Break–apart interphase fluorescence in situ hybridization assay in papillary thyroid carcinoma: on the road to optimizing the cut-off level for RET/PTC rearrangements

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Abstract

Objective: Chromosomal rearrangements of the RET proto-oncogene is one of the most common molecular events in papillary thyroid carcinoma (PTC). However, their pathogenic role and clinical significance are still debated. This study aimed to investigate the prevalence of RET/PTC rearrangement in a cohort of BRAF WT PTCs by fluorescence in situ hybridization (FISH) and to search a reliable cut-off level in order to distinguish clonal or non-clonal RET changes.

Design: Forty BRAF WT PTCs were analyzed by FISH for RET rearrangements. As controls, six BRAFV600E mutated PTCs, 13 follicular adenomas (FA), and ten normal thyroid parenchyma were also analyzed.

Methods: We performed FISH analysis on formalin-fixed, paraffin-embedded tissue using a commercially available RET break–apart probe. A cut-off level equivalent to 10.2% of aberrant cells was accepted as significant. To validate FISH results, we analyzed the study cohort by qRT-PCR.

Results: Split RET signals above the cut-off level were observed in 25% (10/40) of PTCs, harboring a percentage of positive cells ranging from 12 to 50%, and in one spontaneous FA (1/13, 7.7%). Overall, the data obtained by FISH matched well with qRT-PCR results. Challenging findings were observed in five cases showing a frequency of rearrangement very close to the cut-off.

Conclusions: FISH approach represents a powerful tool to estimate the ratio between broken and non-broken RET tumor cells. Establishing a precise FISH cut-off may be useful in the interpretation of the presence of RET rearrangement, primarily when this strategy is used for cytological evaluation or for targeted therapy.

Introduction

Papillary thyroid carcinoma (PTC) is the most prevalent form of thyroid cancers, accounting for 80% of all cases. It is characterized by genetic alterations leading to the activation of the MAPK signaling pathway. Together with BRAF point mutations, RET gene rearrangements represent the two most common molecular events in PTC (1, 2, 3).

The rearranged during transfection (RET) proto-oncogene maps to the long arm of chromosome 10 at band q11.2 and encodes for a transmembrane tyrosine-kinase receptor involved in the control of cell differentiation, cell proliferation, and cell survival (4, 5). Oncogenic activation of the RET gene via chromosomal...
rearrangement is generally related to radiation exposure and young age (40–70%), but may be found in non-radiated thyroid tumors and in adults (20–40%) (6, 7).

Moreover, a recent study has revealed that 18% of poorly differentiated thyroid carcinomas (PDTC) and 9% of radioactive iodine (RAI) refractory-FDG-PET-positive PDTC harbored RET/PTC rearrangements (8).

These rearrangements (balanced inversions or translocations) derive from the fusion of the 3' portion of the RET gene to the 5' portion of several heterologous genes and create fusion proteins with transforming activity, as demonstrated in in vitro experiments and in transgenic mice models (9, 10, 11, 12).

To date, at least 13 different forms of RET rearrangement have been documented (13), with RET/PTC1 (consisting of the fusion of RET with the H4 gene) and RET/PTC3 (consisting of the fusion of RET with the RFG/ELE1 gene) being the most common (2, 14).

A wide range of prevalence of RET/PTC rearrangements in human PTC has been reported, ranging from 3% in Saudi Arabia, 29–35% in Italy, 40% in Canada, to 85% in Australia (15, 16, 17, 18), which can be attributed to ethnic and geographic variability as well as to different sensitivities of detection methods, tumor heterogeneity, age, and radiation exposure (6, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31). Indeed, non-clonal RET/PTC rearrangements have been found not only in PTC but also in 10–45% of follicular thyroid adenomas, oncocyctic thyroid tumors, and Hashimoto’s thyroiditis (30, 32, 33, 34, 35, 36, 37, 38, 39).

The specificity of this rearrangement, as a marker of PTC, has been challenged, and its clinical significance is still under debate. Thus, finding a reliable and biologically relevant strategy for RET/PTC detection may have important clinical and diagnostic implications as the detection of RET/PTC has been offered as a diagnostic tool in the surgical and preoperative cytological material (40, 41, 42, 43, 44, 45). Moreover, the emergence of drugs that selectively inhibit RET kinase activity highlights the need of a better understanding of RET/PTC distribution within the tumor volume and of standardization of the detection methods for this rearrangement (46, 47, 48, 49). Interphase fluorescence in situ hybridization (FISH) represents the gold standard method for detecting gene rearrangements at the single-cell level and is the most sensitive mean for identifying and quantifying intratumoral genetic heterogeneity (50, 51, 52).

The aim of this study was to test a new commercially available RET break–apart probe on formalin-fixed, paraffin-embedded (FFPE) samples, to investigate the prevalence of RET/PTC in a cohort of BRAF WT PTCs, to search for a reliable cut-off level in an attempt to distinguish the clonal or non-clonal event of the RET rearrangements, and to explore whether RET/PTC may be a relevant pathogenic factor.

Materials and methods

Samples collection

Forty cases of BRAF WT PTC (31 sporadic; two familial, one familial adenomatous polyposis-associated PTC and six with history of exposure to external beam radiotherapy) were analyzed during the study.

The cases were selected from a consecutive series of 250 PTCs collected from 2003 to 2013 from the files of the Pathology Unit, University of Verona. Previously, all samples had been tested for BRAF V600E mutation status (Fig. 1). The histology of all tumor samples was confirmed independently by two pathologists (C C and M B) and classified according to the World Health Organization guidelines (53). As a control group, six BRAFV600E mutated PTCs and 13 follicular adenomas (FA) (12 sporadic and one with a history of exposure to external beam radiotherapy) were also tested for RET rearrangements (Fig. 1). BRAF WT tumor tissue samples were obtained from 37 patients; in three patients with multifocal disease we examined two neoplastic foci (Table 1, cases 2a and 2b, 17a and 17b, 20a and 20b). Moreover, one case of BRAFV600E mutated PTCs (Table 1, case 18b) belonged
Table 1  Clinico-pathological and molecular findings in PTC.

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<th>Diameter (mm)</th>
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NED, not evidence of disease; SpeD, structural persistence disease; BPD, biochemical persistence disease; PD, progression disease.  
2a and 2b, 17a and 17b, 18a and 18b, 20a and 20b: each paired sample derived from the same patient.
to a patient included in the BRAFV600E WT group (Table 1, case 18a). Concerning the cases exposed to external irradiation (six PTC and one FA), the patients received radiation therapy for primary cancer (one thymoma, one brainstem glioma, three leukemias, one cerebellar astrocytoma, one rhabdomyosarcoma of the neck), during childhood (four patients) or as adults (three patients). The radiation dose was available only for one patient and amounted to 18 Gy (Table 1, case 35).

Regarding the PTC subset, the tumor latency was as follows: 7, 3, 6, 25, 16, and 45 years respectively (Table 1, cases 32–37); for the FA, the latency was 25 years (Table 2, case 1).

The medical records of each patient (42 with PTC: 37 WT, and five BRAF-mutated and 13 with FA) were reviewed to obtain clinical and demographic data. Informed consent was obtained from all patients, as per the recommendations of our Ethics Committee.

Fluorescence in situ hybridization

To evaluate RET/PTC rearrangements (either inversion 10q11.2 or translocations), FISH was performed using the REPEAT-FREE POSEIDON RET (10q11) break–apart probe (Kreatech Diagnostics, Amsterdam, The Netherlands) on FFPE samples.

This commercial probe is designed as a dual-color probe where the two regions across the break-point, the proximal and the distal region to RET (10q11), are direct-labeled with Platinum Bright 550 and with Platinum Bright 495 respectively.

The FISH procedure was performed following Kreatech’s protocol with modifications designed in our laboratory, in particular regarding the tissue digestion and the hybridization times (54).

In brief, 3 μm thick FFPE tissue sections were mounted on positively charged slides and air dried. Targeted tumor areas were circled with a pen, after review of the corresponding hematoxylin and eosin (H&E) stained slide by a pathologist.

The sections were deparaffinized with two 10-min washes in xylene, hydrated in 100, 85, and 70% ethanol solutions for 10 min each, rinsed in distilled water for 10 min, fixed in methanol:acetic acid 3:1 for 10 min and air-dried. Next, the sections were treated in a 2× SSC solution for 15 min at 37 °C, and then dehydrated in consecutive 70, 85, and 100% ethanol solutions for 1 min each, then dried. The sections were then bathed in 0.1 mM citrate buffer (pH 6) solution at 85 °C for 30 min and again dehydrated in a series of ethanol solutions and dried.

The slides were incubated in 0.75 ml of pepsin (Sigma) solution (4 mg/ml in 0.9% NaCl, pH 1.5) for 15 min at 37 °C, washed again, dehydrated again in graded ethanol solutions (70, 85, and 100%) for 2 min each and dried. A total of 10 μl RET (10q11) break–apart probe was placed on the designated hybridization area and sealed with rubber cement.

A Thermobrite denaturation-hybridization system (Abbott Molecular) set at 80 °C was used for codenaturation of probe and target DNA for 10 min, before hybridization at 37 °C overnight.

The rubber cement and coverslip were removed and the slides were placed in 0.3% NP-40/2× SSC solution at first for 15 min at room temperature and then at 72 °C for 2 min. The sections were then rinsed in H2O for 1 min, air-dried, and counterstained with 10 μl of DAPI/Antifade

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<td>F</td>
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<td>8</td>
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<td>30</td>
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<tr>
<td>9</td>
<td>54</td>
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<tr>
<td>10</td>
<td>60</td>
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<td>1</td>
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<tr>
<td>11</td>
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<td>M</td>
<td>No</td>
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<td>Oncocytic</td>
<td>Normo-macrofollicular</td>
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<tr>
<td>12</td>
<td>56</td>
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<td>No</td>
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<td>4</td>
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<tr>
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<td>51</td>
<td>F</td>
<td>No</td>
<td>8</td>
<td>Hyalinizing</td>
<td>Trabecular</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2 Clinico-pathological and molecular findings in follicular adenoma.
(ProLong Gold Antifade Reagent with DAPI; Life Technologies). The slides were examined using an Olympus BIX-61 microscope (Olympus, Hamburg, Germany) with appropriate fluorescence excitation/emission filters. The signals were recorded by a CCD camera (Olympus Digital Camera). For microscopic evaluation, at least 100 intact and nonoverlapping cell nuclei were scored for the presence of a split signal. Only cells with two overlapping signals or one split and one overlapping signal were counted to ensure only complete cell nuclei had been scored. The signal pattern interpretation was as follows: interphase nucleus with two co-localized green/red fusion signals identified normal chromosomes ten, while a separated red and green signals and green/red fusion signals indicated rearranged RET.

**FISH cut-off level**

To establish the cut-off level for RET/PTC rearrangements, we performed FISH analysis on ten normal thyroid parenchyma and 100 nuclei were scored for the presence of a split signal. As previously reported, the cut-off value was calculated as mean value +3 s.d. of RET rearranged cells (23, 37, 50, 55). The resulting mean value was 3.6% with a s.d. of 2.2%, leading to a positivity threshold of 10.2% (3.6 ± 3 × 2.2). Therefore, a sample was considered positive if a broken signal was observed in >10.2% of nuclei.

**RNA isolation and detection of RET/PTC rearrangements from frozen neoplastic thyroid tissue**

Total RNA was extracted and reverse transcribed into cDNA. RET/PTC1 and RET/PTC3 rearrangements have been investigated by qRT-PCR. In a final volume of 20 µl, we amplified 1 µg cDNA in a mix containing 200 nM final concentration of specific primers and 100 nM of probes.

Prime forward and probes were as follows: RET/PTC1, F: 5'-GGCGGCTGACGTGCGCAA-3'; RET/PTC3, F: 5'-CCCGAGGACCTGGGCTTACC-3'; PTC1 probe, 5'-CAAGTTCTTCCGAGGGAATTCC-3; PTC3 probe, 5'-CTGCGAGCCCGCAAGTGGCTTGGAAAACTCTAG-3'. To verify the presence of non-rearranged RET, the following primers and probe were used: RET, F: 5'-TGGCTTCTGCAGAGGCACAG-3'; R: 5'-ATCACCGTGCGGAGACAG-3'; RET probe 5'-CTAGCAGGACTGGCTTACCC-3'. For both fragments, primer reverse was as follows:

\[ \text{R: 5' - CAGGATCCACTGTGCA-3'} \]
\[ \text{R: 5' - CACCCAGGCCCAACTCCTCCA-3'} \]
\[ \text{R: 5' - TGTTCTTGGAAAAACTCTAG-3'} \]
\[ \text{R: 5' - CTGCGAGCCCGCAAGTGGCTTGGAAAACTCTAG-3'} \]

For both fragments, primer reverse was: RET/PTC, R: 5'-CAAGTTCTTCCGAGGGAATTCC-3'. To verify the presence of non-rearranged RET, the following primers and probe were used: RET, RET/PTC1 rearrangement and NIH3T3 cells with RET/PTC3 rearrangement were used to form a standard curve composed of five points (from 1000 to 0.1 ng of cDNA with 1:10 dilution) (56).

**Agarose gel PCR**

The generic rearrangement for RET (RET/PTCX) was analyzed searching for the expression of tyrosine kinase (TK) and extracellular (EC) domains using the following primers: EC, F: 5'-GGCGGCTGACGTGCGCAA-3'; RET/PTC1, F: 5'-CCCGAGGACCTGGGCTTACC-3'; RET/PTC3 probe, 5'-CTGCGAGCCCGCAAGTGGCTTGGAAAACTCTAG-3'. Only samples showing TK expression and not associated with EC were considered positive for rearrangement. Thermal cycling conditions included an initial step (94 °C for 10 min) followed by 35 cycles at 60 °C and a final extension (72 °C for 10 min). TPC1 cells (rearranged for RET/PTC1) were used as a positive control and BCPAP cells (carrying the BRAFV600E mutation) were used as a negative control (42).

**BRAF status**

BRAF sequence was screened for V600E mutation by pyrosequencing. DNA was first amplified using ‘RotorGene 6000’ (Corbett Research, St. Neots, Cambridgeshire, UK) and then sequenced using PyroMark Q96 ID system. PCR was performed with the following conditions: initial denaturation at 95 °C for 3 min; 40 cycles at 95 °C for 30 s, 55 °C for 30 s, 72 °C for 30 s; final step 60 °C for 5 min with TaKaRa Ex Taq (Qiagen). PCR amplification and mutational analysis were performed in accordance with the Diatech manual (anti-EGFR Moab response BRAF status).

**Statistical analyses**

For statistical analysis, the unpaired Student’s t-tests, the \( \chi^2 \), and the Fisher’s exact test were used, as appropriate. Statistical significance was defined at \( P < 0.05 \). The \( P \) values were corrected for multiple testing according to Bonferroni. All analyses were performed using GraphPad Prism version 5.00 for Windows (GraphPad Software, San Diego, CA, USA; www.graphpad.com).

**Results**

The clinico-pathological and molecular features of the 46 PTC (40 PTC BRAF WT and six PTC with BRAFV600E mutation) and 13 FA cases are given in Tables 1, 2 and 3.
The mean age of the patients with BRAF WT PTC and with FA was 35.5 and 46.7 years respectively. In the former group, there were 28 females and nine males, resulting in a female: male ratio of 3.1:1. In the latter group, there were seven females and five males with a sex ratio of 1.4:1.

The mean tumor size of the BRAF WT PTC samples was 22.5 mm and 32.5% of them were microcarcinomas. Moreover, multifocality was present in 33% of the samples, and lymph node metastases were found in about 49% of the patients. Following the TNM staging (57), 31 patients were at stage I and II (Table 3).

Assuming that BRAFV600E mutation and RET/PTC aberration are usually mutually exclusive (58, 59), the overall prevalence of RET rearrangement, including all 250 PTCs, was 4% whereas if we consider only the BRAF WT PTC samples, the prevalence was 25% (10/40 cases) (Fig. 1).

In detail, eight out of ten RET-positive cases showed a high percentage of split, ranging from 18 to 50%, while two cases harbored 12 and 13% of positive nuclei, respectively (Table 1). In the cases with low percentage of split, the aberrant cells were found scattered in the contest of cells harboring normal chromosome 10, without clustering. RET rearrangement was observed in nine sporadic PTCs (two solid, two classical, three follicular, two diffuse sclerosing variants) and in one with a history of exposure to external beam radiotherapy (classical variant; Fig. 2). Considering only the group of PTCs exposed to radiation, the frequency of RET rearrangement was 17% (one out of six cases with 30% of rearranged cells). The patient had received whole total body radiotherapy for leukemia 7 years before the diagnosis and removal of thyroid cancer (Table 1, case 32). Overall, the patients are young in age, the majority have lymph node metastases at the diagnosis and have PTC variants at the histology, frequently linked to RET genotype (Table 1).

All six PTC samples, carrying BRAFV600E mutation detected through pyrosequencing, showed a percentage of RET-positive cells under the cut-off threshold (range 2–8%) (Table 1). Both molecular aberrations were mutually exclusive.

The comparison between FISH and qRT-PCR results are depicted in Table 1.

### Table 3 Clinico-pathological features of BRAF WT PTC patients. One case of FAP-associated papillary carcinoma; one case of sporadic cribriform-morular variant of papillary carcinoma; one case of a recurrence nodule in thyroid bed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age (years)</td>
<td>35.5 (8–75)</td>
</tr>
<tr>
<td>Mean tumor size (mm)</td>
<td>22.5 (3–60)</td>
</tr>
<tr>
<td>Diameter ≤ 1 cm</td>
<td>13 (32.5%)</td>
</tr>
<tr>
<td>Multifocality</td>
<td>12 (33%)</td>
</tr>
<tr>
<td>Thyroiditis</td>
<td>16 (44%)</td>
</tr>
<tr>
<td>pT1-2</td>
<td>18 (49%)</td>
</tr>
<tr>
<td>pT3-4</td>
<td>19 (51%)</td>
</tr>
<tr>
<td>pN1</td>
<td>18 (49%)</td>
</tr>
<tr>
<td>Stage (AJCC 2009)</td>
<td></td>
</tr>
<tr>
<td>I–II</td>
<td>31 (84%)</td>
</tr>
<tr>
<td>III–IV</td>
<td>6 (16%)</td>
</tr>
</tbody>
</table>

The mean age of the patients with BRAF WT PTC and with FA was 35.5 and 46.7 years respectively.

In the former group, there were 28 females and nine males, resulting in a female: male ratio of 3.1:1. In the latter group, there were seven females and five males with a sex ratio of 1.4:1.

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Assuming that BRAFV600E mutation and RET/PTC aberration are usually mutually exclusive (58, 59), the overall prevalence of RET rearrangement, including all 250 PTCs, was 4% whereas if we consider only the BRAF WT PTC samples, the prevalence was 25% (10/40 cases) (Fig. 1).

In detail, eight out of ten RET-positive cases showed a high percentage of split, ranging from 18 to 50%, while two cases harbored 12 and 13% of positive nuclei, respectively (Table 1). In the cases with low percentage of split, the aberrant cells were found scattered in the contest of cells harboring normal chromosome 10, without clustering. RET rearrangement was observed in nine sporadic PTCs (two solid, two classical, three follicular, two diffuse sclerosing variants) and in one with a history of exposure to external beam radiotherapy (classical variant; Fig. 2). Considering only the group of PTCs exposed to radiation, the frequency of RET rearrangement was 17% (one out of six cases with 30% of rearranged cells). The patient had received whole total body radiotherapy for leukemia 7 years before the diagnosis and removal of thyroid cancer (Table 1, case 32). Overall, the patients are young in age, the majority have lymph node metastases at the diagnosis and have PTC variants at the histology, frequently linked to RET genotype (Table 1).

All six PTC samples, carrying BRAFV600E mutation detected through pyrosequencing, showed a percentage of RET-positive cells under the cut-off threshold (range 2–8%) (Table 1). Both molecular aberrations were mutually exclusive.

The comparison between FISH and qRT-PCR results are depicted in Table 1.

### Figure 2
History and corresponding FISH images of representative RET rearranged PTC samples. (A and B) Classical variant PTC with predominant follicular growth pattern (case 29, Table 1). Black arrows indicate papillary structures. (C and D) Classical variant PTC with a history of exposure to external beam radiotherapy (case 35, Table 1). (E and F) Solid variant PTC (case 27, Table 1). (G and H) Diffuse sclerosing variant PTC (case 33, Table 1). White arrows indicate the rearranged copy of RET. A full colour version of this figure is available at http://dx.doi.org/10.1530/EJE-14-0930.
All ten RET positive PTC cases analyzed by FISH matched well with qRT-PCR data. In particular, nine out of ten cases (n. 20b, 24, 26, 27, 28, 29, 30, 31, and 32) showed detectable RET/PTC1 mRNA, while one case (n. 25) exhibited RET/PTC3 mRNA.

Controversial data were obtained in five cases showing a frequency of rearrangement very close to the cut-off level. Cases 6, 12, and 16, displaying 6, 9, and 10% of aberrant nuclei, respectively, showed detectable RET/PTC1, RET/PTC1, and tyrosine kinase domain mRNA expression and 10% of split FISH signals.

Moreover, the remaining 25 BRAF WT PTC cases and all six BRAFV600E cases were negative by both methods.

Finally, we found RET/PTC activation in one spontaneous FA (one out of 13 cases, 7.7%), harboring split signals above the cut-off threshold (Table 2).

The comparison between RET rearranged and non rearranged PTCs is summarized in Table 4. No significant differences were found concerning the clinico-pathological features, with the exception of the frequency of extrathyroidal invasion which was significantly higher in tumors with RET rearrangement than those harboring RET WT (P=0.027; Table 4).

### Discussion

RET/PTC was the first chimeric gene with oncogenic potential described in a tumor of epithelial origin and represents one of the major genetic alterations found in PTC (1, 60).

For almost two decades, the pathogenic role of this hybrid gene both in sporadic PTC (adult and pediatric) and in PTC developing after ionizing radiation exposure, has been considered a dogma, but the detection of RET-positive cells in benign thyroid lesions and the discovery of heterogeneous distribution of this rearrangement within an individual nodule have called into question the belief (22, 24, 25, 37, 61).

Moreover, the clinical significance of RET/PTC rearrangements is still debated. Indeed, some authors have suggested that RET rearrangements are associated with local invasion and distant metastases (17, 26, 62, 63, 64, 65) while other authors associated with early-stage small PTCs and better prognosis (30, 66, 67, 68, 69, 70). However, these studies assumed that all types of rearrangement have comparable properties and considered them as a group (19).

Thus, the current challenge in using RET/PTC analysis affects the interpretation of dataset results. Finding an accurate, reliable, and clinically pragmatic strategy for RET/PTC detection becomes imperative because the detection of RET/PTC has been offered as a diagnostic tool for PTC in the surgical and preoperative cytological material (3, 21, 40, 41, 42, 43, 44). FISH is considered as the assay of choice for rearrangement detection on formalin-fixed surgical samples (71) and according to Marotta et al. (21), at present, it is the most suitable method for detecting clonal changes. Moreover, the application of interphase FISH on thyroid tumors is appropriate as tumors of endocrine glands are known to have a low growth rate (72).

The aim of this study was to investigate the prevalence of RET rearrangement by interphase FISH analysis in a cohort of BRAF WT PTC and to search for a reliable cut-off value in order to distinguish the occurrence of clonal or non-clonal RET changes and to explore whether RET/PTC may be a relevant pathogenic factor.

In our series, we found a total of ten out of 40 (25%) BRAF WT PTC samples with broken RET above the cut-off level, a prevalence slightly lower than that reported in other Italian studies of comparable size, ranging from 27.5 to 35% (16, 30, 62, 73, 74).

This finding could be explained by the significant decrease in RET/PTC over the years and the equivalent increasing rate of BRAFV600E and RAS mutations in PTC, possibly attributed to the decreased exposure to ionizing radiation in the last decades or to new pollutants (75, 76, 77, 78, 79).

Moreover, the prevalence of 4% of RET-positive samples in our consecutive series of 250 PTCs is consistent
with Jung et al. (76) who documented the decreasing in RET/PTC rearrangement from 11 to 2%. This prevalence was calculated assuming that RET rearrangement and BRAFV600E mutation are mutually exclusive as reported in some studies which consider the two genetic alterations as separated events in PTC without overlap (58, 59). Moreover, de Biase et al. (80) demonstrated that BRAFV600E is present in virtually all/the majority neoplastic cells in many mutated PTCs supporting the idea of that this genetic alteration is a founding event, acquired early during PTC development.

All six BRAFV600E samples tested for RET rearrangements exhibited split signal under the cut-off level. This finding indirectly confirms the pertinence of the 10.2% threshold for distinguishing non-clonal from subclonal or clonal RET/PTC rearrangement given that BRAFV600E mutation and RET/PTC aberration are usually mutually exclusive (58, 59). Moreover, this cut-off level parallels previous studies, which used a cut-off level of between 5 and 10% to separate cases from false-positives (22, 81, 82, 83).

We detected RET/PTC rearrangement in one of the six patients (17%) with a history of exposure to external beam radiotherapy. In the context of thyroid irradiation, this finding is to be considered a low figure, although the values reported in the literature have been decreasing recently (71, 75, 84). The high variation of RET/PTC rearrangements reported in different series can be due to differences in the prevalence of this alteration in specific age groups or due to the different time of latency of the tumors (3, 71, 84, 85).

In order to validate FISH results, we performed qRT-PCR assay in our study cohort composed of 40 BRAF WT and six BRAFV600E PTC cases. The FISH results matched well with qRT-PCR in 41 PTC cases (31 BRAF WT and six BRAFV600E PTCs), whereas five cases (n. 6, 12, 15, 16, and 19), showing a frequency of rearrangement very close to the cut-off level, were discordant (Table 1).

This discrepancy may reflect the genetic heterogeneity within an individual tumor, the different sensitivity of the detection approaches used in the study and the samples type used for the comparative analysis, e.g. FFPE material for FISH analysis and frozen tissue for qRT-PCR, representing different regions of the same tumor presumably with different distribution of RET-positive cells (3, 22). Moreover, the documented highly variable levels of RET/PTC expression in PTC, the identification of which is strictly dependent on factors that affect the sensitivity, could contribute to explaining the inconsistencies in detection rates between the DNA-based method (FISH) and RNA-based assay (qRT-PCR). The existence of quantitative variation in the expression levels should be taken into account to investigate the correlation of RET/PTC with clinical findings (83, 86).

The clinical significance of RET/PTC remains unclear, with conflicting results between the studies. Considering the clinico-pathological features evaluated in our series, we found no correlation of RET/PTC expression with age, gender, tumor size, histological variant, multifocality, lymphocytic infiltration, and lymph node metastasis, but the frequency of extrathyroidal invasion in tumors with RET/PTC expression (9/10, 90%) was significantly higher than those of RET/PTC negative (9/27, 33%, $p=0.027$), as already reported in three other studies (87, 88, 89). However, follow-up analysis seems to indicate no influence of RET expression on patients’ outcome, although the short follow-up period makes it difficult to draw definitive and firm conclusions on the prognosis. According to Tallini et al. (68), only one case of PTC with minor poorly differentiated component (case 23) was negative for RET rearrangement, confirming the low potential (the apparent inability) of RET/PTC-positive PTC to progress to a less differentiated phenotype.

As in the study of Soares et al. (69), our series did not include papillary microcarcinoma, carrying RET rearrangement. However, a high prevalence of RET rearrangement has been detected in papillary microcarcinomas by Viglietto et al. (67), leading the authors to conclude that this genetic alteration is an early event in PTC tumorigenesis and occurs in tumors with less propensity to evolve toward clinically more aggressive forms. Also Corvi et al. (90) found RET activation in 11 microcarcinomas out of 21 (52%) using FISH method. It is likely that these discrepancies could be attributed to the different study populations evaluated.

We found RET/PTC activation in one spontaneous FA (one out of 13 cases, 7.7%), harboring split signals in 12% of the nuclei. Although, initially, RET rearrangements were considered as a specific marker for PTC, they have been sporadically reported in nodules classified as benign at histology by means of different detection methods (21, 29, 32, 46). The biological significance of RET/PTC in benign lesions remains difficult to explain, if we exclude the occurrence of microfoci of PTC within an otherwise benign nodule. Some authors have hypothesized that the RET-positive adenomas are composed of a mixture of cells with and without rearrangement (non-clonal event), while others suggested that adenomas RET/PTC-positive may grow faster than those RET/PTC-negative (23, 32, 36, 46).
In conclusion, this study demonstrates that interphase break-apart FISH analysis provides a reliable and sensitive strategy to detect RET/PTC activation in thyroid tumors, comparable with RT-PCR or Southern blot analysis with the advantage to allow, on histology sections, the direct correlation between the histopathological features and the distribution of RET rearrangements in the tumor/normal cells. It also represents a powerful tool to estimate the ratio between broken and non-broken RET cells in an individual tumor, with the possibility to separate the clonal (driver mutation) from subclonal event (passenger mutation) and to quantifying intratumoral genetic heterogeneity.

Finally, the identification of a precise laboratory FISH cut-off appears to be a pivotal prerequisite in the interpretation of the presence of RET rearrangement, particularly when RET/PTC detection is used for cytological evaluation of malignancy or for targeted therapy.

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

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Author contribution statement
All authors approved the final version of the manuscript. Study concept and design: C Colato, M Ferdeghini, M Chilosi, F Pacini, and M Brunelli. Acquisition of data: C Colato, C Vicentini, S Cantara, S Pedron, P Bazzarola, I Marchetti, and G D Cosco. Analysis and interpretation of data: C Colato, C Vicentini, S Cantara, F Pacini, M Chilosi, M Ferdeghini, and M Brunelli. Drafting of the manuscript: C Vicentini and C Colato.

References


35 Cesla F, Gori M, Montalto G, Zuckermann M & Tronco G. Different significance of ret/PTC(1) and ret/PTC(3) rearrangements in thyroid carcinogenesis: lesson from two subgroups of patients with papillary thyroid carcinomas showing the highest incidence of ret/PTC activation. *Journal of Clinical Endocrinology and Metabolism* 2001 86 1429. (doi:10.1210/jcem.86.3.7352-8)


60 Elisei R. Molecular profiles of papillary thyroid tumors have been changing in the last decades: how could we explain it? Journal of Clinical Endocrinology and Metabolism 2014 99 412–414. (doi:10.1210/jc.2014-1130)


Cancer Research 2010 70 4123–4132. (doi:10.1158/0008-5472.CAN-09-4336)

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