{-2.546} \) and it was significantly lower than that observed (90 instead of 7; \( \chi^2 < 0.001 \)). On the basis of this observation, we defined arm-level CN aberrations those with an extension longer than 80% of the respective chromosome arm. These data suggest that small (focal) and long arm-level aberrations might arise through different mechanisms during cancer development.

Figure 1b depicts the frequency of arm-level CN aberrations and their distribution according to TET histotypes (see also Supplementary Table S1). Hierarchical cluster analysis of frequency of CN aberrations observed in different histotypes indicated a close relatedness between B3 and TCs. B2 + B2/B3, AB and A types were incrementally dissimilar to TCs (Figure 1b). Type A thymoma showed occasional chromosome arm-level CN aberrations (Supplementary Table S1).

On the contrary, types B3 and TCs shared frequent arm-level CN gains of 1q, as well as losses of chromosomes 6 and 13q. In addition, TCs presented frequent losses of 16p and 17q. Although the potential continuum with A subtypes is impossible to evaluate due to excess of non-neoplastic thymocytes in B1 and B2 histotypes, which were not evaluated in our study, our results support the presence of a continuum of genomic aberrations between B2/B3, B3 and TC histotypes (Figure 1b).

Chromosome arm-level CN loss of 13q occurs in more aggressive TETs. In univariate analyses, loss of 13q was associated with a poorer time to progression (TTP; log-rank test, \( P = 0.013 \); Figure 1c) and disease-related survival (DRS; \( P = 0.065 \); Figure 1d). Arm-level CN loss of 13q was found only in more aggressive histotypes (B3 and TCs; \( P = 0.005 \)). Conventional factors (sex, age, stage or extent of resection) were not associated with DRS in the 59 patients. Also, as there was no death in patients in a lower risk WHO category (A/AB/B1), it was not possible to construct a Cox model including the markers relative to conventional factors for this outcome in this subset of patients, because it would have an infinite hazard ratio (HR) and be unusable in a model. As such, it was not possible to show whether CN loss of 13q is an independent prognostic factor for DRS. CN loss of 13q was not an independent prognostic factor (\( P = 0.17; \) HR: 2.11; 95% CI on HR: 0.73–6.07) after adjustment for WHO category (\( P = 0.029; \) HR: 9.72; 95% CI on HR: 1.26–75.20 in a Cox multivariable analysis for TTP (Supplementary Table S2). Deletions of the whole or parts of chromosome 13 have been shown to have survival implications in other tumors, such as multiple myeloma (whole chromosome 13) and breast cancer (13q12–13).

Identification of significant CN aberrations by GISTIC.

To identify the potential importance of CN aberrations in the biology of TETs, we applied the GISTIC algorithm to TET CGH data and identified 72 peaks of CN gain (817 genes + 23 miRNAs) and 54 of CN loss (155 genes + 3 miRNAs) (Figures 2a and b, Supplementary Table S3). Of the genes mapped into GISTIC peaks, known cancer-related genes were selected and depicted in Figures 2a and b based on the following criteria: (1) in focal GISTIC peaks (\( \geq 5 \) Mb), (2) recurrent (in at least two tumors) and (3) \( < 15 \) genes in a peak. CN aberrations of CDK4, CDKN2A/B and IKBKB have been reported previously in other tumors. Other known cancer-related genes identified in our analysis include HRAS, CDKN2A/B and PIK3CD, suggesting an important role of apoptosis in TET pathogenesis. Moreover, CN loss of a DNA damage repair gene FANC suggests a link with BRCA/ATM pathway and uncontrolled cell cycle progression.

Among these peaks, the CN gain of BCL2 and the CN loss of CDKN2A and CDKN2B loci were selected for further characterization. The role of BCL2 has been well characterized in cancer and an amplification of this gene may result in a block of apoptosis with consequent accumulation of...
tumor cells. The deletion of CDKN2A and CDKN2B, two known tumor suppressor genes acting on the control of cell cycle, may be related to uncontrolled tumor cell proliferation. The CN gain peak of 18q21.33 affected only the BCL2 gene locus, and the amplitude of the gain suggested the presence of several copies of the gene (Figure 2c). The CN loss peak of 9p21.3 included only CDKN2A/B loci and was found in four tumors. The amplitude of the deletion suggested the presence of a homozygous CDKN2A/B deletion (Figure 2d). Moreover, BCL2 CN gains or CDKN2A/B CN losses were both associated with poorer prognosis (DRS and TTP log-rank test, \( P < 0.05 \)). In the multivariate analysis for TTP, there was a trend toward a significant gain by adding BCL2 CN (\( P = 0.069; \) HR 2.92; 95% CI on HR: 0.92–9.27) to WHO category, the only significant independent prognostic factor (details in Supplementary Results).

CDKN2A CN loss correlates with low p16INK4a expression and poor prognosis. Tumors carrying homozygous 9p21.3 CN loss (two B3 thymomas and two TCs) (Figure 2c) had a significantly worse DRS (log-rank test, \( P = 0.021 \)) and TTP (log-rank test, \( P = 0.019 \)) in univariate analysis but not in the TTP multivariate model (details in Supplementary Methods). Focal deletion of 9p21.3 is a frequent event in cancer (40% overall and 16% focal CN loss), and poor outcome for patients carrying 9p21.3 deletion has also been described in

Figure 1   Arm-level CN aberrations in TETs identified by CGH. (a) Arm-level CN aberrations were divided into 10 categories according to their length expressed as the percentage of the relative chromosome arm affect by the aberration. The number of CN aberrations covering \(< 10\%\) of the chromosome arm length were the most abundant. The power function \( y = 6.5636x^{-2.546} \) summarizes the distribution of CN aberrations based on chromosome arm length from 0 to 80%, and based on this equation the expected number of 90–100% arm-length CN aberrations was 7 instead of 90 observed (\( \chi^2, P < 0.001 \)). (b) Arm-level CN gains (red) and losses (blue) of autosomal chromosomes. Arm-level CN aberrations were defined by the sum of all the CN gain or all the CN loss affecting one chromosome arm in each tumor. If this sum was \( > 80\% \) of the chromosome arm length it was considered an arm-level CN aberration. The top panel depicts the overall summary of frequency of arm-level CN aberrations. The arm-level CN aberrations grouped by histotype (A, AB, B2 + B2/B3, B3 and TCs) are summarized in the bottom panel. * indicates B2 and B2/B3. Thymic carcinomas and B3 thymomas exhibit similar patterns of arm-level CN aberrations. Only few arm-level CN aberrations were observed in type A thymomas. (c) Time to progression and (d) disease-related survival curves in relation to 13q CN loss.
lymphoblastic leukemia. This region contains two known tumor suppressor genes, *CDKN2A* and *CDKN2B*. *CDKN2A* encodes p16 INK4 and p14 ARF by alternative splicing. We confirmed the CN loss of *CDKN2A* identified by CGH using CN-PCR analysis in all the four tumors evaluated but not in five TETs without *CDKN2A* deletion assessed by CGH (Fisher exact test, \( P = 0.008 \)).

We evaluated p16 INK4 expression in TET samples using a tissue microarray containing 132 TET tumors, which include those evaluated by CGH. None of the five tumors carrying 9p21.3 CN loss expressed p16\(^{\text{INK4}}\) (four with CN loss log2 ratio less than −0.7 and one with CN loss \( −0.3 < x < −0.7 \)). Out of 119 evaluable cases, 34 were positive for p16\(^{\text{INK4}}\) (Supplementary Table S4), which was associated with better DRS (Figure 2e; log-rank test, \( P = 0.041 \)) but not with TTP. As no events were observed for DRS in p16-positive tumors, the multivariate model could not be built. Interestingly, 61% of the primary TETs (34/56) and the three TET cell lines showed no detectable p16\(^{\text{INK4}}\) expression in the absence of *CDKN2A* CN loss (Supplementary Figure S1), indicating that negative p16\(^{\text{INK4}}\) expression was not exclusively due to *CDKN2A* CN loss. The loss of p16 INK4 expression has been shown to be possibly related to p16\(^{\text{INK4}}\) promoter methylation\(^9,10\) or miR-24 deregulation.\(^11\)

Deregulation of BCL2 family genes in TETs. BCL2 locus presented CN gain in 10% (6 out of 59) of the TET samples, including one type A, two B3 thymomas and three TCs. Moreover, focal BCL2 amplification (Figure 2d) was also confirmed in five TCs of an independent series of 12 frozen TETs (42%). For two TCs, which showed BCL2 CN gain, there was enough material to test BCL2 expression by

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**Figure 2** Identification of significant CN aberration peaks with survival implications. (a) Peaks of CN gain and (b) CN loss identified by GISTIC algorithm. GISTIC q-values (x axis) are plotted across the genome (y axis). q-value of <0.25 was considered significant. Thirteen cancer-related genes were identified in the GISTIC peaks. (c) Representative samples with focal CN loss of *CDKN2A/B* locus and (d) focal CN gain of BCL2 locus on chromosomes 9p and 18q, respectively. x axis indicates genome map position, and y axis the log2 ratio of red and green signals from the array. Blue dots represent the array probes. Red circles indicate CDKN2A/B and BCL2 loci. (e) Disease-related survival in relation to CDKN2A expression evaluated by immunohistochemistry.
western blot, which demonstrated an increased expression of BCL2 protein in comparison with normal thymus, thymomas (AB and B2) and a TC without BCL2 CN gain (Figure 3a). Previous study showed that BCL2 is expressed in about 60% of type A and the A component of type AB thymomas. More than 90% of TCs express BCL2, whereas only few type B thymomas are positive for BCL2.\(^\bib12\bib15\) Consistent with previous reports that MCL1 and BCL2 were frequently coexpressed in TCs\(^\bib16\) and MCL1 CN gain is a frequent event in several cancers,\(^\bib6\) we observed MCL1 CN gain in 51% of all TET cases, and higher in B3 (70%) and TCs (57%). However, this CN gain was mainly the result of the whole 1q gain rather than focal MCL1 CN amplification. Moreover, BCL-XL locus was identified in a significant peak of CN gain by GISTIC analysis (Supplementary Table S3).

CGH evaluation of TET cell lines revealed only MCL1 CN gain and BCL2 CN loss in T1889 (Supplementary Figures S1C–F). BCL2 expression was higher in T1889 and T1682 than in T1889 (Figure 3b). Although all TET cell lines expressed BCL-XL, MCL1, BCL-w, A1 expression was prominent only in Ty82 cells (Figure 3b). To figure out which of these anti-apoptotic proteins was necessary for TET proliferation, siRNA knockdowns were performed for each anti-apoptotic molecule (BCL2, MCL1, BCL-XL, BCL-W and A1) in all cell lines (Figure 3c). BCL2 knockdown induced a significant reduction of cell proliferation in all three TET cell lines whereas MCL1 knockdown affected exclusively proliferation of T1889 and Ty82. These results suggest that these cells may be addicted to BCL2 and MCL1 for growth.
TET cell lines are resistant to ABT263 but sensitive to ABT263/sorafenib combination treatment. All TET cell lines were relatively resistant to ABT263, a small-molecule BH3 mimic that inhibits the anti-apoptotic proteins BCL2, BCL-XL and BCL-W \(^\text{17}\) (Figure 4a, left panel), similar to H82, a small cell lung cancer cell line that does not express BCL2. \(^\text{17}\) Resistance to ABT263 treatment has been associated to MCL1 expression in multiple cell line models. \(^\text{17}\) Although T1682 expressed MCL1 at relatively low level, T1682 cells were highly resistant to ABT263 (IC50 = 2.52 \(\mu\)M) as compared with H146 small cell lung cancer cells (IC50 = 33 nM) (Figure 4a), which may be attributed to the
MCL1 overexpression induced by ABT263 in T1682 cells (Figure 4b).

Sorafenib, a tyrosine kinase inhibitor, known to attenuate MCL1 expression18 (Supplementary Figure S2A), was used in ABT263 combination studies. Combination of sorafenib and ABT263 resulted in an impressive synergistic effect for most concentrations tested (Figure 4c; Supplementary Table S5). These data reinforce the evidence that TET cell lines are addicted to MCL1 and BCL2 and suggest that these proteins can be targets for therapy.

Gx15-070 inhibits TET cells growth through autophagy-dependent necroptosis. Obatoclax (Gx15-070), a small-molecule BH3 mimetic, bona fide inhibitor of all the anti-apoptotic BCL2 family proteins, including MCL1,19 reduced the proliferation of TET cell lines with an IC50 ranging from 36–100 nM, (Figure 4a, right panel). Tumor xenografts in mice treated with Gx15-070 grew significantly slower than in those treated with placebo (P = 0.0229; Figure 4d).

Interestingly, Gx15-070 treatment did not enhance caspase-3 activity in TET cell lines, whereas induction of caspase-3 activity was clearly observed in ABT263-treated BCL2-positive tumor cells (Supplementary Figure S2C). Cleavage of PARP and caspase-3 was predominantly observed in T1682 cells treated with ABT263 but not with Gx15-070 (Figure 4e), which was in sharp contrast with the finding that 60% of T1682 cells underwent cell death at 1000 nM Gx15-070, whereas only 25% of the cells were dead at 100 nM ABT263 (Figure 4f). T1689 cells were resistant to ABT263 as determined by MTS assay (Figure 4a), which measures the proliferation rate based on both the cell growth and survival. However, TOPRO3 viability assay demonstrated that ABT263 induced cell death in T1689 cells (Figure 4f). Moreover, the pan-caspase inhibitor ZVAD-FMK was able to restore cell proliferation of ABT263 – but not of Gx15-070-treated TET cell lines (Figure 5a). Together these findings demonstrate that Gx15-070 and ABT263 induce caspase-3-independent and -dependent cell death, respectively. As Gx15-070 only elicited minimal cell death in T1889 cells (Figure 4f), we examined the effect of Gx15-070 on cell proliferation. Though no sign of cell cycle arrest was found (data not shown), a dramatic increase of cell doubling time was observed in all Gx15-070-treated TET cell lines (Supplementary Figures S3A–C). These data suggest that Gx15-070 treatment of TET cells leads to both growth inhibition and cell death. As recent studies suggested that Gx15-070 induces autophagy-dependent necroptosis in acute lymphoblastic leukemia cells,20 we performed electron microscopy (EM) in TET cells, which demonstrated changes in mitochondrial structure as early signs of autophagy after 1 h Gx15-070 treatment (Figure 5b). After 6 h treatment, cytoplasmic vacuolization and mitochondrial swelling with early signs of necrotic cell death were evident. Intriguingly, cytoplasmic vacuolization, late-stage necrotic or autophagic cell death were the main features 48 h after Gx15-070 (1 μM) treatment. EM showed no increase of apoptotic cell death in Gx15-070-treated cells, being the apoptotic cells less than 1% in untreated and treated cells; consistent with the observation that caspase-3 was not involved in Gx15-070-induced cell death (Figures 4E and 5A; Supplementary Figure S2C). Out of 100 cells evaluated by EM for each condition, necrototic cells were only 1% of untreated T1682 cells but increased to 9.5% after 1 h and to 12.8% after 6 h treatment with 250 nM Gx15-070. After 48 h, 77% of T1682 cells treated with 100 nM Gx15-070 were necrototic. As shown in Figure 5c, accumulation of the autophagy marker LC3B-II was detected in all Gx15-070-treated TET cell lines and occurred as early as 1 h after Gx15-070 treatment, suggesting that Gx15-070 activates the autophagy pathway in TET cells. To confirm that Gx15-070 induces autophagy-dependent necrototic cell death, we evaluated the effect of necrostatin 1 (Nec1; necroptosis inhibitor), 3MA (autophagosome formation inhibitor) and chloroquine (CQ; autophagosome maturation inhibitor) in Gx15-070-treated TET cells, and demonstrated that Gx15-070-induced growth inhibition (Figure 5a) and cell death (Supplementary Figure S4) could be effectively rescued by necroptosis and autophagy inhibition. Depletion of Beclin 1 (BECN1), a key regulator of autophagy pathway, and RIPK1, a key regulator of necrotic pathway, (Figure 5d) recapitulated the results obtained with Nec1 and CQ (Figure 5a). In line with previous reports, our results suggest that Gx15-070-induced necroptosis is autophagy-dependent.20

Gx15-070 also induced a progressive reduction of AKT Ser473 and Thr308 phosphorylation and a reduction of p-RPS6 phosphorylation, suggesting inhibition of mTOR pathway, in line with previous reports23 (Figure 6). Moreover, we noticed that Gx15-070 induced phosphorylation of AMPKα, a Ser/Thr kinase normally activated when ATP level is reduced.22 AMPK phosphorylation and LC3B cleavage appeared within 1 h after Gx15-070 treatment (Figure 6). Together, these data suggest that Gx15-070 may trigger autophagy either through direct inhibition of the mTOR pathway24 or activation of AMPK via mitochondria damage as revealed by our EM study.

Discussion

We studied the genomic CN aberrations of TETs to identify potential prognostic factors and targets suitable for therapy. High-resolution array-CGH allowed to identify CN aberrations that cosegregate with WHO histotypes. A total of 126 significant CN aberrations including focal/recurrent CN aberrations of 13 cancer-related genes were found by GISTIC algorithm analysis. Combining GISTIC analysis and patients’ survival data, we selected BCL2/CN gain and CDKN2A/B/CN loss for further studies, because they were associated with a poor DRS and TTP, and because they are well-known cancer genes in other tumors. Moreover, loss of p16INK4 expression was associated with worse prognosis. Using RNAi and small molecule inhibitor approaches, we showed that TET cells underwent autophagy-dependent necroptosis after Gx15-070 treatment and that ABT263-sorafenib combination inhibited TET cell growth, providing the first preclinical evidence that deregulated BCL2 family genes may serve as suitable targets for TET therapies.

Large arm-level aberrations identified in our study are in general agreement with genetic alterations reported by conventional CGH.23–25 Only few CN aberrations and LOHs have been reported in type A thymomas, which have a very indolent behavior and excellent survival.25 The B2/B3
Histotypes showed frequent arm-level CN gain of 1q and loss of chromosome 6, together with other CN aberrations that are present in less than 20% of the cases. B3 thymomas and TCs displayed a pattern of CN aberrations similar to B2/B3 tumors except for the losses of 13q, 16q and 17p, which were not observed in B2/B3 tumors. Consistent with previous reports,23,26 hierarchical cluster analysis of arm-level CN aberrations revealed that type A thymomas were very distantly related to aggressive tumors (B3 and C), suggesting that arm-level CN aberrations determine the aggressiveness of the disease. In addition, loss of 13q, which has been previously described in B3 and TCs by conventional CGH,24 correlated with worse prognosis. RB1, a well-characterized tumor suppressor gene, has been mapped to 13q. We found only one TET with concomitant loss of 13q and CDKN2A locus. The latter encodes p16INK4 and p14ARF via alternative splicing. As p16INK4, an inhibitor of CDK4-cyclin D, acts upstream of RB, inactivation of either gene will be in theory sufficient to compromise the RB pathway. The near mutual exclusive loss of 13q and CDKN2A, which together

Figure 5  Gx15-070 induces autophagy and necroptosis in TET cells. (a) Inhibitors of pan-caspase (50 μM ZVAD-FMK), necroptosis (30 μM NEC1), autophagosome formation (5 μM 3MA) and autophagosome maturation (25 μM CQ) rescued Gx15-070-induced growth inhibition. Percentage of reduction in cell growth induced by 100 nM Gx15-070 was calculated from the MTS data in the presence or absence of the indicated inhibitors for the three TET cell lines and for the small cell lung cancer cell line H146 as control. (*one-way ANOVA post hoc P < 0.05; experiments were repeated three times). (b) Time-course electron microscopic morphology of T1682 cells treated with Gx15-070 at the indicated concentrations. After 1-h treatment, lamellar bodies (yellow arrow) consistent with early signs of autophagy and mitochondrial structural changes with loss of cristae (orange arrow) were evident. After 6-h treatment, early signs of necroptosis with intact nuclear envelope (top panel), and mitochondrial swelling with loss of mitochondrial matrix and cytoplasm vacuolization were observed (bottom panel). After 48-h treatment, late stages of necrotic cell death (yellow arrow) and advanced stages of autophagy (orange arrow) were evident. The bottom panel depicts advanced stage of autophagic cell death with cytoplasmic vacuolization and lamellar bound structures consistent with autophagosomes. (c) Gx15-070 (1 μM) induced LC3BII accumulation after 48-h treatments in TET cells (top blot). LC3BII accumulation was observed in T1682 cells 1-h after Gx15-070 treatment at a concentration as low as 100 nM (bottom blot). (d) BECN1 and RIPK1 knockdown rescues Gx15-070-induced growth inhibition. Western blot shows shRNA knockdown of Beclin1 (sh-BECN1-1 and sh-BECN1-2) and RIPK1 (sh-RIPK1-1 and sh-RIPK1-2) in T1682 and TY82 cell lines. Sh-FF2: shRNA control vector carrying anti-exogenous luciferase shRNA FF2 (top). MTS assay of BECN1 and RIPK1 knockdown cells treated with 250 nM Gx15-070 (bottom). *denotes statistically significant differences compared with control (P < 0.05); experiments were repeated three times.
represented 15% (9/59) of TETs in our series, and the tight association of poor DRS with either loss of 13q CN (Figures 1c and d) or p16\(^{NK4A}\) expression (Figure 2e) suggest that the RB pathway has an important role in TET pathogenesis.

Using GISTIC algorithm we identified several cancer related genes involved in cell cycle control (CDKN2A/B and CDK4), or intracellular signal transduction (AKT1, PIK3CD and HRAS). Interestingly, many of these genes (BCL2, BCL-XL, PDCD1, CRK) were related to apoptosis control, and BCL2 CN gain was associated with poorer TTP and DRS. CN gain of MCL1, another member of the BCL2 family gene, was found in 51% of TETs and mainly in aggressive histotypes (83% B2/B3, 70% B3 and 57%TCs). However, MCL1 CN gain was mostly the result of the whole 1q gain rather than focal MCL1 amplification.

The oncogenic role of BCL2 is well-known in follicular lymphomas in which constitutive BCL2 activation due to IgH-MCL1 amplification.

inhibiting the normal apoptosis of B lymphocytes. 27 BLC2 juxtaposition is thought to result in lymphomagenesis by lymphomas in which constitutive BCL2 activation due to IgH-MCL1 amplification.

was mostly the result of the whole 1q gain rather than focal CN gain was associated with poorer TTP and DRS. CN gain of MCL1, another member of the BCL2 family gene, was found in 51% of TETs and mainly in aggressive histotypes (83% B2/B3, 70% B3 and 57%TCs). However, MCL1 CN gain was mostly the result of the whole 1q gain rather than focal MCL1 amplification.

The oncogenic role of BCL2 is well-known in follicular lymphomas in which constitutive BCL2 activation due to IgH-BLC2 juxtaposition is thought to result in lymphomagenesis by interfering with the normal apoptosis of B lymphocytes. 27 BCL2 overexpression was observed in other types of lymphoproliferative disorders and small cell lung cancer. 17 In addition to their involvement in regulation of apoptosis, BCL2 family members are also involved in the regulation of autophagy and necroptosis pathways. We validated the functional significance of BCL2 family genes in TET cells via siRNA approaches, and demonstrated that all TET cell lines (T1889, TY82 and T1682) were addicted to BCL2, whereas T1889 and TY82 required also MCL1 for growth and survival. More importantly, we showed that sorafenib (a multi-tyrosine kinase inhibitor), as shown in other models, 18 could reduce MCL1 expression induced by ABT263 in all the TET cell lines tested, and that ABT263/sorafenib combination was highly synergistic in inhibiting TET cell proliferation. We also showed that Gx15-070, a pan inhibitor of BH3 BCL2 anti-apoptotic family members, potently inhibited TET cell proliferation and induced cell death. Interestingly, cell death could be rescued by Beclin1, RIPK1 knockdown or by autophagy and necroptosis inhibition, suggesting that Gx15-070 induced cell death is autophagy-dependent. Taken together, our data strongly indicate that BCL2 family genes are deregulated in TET cells and are potential targets for TET treatment.

In conclusion, we identified CN losses of CDKN2A and 13q as potentially poor prognostic markers in TETs, implying that RB pathway deregulation may be important in TET pathogenesis. Targeting anti-apoptotic BCL2 family members by Gx15-070 or by ABT263-sorafenib combination may represent a novel treatment strategy for TET patients.

Materials and Methods

This study was conducted in agreement with the Declaration of Helsinki and was approved by the involved institutional ethical review boards (ClinicalTrials.gov ID: NCT00965627).

Patients. FFPE samples were collected from a series of 132 consecutive patients who underwent surgery for TET. This series has been described previously in detail elsewhere. 19 Patients were staged according to the Masaoka staging system. 20 Completeness of resection was defined as R0 when complete, R1 when residual disease was microscopic and R2 when macroscopic. 30 After resection, tumor diagnosis was confirmed by two independent pathologists (HSL and MRM) and histology was according to the 2004 WHO classification. 9 Patient characteristics are reported in Table 1. Median follow-up was 84.5 months (95% CI 72.1–96.8). Frozen tumors were collected from an additional 12 patients who underwent tumor biopsy or radical resection within the past 2 years at the National Cancer Institute (Bethesda, MD, USA).

DNA extraction and array-CGH. Of the 132 samples, 59 only were selected for CGH, based on presence of >80% cancer cells in the sample, as assessed by Hematoxylin- and eosin-stained slides. DNA was extracted using DNeasy kit (Qiagen, Inc., Valencia, CA, USA) according to Genomic DNA ULS labeling kit protocol (Agilent Technologies, Inc., Palo Alto, CA, USA). The labeling procedure was conducted using Genomic DNA ULS labeling kit (Agilent), according to the vendor instructions. Twenty samples were hybridized on Human Genome CGH Array 105A (Agilent) and the remaining on SurePrint G3 Human CGH Array 180K (Agilent). The arrays were scanned on a laser-based microarray scanner (Agilent), and the data were extracted and normalized using Feature Extraction 10.5 (Agilent). Cancers were centered to the mode using R script. CN profile was inferred using Rank Segmentation algorithm in Nexus 5.1 (Biodiscovery Inc., El Segundo, CA, USA). CN call thresholds were defined: high gain > 0.7, gain +0.3, loss –0.3 and homozygous loss –0.7. Sex chromosomes were excluded from the analysis. GISTIC algorithm was applied using the online version on Gene Pattern server 2.0. 31 GISTIC algorithm scores the frequency and amplitude of CN changes (number of abnormal copies) across the sample set. To assess chromosomal regions that significantly associate with CN aberrations, GISTIC identifies regions with scores above the random aberrations simulated by null distribution. The generated P-values were corrected for multiple hypotheses testing by Benjamini-Hochberg FDR procedure to obtain q-values. 32 Q-value < 0.25 were considered significant.

Immunohistochemistry. Immunohistochemistry was performed on a tissue microarray that included samples from 132 TET patients as previously described. 28,32 The staining with anti-p16\(^{NK4A}\) antibody (BD Pharmingen, San Diego, CA, USA) was graded according to the percentage of positive cells and intensity of the staining. Percentage of positive cancer cells was ranked 0 (0–5%), 1 (6–25%), 2 (26–50%), 3 (51–75%) or 4 (76–100%). Signal intensity (1–3) was multiplied by the percentage of positive cells in order to get a positivity score. P16\(^{NK4A}\) scores 0–3 were considered negative (G0), 4–6 were G1, 7–9 were G2, and 10–12 were G3.

Western blot. Protein extraction, western blot and immunoprecipitation were performed as previously described. 33,34 Anti-BCL2 antibody was purchased from
DAK (Carpinteria, CA, USA); anti-MCL1 and anti-p16Ink4a from BD PharMingen and anti-A1 from Abcam (Cambridge, MA, USA). Antibodies against BCL- XL, BCL-W, BAX, γ-tubulin, PARP, caspase-3, cleaved caspase-3, LC3B, Beclin1 and RIPK1 were purchased from Cell Signaling (Danvers, MA, USA).

Real-time PCR. TaqMan CN assay was used to confirm the deletion of CDKN2A locus (Applied Biosystems, Foster City, CA, USA). Primers for CDKN2A (Applied Biosystems) and the reported locus RPPH1 (Applied Biosystems), the endogenous control, were combined to estimate the CN status. Real-time PCR was performed on ABI 7900HT fast real-time PCR system (Applied Biosystems). Gene CN was determined by CopyCaller software v1.0 (Applied Biosystems).

Conflict of Interest

The authors declare no conflict of interest.

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Supplementary Information accompanies the paper on Cell Death and Disease website (http://www.nature.com/cddis)