Microsatellite unstable gastrointestinal neuroendocrine carcinomas: a new clinicopathologic entity

Nora Sahnane, Daniela Furlan, Matilde Monti, Chiara Romualdi, Alessandro Vanoli, Emanuela Vicari, Enrico Solcia, Carlo Capella, Fausto Sessa and Stefano La Rosa

Section of Anatomic Pathology, Department of Surgical and Morphological Sciences, University of Insubria, Via O. Rossi, 9, 21100 Varese, Italy
1CRIBI Biotechnology Center, University of Padova, Padova, Italy
2Department of Molecular Medicine, Institute of Pathology, University of Pavia, IRCCS Policlinico San Matteo, Pavia, Italy
3Department of Pathology, Ospedale di Circolo, Varese, Italy

Abstract

Gastroenteropancreatic (GEP) neuroendocrine carcinomas (NECs) and mixed adenoneuroendocrine carcinomas (MANECs) are heterogeneous neoplasms characterized by poor outcome. Microsatellite instability (MSI) has recently been found in colorectal NECs showing a better prognosis than expected. However, the frequency of MSI in a large series of GEP-NEC/MANECs is still unknown. In this work, we investigated the incidence of MSI in GEP-NEC/MANECs and characterized their clinicopathologic and molecular features. MSI analysis and immunohistochemistry for mismatch repair proteins (MLH1, MSH2, MSH6 and PMS2) were performed in 89 GEP-NEC/MANECs (six esophageal, 77 gastrointestinal, three pancreatic, and three of the gallbladder). Methylation of 34 genes was studied by methylation-specific multiplex ligation probe amplification. Mutation analysis of BRAF and KRAS was assessed by PCR-pyrosequencing analysis. MSI was observed in 11 NEC/MANECs (12.4%): seven intestinal and four gastric. All but two MSI-cases showed MLH1 methylation and loss of MLH1 protein. The remaining two MSI-cancers showed lack of MSH2 or PMS2 immunohistochemical expression. MSI-NEC/MANECs showed higher methylation levels than microsatellite stable NEC/MANECs (40.6% vs 20.2% methylated genes respectively, $P<0.001$). BRAF mutation was detected in six out of 88 cases (7%) and KRAS mutation was identified in 15 cases (17%). BRAF mutation was associated with MSI ($P<0.0008$), while KRAS status did not correlate with any clinicopathologic or molecular feature. Vascular invasion ($P=0.0003$) and MSI ($P=0.0084$) were identified as the only independent prognostic factors in multivariate analysis. We conclude that MSI identifies a subset of gastric and intestinal NEC/MANECs with distinct biology and better prognosis. MSI-NEC/MANECs resemble MSI-gastrointestinal adenocarcinomas for frequency, molecular profile and pathogenetic mechanisms.
Introduction

High-grade (or poorly differentiated) gastroenteropancreatic (GEP) neuroendocrine carcinomas (NECs) are aggressive cancers with a high propensity for distant metastases. Like the more frequent pulmonary counterparts, they have traditionally been divided into the small- and large-cell subtypes, depending on the morphological features of neoplastic cells (La Rosa & Sessa 2014). Small-cell carcinomas are composed of small to medium-sized (two to four times the size of a lymphocyte), round to oval cells with scant cytoplasm and hyperchromatic nuclei with indistinct nucleoli. Large-cell subtypes are composed of large cells with vesicular nuclei showing prominent nucleoli and abundant eosinophilic cytoplasm. In both cases, tumor cells grow forming sheets or nests, although in the large-cell subtype a more structured trabecular or organoid architecture is frequently observed. Infiltration of the gut wall or peripancreatic tissue, extensive necrosis, high mitotic count, and perineural and vascular invasion is the rule.

Cancers with these morphological features have been named in the past few years using different names including poorly differentiated NECs and high-grade NECs. Accordingly to the 2010 WHO classification of tumors of the digestive system, they are currently named NECs and, by definition, they are grade 3 (G3) neoplasms ranging from adenomas to adenocarcinomas or squamous cell carcinomas with different degrees of differentiation in exocrine components and from well-differentiated to poorly differentiated neuroendocrine tumors in neuroendocrine components (La Rosa et al. 2012a,b). The pathogenesis of GEP-NECs and MANECs is still largely unknown (Smith & Reidy-Lagunes 2013). Regardless of anatomic site, TP53 alterations have been found to be frequent in NECs (Dacic et al. 2002, Furlan et al. 2005), together with the impairment of the CDKN2A/p16-Rb pathway (Parwani et al. 2003, Nassar et al. 2005, Yachida et al. 2012). Most GEP-NECs have high chromosomal instability (Furlan et al. 2005, Lubensky & Zhuang 2007), while microsatellite instability (MSI) has rarely been observed (Ghimenti et al. 1999, Nassar et al. 2005, Stelow et al. 2006, La Rosa et al. 2012a,b) and the role of other epigenetic mechanisms is still poorly understood.

Although GEP-NECs are generally aggressive cancers, showing ominous prognosis with a median survival (MS) ranging from 6 to 12 months (La Rosa & Sessa 2014), recent findings from a few published studies (Shia et al. 2008, Power et al. 2010, La Rosa et al. 2012a,b) and from anecdotal experience seem to suggest that there is a fraction of patients with GEP-NECs showing a better than expected survival rate. We have recently demonstrated that a subset of colorectal NECs exhibiting MSI and extensive gene hypermethylation showed a better prognosis than NECs without these features (La Rosa et al. 2012a,b). Apparent similarities between MSI-NECs and MSI-adenocarcinomas of the colon–rectum has led to the hypothesis that similar pathogenetic mechanisms may be involved in the development of these two tumor subsets (Furlan et al. 2013). However, there are no studies on large series of GEP-NECs demonstrating that MSI and gene hypermethylation can occur in other sites of the GEP system and that this is related to patients’ prognosis.

In this study, we investigated the incidence of the MSI phenotype in a large and well-characterized cohort of GEP-NEC/MANECs in order to characterize the clinicopathologic features and the outcome of such carcinomas, evaluating the type of mismatch repair (MMR) defect and its correlation with high levels of gene hypermethylation and KRAS and BRAF mutations.

Materials and methods

Cases

Tissue samples from 89 surgically resected GEP-NECs and MANECs cohort were collected from the files of the Departments of Pathology of the Ospedale di Circolo – University of Insubria, Varese and from the archives of the Institute of Pathology of the IRCCS Policlinico San Matteo-University of Pavia, Pavia, Italy. All the cases were reviewed to confirm the diagnoses before starting the investigation. The cases included 53 NECs and 36 MANECs located as follow: six in the esophagus, 36 in the stomach, four in the duodenum, 37 in the colon–rectum, three in the gallbladder, and three in the pancreas. The presence of Lynch syndrome or other inherited tumor
syndromes was carefully explored clinically and was not found in any patient. Germline studies were not performed because several patients were died at the time of this retrospective investigation. None of the patients had a history of primary pulmonary neuroendocrine neoplasms. Clinical information including sex, age, type of surgery, clinical history, the presence of distant metastases, and follow-up findings was collected by consulting clinical charts.

This study was performed according to the clinical standards of the 1975 and 1983 Declaration of Helsinki and was approved by the Ethical Committee of the Ospedale di Circolo of Varese (no. 0008465).

**Morphological and immunohistochemical study**

All tissue samples were fixed in buffered formalin (formaldehyde 4% w/v and acetate buffer 0.05 M) and routinely processed in paraffin wax. Five micrometre-thick sections were stained with hematoxylin–eosin (H&E) and alcian-blue/periodic acid-Schiff for the morphological evaluations. All cases were thoroughly investigated for the following histological features: neuroendocrine cytologic subtype (small and large cell), type of the exocrine component (adenomas, adenocarcinomas, squamous cell carcinomas), vascular and perineural invasion, presence of necrosis, mitotic count per ten HPF, level of gut wall invasion or infiltration of peripancreatic tissues, and presence of metastases in local lymph nodes. Intra and peritumoral lymphoid infiltration was evaluated using H&E stained sections and CD3 immunostaining and following the criteria proposed by Walsh et al. (2013): peritumoral lymphocytes infiltration was defined as a mantle or cap of lymphoid cells at the deepest point of direct spread. We also counted the number of lymphocytes in three different areas at ×40 magnification at this level. Crohn’s-like lymphocytic reaction was considered when at least three nodular lymphoid aggregates were observed deep into the invasive margin in a ×4 field magnification. Intratumoral-infiltrating lymphocytes were considered when at least four intraepithelial lymphocytes per ×40 field magnification were observed. The Ki67 proliferative index was calculated in all NECs and in the neuroendocrine components of all MANECs. It was expressed as a percentage value corresponding to the count of Ki67-positive cells in 2000 tumor cells performed in areas of the highest immunostaining as previously reported (La Rosa et al. 2009, 2011). Finally, a stage was assigned according to the ENETS criteria.

For immunohistochemical analyses, 3 μm-thick sections were mounted on poly-L-lysine coated slides, deparaffinized, and hydrated through graded alcohols to water. Endogenous peroxidase activity inhibition was carried out by dipping the sections in 3% hydrogen peroxide for 10 min, followed by incubation with the primary antibodies (Supplementary Table 1, see section on supplementary data given at the end of this article) at 4°C for 18–20 h and subsequently the avidin–biotin complex procedure. Immunoreactions were developed using 0.03% 3,3’-diaminobenzidine tetrahydrochloride and then sections were counterstained with Harris’ hematoxylin.

**MSI analysis**

Tumor DNA from each patient was obtained from formalin-fixed and paraffin-embedded tissues using three representative 8 μm-thick sections of tumor samples. DNA was extracted after manual micродissection, using a QIAamp DNA FFPE tissue kit according to the manufacturer’s protocol (Qiagen). Integrity and amplifiability of each DNA sample were evaluated using BIOMED-2 multiplex PCR (van Dongen et al. 2003). MSI analysis was carried out using a pentaplex panel of monomorphic mononucleotide repeats (BAT25, BAT26, NR-21, NR-22, and NR-24) as previously reported (Suraweera et al. 2002).

**Methylation-specific multiplex ligation probe amplification**

Methylation analysis of 34 gene promoters was performed in two replicates for each sample using methylation-specific multiplex ligation probe amplification (MS-MLPA) with the SALSA MS-MLPA ME001 Tumor Suppressor-1 Kit and SALSA MS-MLPA ME002 Tumor Suppressor-2 Kit (MRC-Holland, Amsterdam, The Netherlands), which were previously validated with other techniques (Furlan et al. 2013). Methylation ratio was calculated using the Coffalyser V7 software (MRC-Holland) and the presence or absence of promoter methylation was scored as discrete variables using the cut-off values previously reported (La Rosa et al. 2012a,b). We also analyzed the promoter methylation of MMR genes using the SALSA MS-MLPA ME011 MMR Kit (MRC-Holland) in MSI-cancers. All the genes examined by MS-MLPA are listed in the Supplementary Table 2, see section on supplementary data given at the end of this article.

**MLH1 methylation analysis by bisulphite pyrosequencing**

MLH1 methylation status was confirmed by pyrosequencing analysis in all the cases that were methylated with MS-MLPA. Bisulphite modification of genomic DNA

http://erc.endocrinology-journals.org
DOI: 10.1530/ERC-14-0410
© 2015 Society for Endocrinology
Printed in Great Britain
Published by Bioscientifica Ltd.
(300 ng) was performed with an EpiTect bisulfite kit (Qiagen) according to the manufacturer’s recommendations. A region of 84 nucleotides inside the Deng C-region (Gausachs et al. 2012) was amplified in two independent reactions using the following primers: forward: 5’-BIOTIN-GAGTTTAAAAAGAATTATAG-GAAGAG-3’ and reverse 5’-ATACTACCCCTACC-TAAAATATAC-3’. To improve the PCR efficiency using bisulfite-treated DNA, PCR was performed with EpiTaq HS (Tkara, Shiga, Japan) using 5 μl of the bisulfite-converted DNA (30–60 ng assuming 100% yield) in a 50 μl reaction containing 2.5 mM MgCl₂, 0.3 μM primer pairs, and 200 μM dNTPs. Thermal cycling conditions were as follows: 2 min at 95 °C, 35 cycles of 95 °C/25 s, 57 °C/30 s, 72 °C/30 s and 72 °C/2 min. Pyrosequencing was carried out on the DNA strand purified by streptavidin-coated beads, addressing five consecutive cytosines starting from the sequencing primer: 5’-CTACCCCTACCTAAATAATAC-3’. Analytical sensitivity and linearity of the assay was assessed using a serial dilution of fully methylated DNA and unmethylated DNA (Chemicon International, Inc., Billerica, MA, USA). Coefficient of variation inter-/intra-assay was calculated using 20 DNA samples from healthy donors and was 3.5%. A sample was classified as methylated when the mean of all the five cytosines was >10%.

**BRAF and KRAS mutation analyses**

Mutations in codon 600 of BRAF and codons 12 and 13 of KRAS gene were analyzed in duplicate by PCR-pyrosequencing using the anti EGFR MoAb response KRAS Status Kit and anti EGFR MoAb response BRAF status Kit (Diatech Pharmacogenomics, Jesi, Italy) according to the manufacturer’s instructions.

**Statistical analyses**

Association analyses were performed using the Fisher exact test, ANOVA analysis, and the independent sample t-test. We used a model-based cluster algorithm (Fraley & Raftery 2002) to appropriately define a threshold for the Ki67 percentage and for gene hypermethylation levels. The method is based on the estimation of different models (mixed Gaussian distribution), characterized by different number of groups; thus, the best model is selected according to the Bayesian Information Criterion or BIC (Schwarz 1978). This analysis was performed with R software (http://www.r-project.com) with the mclust package (Schwarz 1978, Fraley & Raftery 2002).

The patient survival was evaluated using the Kaplan–Meier method and statistically tested with the log-rank test. Patients who died within 1 month of surgery were excluded from the survival analyses. Multivariate analysis was performed with the Cox proportional hazard model using the backward method. A P value <0.05 was considered to be statistically significant. These analyses were performed using MedCalc Statistical (version 11.0.1.0) and GraphPad Prism V5.0 software (San Diego, CA, USA).

**Results**

**Morphological features of the 89 NEC/MANECs investigated**

All NECs and the neuroendocrine components of all MANECs were composed of poorly differentiated cells of either small- (49 cases) or large-cell (40 cases) subtype showing, by definition, >20% of Ki67 proliferative index. Small-cell NECs were found in all sites examined, including the esophagus where the large-cell subtype was not observed. Barrett metaplasia was found in only one esophageal MANEC. No cases presented as morphologically well/moderately differentiated neoplasms, corresponding to the recently described, but not finally accepted, group of the so-called ‘NET G3’ (Velayoudom-Céphise et al. 2013, Hijioka et al. 2014, La Rosa et al. 2014).

The exocrine component of MANECs was represented by squamous cell carcinoma in the two esophageal MANECs, while in MANECs of other sites it was represented by an adenocarcinoma in eight cases, by a tubular or tubulo-villous adenoma in six cases, by an adenoma with adenocarcinoma in 17 cases, by a squamous cell carcinoma in two cases, and by a combination of adenoma with squamous cell carcinoma in one case.

For 16 MANECs, we were able to evaluate both the primary neoplasm and the relative metastasis (Supplementary Table 3 and Supplementary Fig. 1, see section on supplementary data given at the end of this article). Interestingly and as expected, in the metastatic sites the NEC component was more extensively represented than the exocrine one (P=0.0002).

**MSI GEP NEC/MANECs**

**MMR defect and clinicopathologic profile** Microsatellite analysis allowed us to identify 11 unstable carcinomas (seven MSI-NECs and four MSI-MANECs) representing 12.4% of our series of 89 cases (Table 1).
nine cases (five colorectal and four gastric cancers) showed histochemical expression of MMR proteins (Table 2). The loss of MMR proteins expression was associated with aberrant methylation, we first checked the promoter concomitant loss of MLH1 and PMS2 proteins, a colorectal NEC showed PMS2 negativity, while a duodenal NEC exhibited loss of both MSH2 and MSH6 expression. By contrast, all MSS-NECs showed MLH1, MSH2, PMS2, and MSH6 immunohistochemical expression.

The mean age of patients with MSI-NEC/MANECs was 74 years vs 65 years for patients with MSS-NEC/MANEC and there was a slight female prevalence. Six out of 11 cases were of the large-cell subtype and, interestingly, no carcinomas showed distant metastases at the time of diagnosis, being classified as stage II or III depending on the nodal status. The main morphological and immunohistochemical findings are summarized in Table 3. Among the various parameters evaluated, it is worth noting that about 54% of MSI-carcinomas showed prominent intra-peritumoral lymphoid infiltration (Fig. 1) (against 25% of MSS cases), large-cell subtype (against 45% of MSS), and vascular invasion (against 74% of MSS), and that they were all negative for CD117 and TTF1. CDX2 was expressed in 3/4 gastric and in 4/6 colorectal MSI-cancers. Interestingly, intra- and peritumoral lymphoid infiltration did not differ between MSI and MSS cases when evaluated in H&E stained sections. Using CD3-immunostained sections, intratumoral lymphoid infiltration was statistically higher (P=0.01) in MSI-cases (mean value of CD3-positive lymphocytes: 20.40±5.580) than in MSS cases (mean value: 7.13±1.914). Similarly, peritumoral lymphoid infiltration was also statistically higher (P=0.0002) in MSI-cases (mean value of CD3-positive lymphocytes 117.6±12.41) than in MSS ones (mean value: 55.53±8.05). In MSI-MANECs, the exocrine component was represented by a mucinous adenocarcinoma in two cases and by an adenocarcinoma not otherwise specified (NOS) in the other two. In such cases the intra- and peritumoral lymphoid infiltration was found close to both exocrine and neuroendocrine neoplastic components. The Ki67 index showed a comparable distribution between MSI- and MSS-cancers without any statistical significant difference between small- and large-cell subtypes. Carcinomas were divided into two groups using a cut-off value of 55% that was calculated with a model-based cluster algorithm (Fraley & Raftery 2002). This threshold value corresponded exactly to that used by Sorbye et al. (2013). More precisely, 80% of MSI- and 72.3% of MSS-cancers showed a Ki67 ≥55%; the mean value of the Ki67 index was 68.4% for MSI and 63.6% for MSS NEC-MANECs.

### MMR gene methylation

To investigate whether the loss of MMR proteins expression was associated with aberrant methylation, we first checked the promoter

---

**Table 1** Clinicopathologic characteristics of unstable (MSI) and stable (MSS) neuroendocrine carcinomas

<table>
<thead>
<tr>
<th>Classification</th>
<th>MSI 11 cases</th>
<th>MSS 78 cases</th>
<th>Total 89 cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender Male</td>
<td>4 (36%)</td>
<td>53 (71%)</td>
<td>57 (66%)</td>
</tr>
<tr>
<td>Female</td>
<td>7 (64%)</td>
<td>22 (29%)</td>
<td>29 (34%)</td>
</tr>
<tr>
<td>Age (years)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>74</td>
<td>65.1</td>
<td>66.3</td>
</tr>
<tr>
<td>Range</td>
<td>61–91</td>
<td>34–93</td>
<td>34–93</td>
</tr>
<tr>
<td>Location Esophagus</td>
<td>0</td>
<td>6 (7%)</td>
<td>6 (6%)</td>
</tr>
<tr>
<td>Stomach</td>
<td>4 (36%)</td>
<td>32 (41%)</td>
<td>36 (41%)</td>
</tr>
<tr>
<td>Duodenum</td>
<td>1 (10%)</td>
<td>3 (4%)</td>
<td>4 (5%)</td>
</tr>
<tr>
<td>Colon–rectum</td>
<td>6 (54%)</td>
<td>31 (40%)</td>
<td>37 (42%)</td>
</tr>
<tr>
<td>Pancreas</td>
<td>0</td>
<td>3 (4%)</td>
<td>3 (3%)</td>
</tr>
<tr>
<td>Gallbladder</td>
<td>0</td>
<td>3 (4%)</td>
<td>3 (3%)</td>
</tr>
<tr>
<td>Pancreas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Necrosis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEC</td>
<td>7 (64%)</td>
<td>46 (59%)</td>
<td>53 (60%)</td>
</tr>
<tr>
<td>MANEC</td>
<td>4 (36%)</td>
<td>32 (41%)</td>
<td>36 (40%)</td>
</tr>
<tr>
<td>Lymph node metastasis</td>
<td>10 (91%)</td>
<td>67 (89%)</td>
<td>77 (89%)</td>
</tr>
<tr>
<td>Tumor stage (ENETS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage I</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Stage II</td>
<td>4 (36%)</td>
<td>6 (9%)</td>
<td>10 (13%)</td>
</tr>
<tr>
<td>Stage III</td>
<td>7 (64%)</td>
<td>42 (63%)</td>
<td>49 (63%)</td>
</tr>
<tr>
<td>Stage IV</td>
<td>0</td>
<td>19 (28%)</td>
<td>19 (24%)</td>
</tr>
<tr>
<td>Follow-up (months)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean time</td>
<td>85.7</td>
<td>19.5</td>
<td>27.7</td>
</tr>
<tr>
<td>Range time</td>
<td>14–230</td>
<td>1–257</td>
<td>1–257</td>
</tr>
<tr>
<td>DOC</td>
<td>1 (9%)</td>
<td>2 (3%)</td>
<td>3 (3%)</td>
</tr>
<tr>
<td>DOD</td>
<td>7 (64%)</td>
<td>59 (75%)</td>
<td>66 (74%)</td>
</tr>
<tr>
<td>AFD</td>
<td>2 (18%)</td>
<td>10 (13%)</td>
<td>12 (14%)</td>
</tr>
<tr>
<td>POD</td>
<td>0</td>
<td>3 (4%)</td>
<td>3 (3%)</td>
</tr>
<tr>
<td>Lost</td>
<td>1 (9%)</td>
<td>4 (5%)</td>
<td>5 (6%)</td>
</tr>
</tbody>
</table>

NEC, neuroendocrine carcinoma; MANEC, mixed adenoneuroendocrine carcinoma; DOC, died of other cause; DOD, died of disease; AFD, alive free disease; POD, post-operative death.

In all of them, we evaluated the size of allelic shifts at each marker and we observed that all five loci were affected by deletions ranging from 5.4 to 9.7 bp. BAT-26 showed the longest allelic shifts with a mean size of 9.7 bp. The mean age of patients with MSI-NEC/MANECs was 74 years vs 65 years for patients with MSS-NEC/MANEC and there was a slight female prevalence. Six out of 11 cases were of the large-cell subtype and, interestingly, no carcinomas showed distant metastases at the time of diagnosis, being classified as stage II or III depending on the nodal status. The main morphological and immunohistochemical findings are summarized in Table 3. Among the various parameters evaluated, it is worth noting that about 54% of MSI-carcinomas showed prominent intra-peritumoral lymphoid infiltration (Fig. 1) (against 25% of MSS cases), large-cell subtype (against 45% of MSS), and vascular invasion (against 74% of MSS), and that they were all negative for CD117 and TTF1. CDX2 was expressed in 3/4 gastric and in 4/6 colorectal MSI-cancers. Interestingly, intra- and peritumoural lymphoid infiltration did not differ between MSI and MSS cases when evaluated in H&E stained sections. Using CD3-immunostained sections, intratumoral lymphoid infiltration was statistically higher (P=0.01) in MSI-cases (mean value of CD3-positive lymphocytes: 20.40±5.580) than in MSS cases (mean value: 7.13±1.914). Similarly, peritumoral lymphoid infiltration was also statistically higher (P=0.0002) in MSI-cases (mean value of CD3-positive lymphocytes 117.6±12.41) than in MSS ones (mean value: 55.53±8.05). In MSI-MANECs, the exocrine component was represented by a mucinous adenocarcinoma in two cases and by an adenocarcinoma not otherwise specified (NOS) in the other two. In such cases the intra- and peritumoral lymphoid infiltration was found close to both exocrine and neuroendocrine neoplastic components. The Ki67 index showed a comparable distribution between MSI- and MSS-cancers without any statistical significant difference between small- and large-cell subtypes. Carcinomas were divided into two groups using a cut-off value of 55% that was calculated with a model-based cluster algorithm (Fraley & Raftery 2002). This threshold value corresponded exactly to that used by Sorbye et al. (2013). More precisely, 80% of MSI- and 72.3% of MSS-cancers showed a Ki67 ≥55%; the mean value of the Ki67 index was 68.4% for MSI and 63.6% for MSS NEC-MANECs.

### MMR gene methylation

To investigate whether the loss of MMR proteins expression was associated with aberrant methylation, we first checked the promoter...
methylation status of the MMR genes using MS-MLPA. As given in Table 2, all the nine cases lacking MLH1 expression showed methylation at the MLH1 promoter. In the two cases showing MLH1 immunoreactivity (cases #50 and #100) MLH1 methylation was not found. MSH2, MSH6 and PMS2 gene methylation was never observed in the 11 MSI-carcinomas. To validate the MS-MLPA results, we performed pyrosequencing analysis addressing the Deng-C region, which has recently been identified as a critical sequence for MLH1 hypermethylation (Gausachs et al. 2012). Pyrosequencing confirmed the MS-MLPA results in all nine cases, with percentages of methylated alleles ranging from 13% to 46% (Table 2).

Among the MSI-cases, four MANECs exhibited MLH1 loss (three cases) or PMS2 loss (one case). In these cases, loss of the immunohistochemical expression and MSI was observed in both the exocrine and the neuroendocrine components. Accordingly, MLH1 methylation was always

**Table 2** Immunohistochemical and molecular characterization of mismatch repair genes and proteins in MSI-NEC/MANECs

<table>
<thead>
<tr>
<th>MSI cases</th>
<th>Anatomic site</th>
<th>Type</th>
<th>IHC</th>
<th>Promoter methylation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MLH1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Met</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Met</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Met</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Met</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Met</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Met</td>
</tr>
</tbody>
</table>

ne, not evaluable; Met, methylated; U, unmethylated.

**Table 3** Morphological and immunohistochemical features of unstable (MSI) and stable (MSS) neuroendocrine carcinomas

<table>
<thead>
<tr>
<th></th>
<th>MSI 11 cases</th>
<th>MSS 78 cases</th>
<th>Total 89 cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-cell subtype</td>
<td>6 (54%)</td>
<td>34 (45%)</td>
<td>40 (46%)</td>
</tr>
<tr>
<td>Vascular invasion</td>
<td>6 (54%)</td>
<td>57 (78%)</td>
<td>63 (75%)</td>
</tr>
<tr>
<td>Perineural invasion</td>
<td>6 (54%)</td>
<td>55 (74%)</td>
<td>61 (72%)</td>
</tr>
<tr>
<td>Necrosis</td>
<td>9 (90%)</td>
<td>62 (79%)</td>
<td>71 (80%)</td>
</tr>
<tr>
<td>Intratumoral lymphoid infiltration</td>
<td>20.40 ± 5.580</td>
<td>7.13 ± 1.914</td>
<td>11.7 ± 13</td>
</tr>
<tr>
<td>Peritumoral lymphoid infiltration</td>
<td>117.6 ± 12.41</td>
<td>55.53 ± 8.05</td>
<td>77 ± 45</td>
</tr>
</tbody>
</table>

Mitoses (× 10 HPF)<sup>a</sup> 37.8 50.8 49.2
Ki67 index<sup>b</sup> 68.4 63.6 64.1
Ki67 index (>55%) 8 (80%) 55 (72.3%) 63 (73.2%)
Chromogranin A 6<sup>c</sup> 62<sup>d</sup> (79%) 68<sup>e</sup> (76%)
Synaptophysin 10 (91%) 76 (97%) 86 (97%)
CD117 positive 0 28 (37%) 28 (32%)
PDX1 positive 1 (10%) 8 (11%) 9 (11%)
CDX2 positive 7 (64%) 34 (45%) 40 (46%)
TTF1 positive 0 16 (21%) 16 (18%)
Cytokeratin 20 1 (9%) 6 (8%) 7 (8%)
Cytokeratin 7 2 (18%) 22 (29%) 24 (27%)

HPF, high power field.
<sup>a</sup>Mean value of CD3 positive cells.
<sup>b</sup>Mean value.
<sup>c</sup>Three cases with < 10% of positive cells.
<sup>d</sup>26 cases with < 10% of positive cells.
<sup>e</sup>29 cases with < 10% of positive cells.
found in both tumor areas in the three MANECs showing MLH1 loss (Fig. 2).

**Mutation analyses** Mutation analyses of codon V600 of BRAF and codons 12 and 13 of KRAS genes were possible for 88 samples. BRAF V600E substitutions were identified in six cases (7%) and all of them were found in colorectal cases. KRAS mutations were identified in 15 cases (17%): 13 in colorectal and two in gastric NECs. The mutations were the following types: G13D (40%), G12D (33%), G12A (20%), and G12V (7%). No cases showed mutations in both genes.

A strong association between BRAF mutation and MSI was observed, with 66% of MSI-cases showing BRAF V600E substitution vs 8% of MSS-cancers ($P < 0.0008$). By contrast, no significant correlation was detected between MSI and KRAS mutations.

**Gene methylation profiles and correlation with MSI status**

Methylation analysis of the 34 promoters listed in Supplementary Table 2 was performed in all 89 GEP-NEC/MANECs by MS-MLPA. Overall, the percentage of methylated genes ranged from 0% to 74%. We used a model-based cluster algorithm (Fraley & Raftery 2002) to appropriately categorize different subsets of NEC/MANECs based on gene hypermethylation levels. With this method, it was possible to define three main subgroups (Fig. 3A): 42% of the tumors (37/89 cases) had a very low level of methylation (L-MET, less than five methylated genes), 26% (24/89) of cases exhibited intermediate levels of methylation (I-MET, more than five and less than eight methylated genes), and 31% (28/89) showed extensive gene hypermethylation (H-MET, more than eight methylated genes). H-MET NEC/MANECs were localized in the stomach, intestine, and gallbladder (17, ten, and one tumors respectively). No significant differences were observed in the methylation frequencies of cancers from different sites. However, more than half of H-MET cancers fell into the gastric group (Fig. 3B).

With regard to MSI status, all 11 unstable NEC/MANECs fell into either the H-MET or the I-MET group and showed higher methylation levels compared with MSS-cases, with a mean value of methylated genes per case equal to 40.6% ± 5.2 vs 20.2% ± 1.9 in MSS cases ($P < 0.001$). The genes most frequently methylated in MSI group were MLH1, P16, PAX6, PAX5, THBS1, TP73, DAPK1, MGMT, PYCARD, CDH13, HIC1 and TIMP3 (for all $P < 0.01$). No genes were significantly methylated at high frequency in MSS cancers.

**Survival analyses**

Survival analyses were carried out to test the prognostic value of all the molecular and clinicopathologic features examined in this study. Kaplan–Meier curves of all statistically significant variables at univariate analysis are shown in Fig. 4. The MSI phenotype was associated with a more favorable prognosis than MSS status, with a MS of...
60 vs 5.5 months respectively ($P=0.0048$). GEP-NEC/MANECs showing aberrant methylation of the MLH1 gene were associated with a better outcome, with a MS of 61.5 months compared with 6 months for MLH1-unmethylated cases ($P=0.01$). The methylation status of any of the other genes did not correlate with prognosis. Clinicopathological characteristics associated with worse prognosis included the presence of vascular invasion (MS: 5 vs 48 months; $P<0.0001$) and CD117 immunoreactivity (MS: 2 vs 14 months; $P=0.0027$). As the Ki67 index has been shown to subdivide NECs into two distinct prognostic groups (Sorbye et al. 2013), we performed survival analysis categorizing patients by using the Ki67 index threshold of 55%, which was identified by a model-based cluster algorithm (Fraley & Raftery 2002). Interestingly, this corresponded to that used by Sorbye et al. (2013). In all 23 cases with <55% Ki67 index (11 NECs and 12 MANECs), the neuroendocrine component was morphologically poorly differentiated of either small cell (13 cases) or large-cell (ten cases) type. The Ki67 index failed to prognosticate NEC/MANECs when applied to the whole series including both MSI- and MSS-cases. However, it successfully identified two different prognostic groups when only MSS carcinomas were considered, after excluding MSI-carcinomas from the analysis ($P=0.049$).

Multivariate analysis was performed including all the variables that were significant at univariate analyses (Table 4). Vascular invasion and MSI phenotype were identified as the only independent prognostic factors ($P=0.0003$ and $P=0.0084$ respectively). A trend was observed for the Ki67 index using a threshold of 55% ($P=0.063$).
Endocrine-Related Cancer

Sepulveda 2005). Secondly, MMR defect seems to occur early
between MSI-neuroendocrine and -exocrine cancers in these
sites. Firstly, the incidence of the MSI phenotype in
neuroendocrine areas of all four MSI-MANECs examined,
the presence of MSI was found in both exocrine and
endothelial tumors. Thirdly, MSI-NEC/MANECs are associ-
ated with widespread gene methylation. This finding
confirmed the close association between MSI and the CpG
island methylator phenotype (CIMP) already described in
gastric and colorectal adenocarcinomas (Toyota et al. 1999,
Samowitz et al. 2005). In these sites, genome-wide methyl-
ation studies have confirmed that CIMP and MSI are a
homogeneous subset of cancers harboring aberrant DNA
methylation mechanisms (Park et al. 2011, Hinoue et al. 2012,
Xu et al. 2012). Fourthly, we demonstrated that the well-
known relationship reported in colorectal adenocarcinomas
between MSI phenotype and BRAF V600E mutation (Boland
et al. 2009) is also found in MSI-NEC/MANECs of the colon–
rectum. Fifth, at least one case of MLH1-negative large-cell
NEC arising in a MLH1-negative sessile serrated adenoma,
which is recognized to be a precursor of colorectal carcinoma
as a part of the MSI pathway of colorectal carcinogenesis, has
been reported (Naert & Dupre 2012).

It is worth noting that morphology alone did not help
to identify MSI-NEC/MANECs. Indeed, none of the
histologic features considered predicted the MSI status.
On the contrary, immunohistochemistry for neuroendo-
crine markers and MMR proteins allowed us to identify
MSI-NEC/MANECs, which were subsequently confirmed
by MSI analysis.

A very important finding of our study regards the
unexpected, more favorable prognosis of MSI-carcinomas
compared with MSS-NEC/MANECs. Indeed, the presence of
a MMR defect allowed us to identify a subset of 11 patients with
MSI-carcinomas showing a MS of 60 months; much longer
than the MS of 5.5 months observed in the patients with
MSS-NEC/MANECs. Moreover, MSI status remains the only
independent prognostic factor ($P = 0.0084$) at multivariable
analysis together with vascular invasion ($P = 0.0003$). Interest-
ingly, the MS of MSI-NEC/MANECs is similar to that of
MSI-adenocarcinomas (Guidoboni et al. 2001).

The identification of MSI status may be also useful for
therapeutic purposes. It is well known that MSI predicts poor
response to 5-fluorouracil and oxaliplatinate (Zaanand et al.
2010). On the contrary, MSI colorectal cancers are sensitive
to irinotucan (Bras-Goncalves et al. 2000) and patients with
MSI tumors have a better survival after adjuvant therapy that
includes irinotecan (Bertagnolli et al. 2009). It remains to be
demonstrated if this different response to therapeutic agents
is similar in MSI-NEC/MANEC.

Regarding the prognostic value of the Ki67 index in
our study, we observed an unexpected finding. The 55%
threshold index failed to prognosticate NEC/MANECs when
applied to the whole series, while it was a
significant prognostic predictor in the group of
78 MSS-NEC/MANECs. It is worth noting that a high
Ki67 index was not associated with a worse survival in
colorectal MSI adenocarcinomas (Kim et al. 2007),
indicating that the Ki67 index has a different prognostic
value in MSI-positive and in MSI-negative neoplasms.

### Table 4 Multivariable analysis

<table>
<thead>
<tr>
<th></th>
<th>HR</th>
<th>95% CI</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vascular invasion</td>
<td>1.96</td>
<td>1.3631–2.813</td>
<td>0.0003</td>
</tr>
<tr>
<td>MSI phenotype</td>
<td>1.81</td>
<td>1.1639–2.814</td>
<td>0.0084</td>
</tr>
<tr>
<td>Ki67 index (55%)</td>
<td>1.36</td>
<td>0.9839–1.878</td>
<td>0.063</td>
</tr>
</tbody>
</table>

HR, hazard ratio.

## Discussion

This study demonstrates for the first time that the analysis
of MMR defects in GEP-NEC/MANECs allows the identifi-
cation of a new clinicopathological entity characterized by
an unexpected, relatively favorable prognosis and by
distinct genetic and epigenetic features.

The MSI phenotype was observed in 12.4% of the GEP-
NEC/MANECs located in the stomach or intestine,
confirming and extending our recently published results
obtained in a cohort of colorectal NEC/MANECs (La Rosa
et al. 2012a,b).

In the present investigation, we demonstrate that the
main pathogenetic mechanism leading to the onset of
MSI-NEC/MANECs is the methylation-mediated silencing
of the MLH1 gene, similar to that which has been widely
reported in sporadic exocrine gastrointestinal adenocarcino-
mas (Kane et al. 1997, Bevilacqua & Simpson 2000).
Accordingly, several other observations suggest similarities
between MSI-neuroendocrine and -exocrine cancers in these
anatomic sites. Firstly, the incidence of the MSI phenotype in
NEC/MANECs is comparable with that reported for colorectal
and gastric adenocarcinomas (Ionov et al. 1993, Gologan
& Sepulveda 2005). Secondly, MMR defect seems to occur early
in the tumorigenic pathway of MSI-NEC/MANECs, if the
large size of the allelic shifts observed in the five micro-
satellites examined is considered. Indeed, it is well known
that the progressive shortening of mononucleotide tracts
may be used as a simple molecular clock of MSI tumor
In this study, we observed microsatellite deletions ranging from 5.4
to 9.7 bp that were very similar to those previously reported
in advanced gastric and colorectal adenocarcinomas showing
MSI (Furlan et al. 2002). In agreement with this hypothesis,
the presence of MSI was found in both exocrine and
neuroendocrine areas of all four MSI-MANECs examined,
suggesting that the MMR defect occurs before the divergent
differentiation starts. Thirdly, MSI-NEC/MANECs are associ-
ated with widespread gene methylation. This finding
confirms the close association between MSI and the CpG
island methylator phenotype (CIMP) already described in
gastric and colorectal adenocarcinomas (Toyota et al. 1999,
In conclusion, this study demonstrates that immunohistochemical expression of MMR protein and MSI analysis, two simple tests routinely available in most laboratories of surgical pathology, can identify a subgroup of MSI-NEC/MANECs which are associated with a significantly more favorable prognosis than that of NEC/MANECs without a MMR defect. MSI-NEC/MANECs are observed in gastric and colorectal sites with very similar frequency to that reported for MSI gastrointestinal adenocarcinomas. The pathogenetic mechanisms as well as the clinicopathologic and the molecular profiles of MSI-NEC/MANECs closely resemble those described for sporadic gastric and colorectal MSI-adenocarcinomas.

Supplementary data
This is linked to the online version of the paper at http://dx.doi.org/10.1530/ERC-14-0410.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

Funding
This study has been supported by Epigenomics Flagship Project – EPIGEN (to D Furlan), by a grant of the Italian Ministry of Health (progetto finalizzato number 08934412), and by a grant from the University of Insubria, Varese for a post-graduate fellowship.

Author contribution statement
N Sahnane performed the experiments, analysis and interpretation of data, and drafting of the manuscript; D Furlan performed study concept and design, analysis and interpretation of data, drafting of the manuscript; M Monti performed the experiments; analysis and interpretation of data; M Rotondi performed statistical analysis; A Vanoli performed analysis and interpretation of data; E Vicari performed the experiments, analysis and interpretation of data; E Solcia and F Sessa critical revision of the manuscript; C Capella analysis and interpretation of data, critical revision of the manuscript; S L Rosa study concept and design, analysis and interpretation of data, drafting of the manuscript.

References
Itonov Y, Peinado MA, Malkhosyan S, Shibata D & Perou MCH 1993 Ubiquitous somatic mutations in simple repeated sequences reveal
a new mechanism for colonic carcinogenesis. Nature **363** 558–561. (doi:10.1038/363580a0)


....