Are we really at the dawn of understanding sporadic pediatric thyroid carcinoma?

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Abstract

Data from the National Cancer Institute and from the literature have disclosed an increasing incidence of thyroid cancer in children, adolescents and adults. Although children and adolescents with thyroid cancer tend to present with more advanced disease than adults, their overall survival rate is excellent; however, there is no clear explanation for the differences observed in the clinicopathological outcomes in these age groups. There has been an ongoing debate regarding whether the clinicopathological differences may be due to the existence of distinct genetic alterations. Efforts have been made to identify these acquired genetic abnormalities that will determine the tumor’s biological behavior and ultimately allow molecular prognostication. However, most of the studies have been performed in radiation-exposed pediatric thyroid carcinoma. Therefore, our understanding of the role of these driver mutations in sporadic pediatric differentiated thyroid cancer development is far from complete, and additionally, there is a strong need for studies in both children and adolescents. The aim of this review is to present an extensive literature review with emphasis on the molecular differences between pediatric sporadic and radiation-exposed differentiated thyroid carcinomas and adult population.

Key Words
- sporadic pediatric papillary thyroid carcinomas
- radiation-exposed papillary thyroid carcinomas
- RET/PTC
- BRAF
- RAS
- ETV6-NTRK3

Introduction

The incidence of thyroid cancer has increased worldwide over the last decades. Essentially, one of the largest annual increases from 2006 to 2010 was for thyroid cancer (Davies & Welch 2006, Lise et al. 2012, Siegel et al. 2014a). Differentiated thyroid cancer (DTC) is most frequently diagnosed among adults aged 45–54, with a mean age at diagnosis of 50 (SEER Stat Fact Sheets: thyroid cancer, available at http://seer.cancer.gov/statfacts/html/thyro.html accessed July 2015) and with a female predominance. Currently, it is the fifth most common cancer in women in the United States (Siegel et al. 2014a), and in Italy, it is the second most frequent cancer in women below age of 45 (Pellegriti et al. 2013). In São Paulo, Brazil, not only the thyroid cancer incidence rates were consistently higher than in the United States but also the female predominance was higher than that reported in SEER (Veiga et al. 2013).

Although rare in the young population, DTC rates are also increasing significantly in children and adolescents. Among DTC, papillary thyroid cancer (PTC) accounts for
nearly 90% and follicular thyroid carcinoma (FTC) accounts for about 5–10% of all thyroid cancer that occurs in the pediatric population (Demidchik et al. 2007, Hogan et al. 2009). It has been suggested that FTC is very rare and occurs in a slightly older age group (Jarzab et al. 2005). Medullary thyroid carcinoma, poorly differentiated thyroid carcinoma and undifferentiated thyroid carcinoma are rare in young patients (Hogan et al. 2009) and are not the focus of this review.

Regardless the ethnicity, an increased trend in incidence rates of pediatric thyroid carcinomas was found in most regions of the United States in both genders (Vergamini et al. 2014). When stratified by age, the annual incidence rate of cancer in children and adolescents is 0.43 (5–9 years), 3.50 (10–14 years) and 15.16 per million (15–19 years) (Vergamini et al. 2014). Others have also demonstrated that the incidence rates increased with age (Hogan et al. 2009, Siegel et al. 2014b). In fact, among 15- to 19-year-old adolescents, thyroid is the eighth most common cancer diagnosed and the second most common cancer among girls (Wu et al. 2003, Ward et al. 2014). Similar to that observed in adults, there is a female predominance (Landau et al. 2000, Hogan et al. 2009, Lazar et al. 2009).

The reasons for increasing incidences rates of pediatric thyroid cancer are currently unknown. Previous studies suggested that the increasing incidence of thyroid cancer among adults was predominantly due to better access to medical care and increased diagnostic scrutiny (Davies & Welch 2006). It is possible that advances in ultrasound imaging technologies have improved diagnosis and, consequently, over time, may have contributed to detect small and asymptomatic pediatric thyroid cancers.

Although increased diagnostic scrutiny may account for some of the rise, the increased incidence across all tumor sizes in young patients argue in favor of a true increase (Vergamini et al. 2014). Besides, it has been suggested that some of this increase may be due to environmental factors and lifestyle changes (Boas et al. 2006). Finally, the increase in the incidence of PTC with no similar increase in the incidence of other histological types of thyroid cancer is an argument in favor that environmental factors may contribute to the increase (Mazzaferri 1993).

There are significant molecular, pathological and clinical differences in DTC among children, compared to the adult population. To indorse best practice standards for the diagnosis and management of thyroid cancer in the pediatric population, a task force appointed by the American Thyroid Association (ATA) recently provided the first recommendations specifically addressing the management of thyroid nodules and DTC in children and adolescents (Francis et al. 2015). The authors suggested applying these recommendations to patients up to 18 years old, when the majority of pediatric patients have completed growth and development.

The aim of this review is to present an extensive literature review with emphasis on the molecular differences between the pediatric and adult population. Although several studies of pediatric DTC included individuals up to 21 years of age, we mainly focused on studies that involved individual ≤ 18 years of age.

**Clinical presentation**

The thyroid cancer in children usually presents as a solitary nodule (Welch Dinauer et al. 1998, Grigsby et al. 2002). The occurrence of palpable cervical adenopathy at diagnosis is also a common finding in pediatric DTC (Grigsby et al. 2002). Previous studies reported significant differences in the clinical presentation and outcomes of DTC in pediatric patients compared to adults (Jarzab & Handkiewicz-Junak 2007).

Although thyroid nodules are uncommon in the pediatric population, there is a greater risk of malignancy in nodules diagnosed in children and adolescents than in adults (26% vs 5%) (Niedziela 2006, Gharib & Papini 2007, Romei & Elisei 2012). Moreover, pediatric cases are more likely to present a more advanced stage of the disease at diagnosis, often a more aggressive local disease and higher rates of distant metastases (Zimmerman et al. 1988, Chow et al. 2004, Kumagai et al. 2004, Jarzab et al. 2005, Alzahrani et al. 2015). Neck lymph node metastasis at diagnosis was reported in nearly 90% of pediatric cases, while they were detected in 35% of adults (Zimmerman et al. 1988). Other series reported lymph node involvement at diagnosis in 40–90% of pediatric cases (Newman et al. 1998, Landau et al. 2000, Dinauer et al. 2008, Lazar et al. 2009, O’Gorman et al. 2010), compared to 20–50% of adults (Zaydfudim et al. 2008, Ahn et al. 2015) (Table 1).

Distant metastasis was found in virtually 7–30% of pediatric patients compared to 2–9% of adults (Zimmerman et al. 1988, Newman et al. 1998, La Quaglia et al. 2000, Chow et al. 2004, Handkiewicz-Junak et al. 2007, Dinauer et al. 2008, Hogan et al. 2009, O’Gorman et al. 2010). Mostly pediatric patients present distant metastasis in the lungs, but few cases have been also reported in the brain, soft tissue or bone (Newman et al. 1998, Jarzab & Handkiewicz-Junak 2007) (Table 1).
Nevertheless, a marked heterogeneity within the pediatric group has been reported. Pediatric cases tend to be more symptomatic in the prepubertal group (Jarzab et al. 2009). It is likely that in populations exposed to external radiation, such as children who underwent thyroid ultrasound examination in the Belarus area after the Chernobyl accident in 1986 (Ashizawa et al. 1997) and the screening of children from different Japanese prefectures after the Fukushima Daiichi Nuclear Power Plant accident in 2011 (Ashizawa et al. 1997, Yasumura et al. 2012, Hayashida et al. 2013), studies reporting the prevalence of small thyroid nodules in the pediatric population are scarce. Ultrasound examination in children from Fukushima, Aomori, Yamanashi and Nagasaki prefectures revealed that between 35 and 51% of children who underwent thyroid ultrasound examination showed thyroid cysts and nearly 1% showed thyroid nodules ≤0.5 cm (Hayashida et al. 2013, Yamashita & Suzuki 2013).

Another difference between pediatric and adult DTC is the higher rates of bilateral and multifocal disease in childhood. Pediatric patients present bilateral disease in about 30% of cases (Grigsby et al. 2002, Lazar et al. 2009) and multifocal disease in 30–80% of cases (Welch Dinauer et al. 1998, Grigsby et al. 2002, Lazar et al. 2009, O’Gorman et al. 2010, Rivkees et al. 2010). This higher rate of bilateral and multifocal disease is one of the arguments used to recommend for a more comprehensive thyroid surgery in pediatric patients (Francis et al. 2015). PTC variants, such as follicular variant of PTC (FVPTC) and diffuse sclerosing PTC (DSPTC), are more frequently found in pediatric patients than in adults (Neiva et al. 2012). Although there is no consensus on the prognosis of a different histological type, it was recently demonstrated that DSPTC is frequently associated with bilateral disease.

### Table 1: Clinical features of pediatric thyroid carcinomas

<table>
<thead>
<tr>
<th>Author</th>
<th>Cases (n)</th>
<th>RI exposure (%)</th>
<th>Mean age/ (range years)</th>
<th>Gender (female) (%)</th>
<th>Multifocality (%)</th>
<th>Bilateral (%)</th>
<th>ET (%)</th>
<th>Cervical meta (%)</th>
<th>Distant meta (%)</th>
<th>Recurrence (%)</th>
<th>Survival (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zimmerman et al. (1988)</td>
<td>58</td>
<td>No</td>
<td>&lt;17</td>
<td>69</td>
<td>NA</td>
<td>NA</td>
<td>24</td>
<td>90</td>
<td>7</td>
<td>30</td>
<td>76</td>
</tr>
<tr>
<td>Newman et al. (1998)</td>
<td>329</td>
<td>13</td>
<td>15.2 (0.4–20.8)</td>
<td>76</td>
<td>NA</td>
<td>NA</td>
<td>32</td>
<td>74</td>
<td>25</td>
<td>32</td>
<td>99</td>
</tr>
<tr>
<td>Welch Dinauer et al. (1998)</td>
<td>137</td>
<td>5</td>
<td>19 (3–21)</td>
<td>76</td>
<td>30.7</td>
<td>NA</td>
<td>39</td>
<td>6</td>
<td>20</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>Fenton et al. (2000)</td>
<td>33</td>
<td>No</td>
<td>18 (6–21)</td>
<td>71</td>
<td>48</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>Alessandri et al. (2000)</td>
<td>38</td>
<td>21</td>
<td>12.6 (4.5–16.8)</td>
<td>74</td>
<td>ND</td>
<td>NA</td>
<td>42</td>
<td>60</td>
<td>5</td>
<td>45</td>
<td>100</td>
</tr>
<tr>
<td>Landau et al. (2000)</td>
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<td>No</td>
<td>&lt;16</td>
<td>77</td>
<td>23</td>
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<td>NA</td>
<td>57</td>
<td>10</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>Grigsby et al. (2002)</td>
<td>56</td>
<td>No</td>
<td>15.8 (4–20)</td>
<td>77</td>
<td>57</td>
<td>30</td>
<td>36</td>
<td>73</td>
<td>13</td>
<td>34</td>
<td>98</td>
</tr>
<tr>
<td>Kumagai et al. (2004)</td>
<td>29</td>
<td>No</td>
<td>11.3 (&lt;15)</td>
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<td>NA</td>
<td>NA</td>
<td>23</td>
<td>68</td>
<td>23</td>
<td>ND</td>
<td>NA</td>
</tr>
<tr>
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<td>27</td>
<td>7</td>
<td>12.8 (6.1–17)</td>
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<td>52</td>
<td>67</td>
<td>41</td>
<td>18</td>
<td>100</td>
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<td>Hogan et al. (2009)</td>
<td>1753</td>
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<td>15.9 (1–19)</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>46</td>
<td>8</td>
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<tr>
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<td>54</td>
<td>No</td>
<td>13 (F); 13.4 (M)</td>
<td>67</td>
<td>75.9</td>
<td>28</td>
<td>NA</td>
<td>46</td>
<td>15</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ito et al. (2012)</td>
<td>110</td>
<td>No</td>
<td>17 (7–19)</td>
<td>89</td>
<td>NA</td>
<td>NA</td>
<td>8</td>
<td>41</td>
<td>7</td>
<td>24</td>
<td>98</td>
</tr>
<tr>
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<td>28</td>
<td>NA</td>
<td>8–19</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>32</td>
<td>50</td>
<td>7</td>
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<td>NA</td>
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<tr>
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<td>No</td>
<td>13.6 (2.8–18)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>42</td>
<td>68</td>
<td>26</td>
<td>11</td>
<td>NA</td>
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<tr>
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<td>No</td>
<td>18.6 (5.8–21.2)</td>
<td>79</td>
<td>NA</td>
<td>22</td>
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<td>63</td>
<td>4</td>
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<td>100</td>
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<tr>
<td>Alzahrani et al. (2015)</td>
<td>97</td>
<td>No</td>
<td>17 (8–20)</td>
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<td>43</td>
<td>NA</td>
<td>53</td>
<td>78</td>
<td>16</td>
<td>34</td>
<td>100</td>
</tr>
</tbody>
</table>

NA, not available.
extrathyroidal extension, lymph node involvement, lung metastasis and lower rates of recurrence-free survival than that of non-DSPTC (Koo et al. 2009).

**Treatment and prognosis**

Because pediatric DTC is an uncommon malignancy, randomized trials have not been applied to test best-care options in this group of patients (Rivkees et al. 2011). Therefore, the optimal initial and long-term treatment and follow-up remain controversial.

Despite a more advanced disease at presentation and a higher risk of recurrence, the prognosis of childhood DTC is generally fairly good. The reported mortality rate is low or even zero in some series (Newman et al. 1998, Alessandri et al. 2000, Henke et al. 2014). For this reason, the ATA guideline for children with thyroid nodules and DTC developed recommendations based on the available scientific evidence and expert opinion (Francis et al. 2015). The authors suggested reconsidering the former recommendation that all children with DTC should be similarly treated with a more extensive surgery and routine RAI therapy (Rivkees et al. 2011). A more comprehensive surgical approach raises the risk of important clinical complications, mainly transient or permanent hypoparathyroidism and recurrent laryngeal nerve damage. The RAI therapy is associated with an increase in the risk of second primary malignancy, especially salivary cancer (Martí et al. 2015).

The ideal surgical approach for the majority of patients is total thyroidectomy (TT) (Francis et al. 2015). However, in patients with a small unilateral tumor and without extrathyroidal extension, a near-TT can be considered to lower the risk of injury to either the recurrent laryngeal nerve or parathyroid glands (Rivkees et al. 2011, Francis et al. 2015). Previous studies that assessed the outcomes of a less comprehensive surgical approach in pediatric patients have shown a higher risk of relapse rates with lobectomy vs TT (Hay et al. 2010, Handkiewicz-Junak et al. 2007). Despite the high rate of cervical metastasis in pediatric DTC, routine central lymph node dissection is no longer recommended. The central neck dissection should be performed when there is evidence of central and/or lateral neck metastasis or gross extrathyroidal invasion (Francis et al. 2015).

Regarding RAI indications, the current recommendation in pediatric DTC is for treatment of nodal or other locoregional disease that is not amenable to surgery as well as distant metastases that are iodine-avid. Moreover, the RAI therapy can also be consider in children with T3 tumors or extensive regional nodal involvement (Francis et al. 2015). Similar to adults, there is no evidence of benefit of RAI remnant ablation in pediatric patients with intra-thyroidal disease and no lymph node disease (Lamartina et al. 2015).

**Risk factors**

The link between ionizing radiation during childhood and thyroid cancer has been known since 1950. The first sharp rise in the incidence of thyroid cancer was reported in epidemiological studies after external radiation to treat common childhood conditions such as acne, *tinea capitis* and enlarged tonsils or thymus gland. A pool analysis of seven studies demonstrated a high risk of thyroid cancer in subjects irradiated at a young age, even for radiation doses as low as 0.10 Gy. Although the risk of developing thyroid cancer is still present more than 40 years after exposure, it is higher between 15 and 30 years. The risk decreased significantly with increasing age at exposure, with very little risk after age 20 (Ron et al. 1995).

The second peak of thyroid cancer was observed in 1996, 10 years after the Chernobyl nuclear power station accident, when over $10^{18}$ Bq of radioactivity was released into the atmosphere, mainly $^{131}$I and $^{137}$Cs. The highest levels of contamination occurred in Belarus, Ukraine and western Russia. Children and adults have been exposed to a relatively high dose of $^{131}$I. Predominantly, through ingestion of contaminated food and drink, their thyroid has accumulated a high dose of $^{131}$I. As childhood thyroid is very radiosensitive, one would expect a high prevalence of thyroid disease in those subjects exposed to radiation at a young age. In fact, the incidence rate of childhood thyroid carcinoma in the heavily contaminated region of Belarus reached 40 per million, while an annual incidence of 1 per million was reported in this area before the accident. The highest risk group was those patients aged 0–4 years at the time of exposure. After 1996, the incidence declined progressively, and after 2001, only sporadic cases (not exposed to radiation) were reported in pediatric patients (<15 years old) (Demidchik et al. 2007, Williams 2008, Tuttle et al. 2011).

The radiation-associated risk of thyroid cancer to the exposed children and residents after the Fukushima Daiichi Nuclear Power Plant accident on March 2011 is still unclear. The RAI measured after the accident was one-tenth or less that measured after the Chernobyl accident, and the radiation exposure dose measured in children from neighboring regions after the accident was at a near negligible level. The Fukushima prefecture started the
Fukushima Health Management Survey Project aimed at long-term health care administration and early medical diagnosis/treatment for prefectural residents. As the first round of screening, a thyroid ultrasound examination was conducted from October 2011 to March 2014 in nearly 300,000 individuals aged <18 years. From a total of 108 (0.8%) children with suspicious nodules, 84 had thyroid carcinoma, most (96%) were PTC (Yamashita & Takamura 2015). Although a not significant increase in the prevalence of thyroid cancer has been reported after the Fukushima Daiichi Nuclear Power Plant accident (Iwaku et al. 2014), a sharp increase in the incidence of thyroid cancer was observed 4–5 years after the Chernobyl accident, and, therefore, it was preceded by a latency phase. Only a long-term follow-up will clarify whether a third peak of thyroid cancer might occur after the Fukushima Daiichi Nuclear Power Plant accident.

These findings recognized the extreme sensitivity of children’s thyroid to radiation, compared to adults. Many epidemiologic studies have explored whether the exposure to radiation during medical diagnostic and therapeutic procedures represent a risk factor for pediatric thyroid cancer. It has been demonstrated that the thyroid exposure to X-rays due to dental radiographic procedures (Memon et al. 2010) or primary beam during computed tomography scan of the neck during childhood is associated with a low but not negligible risk of cancer (Mazonakis et al. 2007, Pellegriti et al. 2013). Regarding therapeutic procedures, it is well known that survivors of pediatric cancer may suffer from late sequelae of treatment, including secondary malignant neoplasia in the irradiated region. Secondary thyroid carcinoma after radiotherapy to the neck has been reported in many publications. Interestingly, the risk of a subsequent thyroid cancer after a first tumor in childhood rose with an increasing radiation dose (greatest risk 20–29 Gy) but doses higher than 30 Gy is consistent with a cell-killing effect (Sigurdson et al. 2005). As an example, the cumulative incidence for patients with up to 30 years of follow-up after the diagnosis of Hodgkin’s lymphoma (HL) was 4.4% for thyroid carcinoma and the mean interval after HL diagnosis was 13.2 years (range 4.0–29.2 years). The most frequent thyroid carcinoma identified in these patients is PTC (Dorfel et al. 2000, Levy et al. 2012, Marti et al. 2012).

This pediatric thyroid cancer peak incidence and a ‘latency phase’ reinforce that a long-term follow-up of patients should be undertaken for survivors of both the Fukushima Daiichi Nuclear Power Plant accident and any cancer during childhood involving radiotherapy to the thorax or head and neck region.

Hints from cancer biology

Recently, the Cancer Genome Atlas (TCGA) Research Network, using next-generation DNA and RNA-sequencing, copy-number variation, miRNA, methylomic, transcriptomic and proteomic profiles, combined with clinic-pathological data, characterizes the landscape of nearly 500 PTCs of adults. The study confirmed that PTC is associated with mutations in genes that code for proteins involved in the MAPK pathway such as RET, BRAF and RAS. The TCGA also identified new cancer-causing gene mutations that occur in PTC (EIF1AX, CHEK2, PM1D), as well as new fusion transcripts and somatic copy number alteration (recurrent 22q deletion and 1p amplification) that reduced the so-called ‘dark matter’ of the PTC. The large collection of genetic alterations, combined with a comprehensive transcriptomic and proteomic analysis, revealed fundamental biological differences between PTCs. This increased knowledge helped stratify PTC into subgroups, which ultimately will refine pre-operative diagnosis of thyroid nodules and prognosis and treatment of adult PTC (The Cancer Genome Atlas Research Network 2014).

Several studies have suggested that the spectrum of mutations may differ between tumors of pediatric patients and tumors of adults (Bongarzone et al. 1996). Moreover, few studies have indicated that radiation-exposed and sporadic pediatric thyroid carcinomas are different biological types of cancer with the same histology (Nikiforov et al. 1997).

To obtain a whole picture of the genomic landscape of the radiation-exposed pediatric thyroid carcinomas, a research team performed RNA-sequencing in five patients with thyroid carcinoma from the regions of Ukraine and who were younger than 10 years at the time of the Chernobyl nuclear accident. They selected patients who were negative for known BRAF mutations and known fusion transcripts (RET/PTC, TPR-NTRK1, PAX8-PPARG and AKA9-BRAF). Moreover, the research group performed low-pass whole-genome sequencing of five radiation-exposed and five patients with sporadic pediatric thyroid carcinoma who were from the same geographical regions (Ricarte-Filho et al. 2013). The authors identified new kinase fusion oncogenes in radiation-exposed thyroid carcinomas. First, this study ratifies that the MAPK pathway plays a critical role in pediatric PTC development (Ricarte-Filho et al. 2013). Second, the prevalence of fusion
oncogenes in radiation-induced tumors (84%) was much higher than the prevalence in sporadic cases (33%). This finding supports the concept that ionizing radiation induces chromosomal rearrangement but contests the notion that the prevalence of fusion oncogenes is similar in both sporadic and radiation-induced pediatric PTC. Last, it reinforces the idea that spectrum of mutations in pediatric tumors differ from adults.

The hints from molecular biology suggest that the clinical and pathological differences observed between pediatric and adults might be fundamentally due to their biological differences. Therefore, the therapy that may be recommended for an adult may not be appropriate for a child, which validates the development of unique pediatric guidelines (Francis et al. 2015).

The major known somatic events associated with radiation-exposed and sporadic pediatric thyroid carcinomas reported in the literature are summarized below (Fig. 1, Supplementary Tables 1 and 2, see section on supplementary data given at the end of this article.).

**RET/PTC fusions transcripts**

The RET (rearranged during transfection) gene, located in the chromosome 10q11.2, encodes for a cell membrane receptor tyrosine kinase (TK). RET rearrangement was initially described in an irradiated PTC (Fusco et al. 1987). Through chromosome rearrangement, RET was fused to the NH2 terminus of a heterologous gene denominated CCD6 (formerly named H4). RET gene is not expressed in normal follicular thyroid cells. However, the fusion product expresses intrinsic and constitutive TK activity. This not only was the first example of oncogene activation in solid tumors but also was the first RET rearrangement described in PTC and, hence, named RET/PTC1 (Fusco & Santoro 2007).

In the subsequent years, other RET/PTC isoforms were identified in sporadic and radiation-exposed PTC. Currently, nearly 20 types of RET/PTC rearrangements were identified (Fusco & Santoro 2007, Romei et al. 2008, Ricarte-Filho et al. 2013, The Cancer Genome Atlas Research Network 2014). In all isoforms the TK domain of RET is conserved and fused to other genes. Although RET/PTC rearrangement was described in benign lesions, in most series it was specifically found in PTC. An elegant work that was performed by the Nikiforova group shows that this thyroid specificity is likely due to nuclear architecture of thyroid cells, i.e., spatial proximity between partners and RET may influence their participation in the RET/PTC rearrangements in the human thyroid cell (Nikiforova et al. 2000).

While in most series RET/PTC fusion is the second most common genetic event in PTC of adults (Romei & Elisei 2012), it is the main genetic event found in both sporadic and radiation-induced pediatric PTC (Figs 1 and 2).

In this systematic review of literature, we estimate the overall prevalence of RET/PTC in pediatric sporadic and radiation-exposed PTC. The overall prevalence of RET/PTC differs between sporadic and radiation-exposed pediatric PTC carcinomas (41% vs 58% respectively) (Fig. 1) (Student’s t-test; P=0.034). The reported prevalence of RET/PTC in sporadic PTC varies from 22% (France/Italy) to 65% (USA), while its prevalence in radiation-exposed varies from 33% (Belarus) to 76% (Belarus) (Fig. 2, Supplementary Tables 1 and 2). The highest incidence was found in post-Chernobyl pediatric PTC patients. As radiation exposure induces DNA double-strand breaks and RET gene and their partners are juxtaposed in...
the nuclei of thyroid cells, it facilitates chromosome recombination. Few studies reported PTC with concomitant RET/PTC in sporadic (Fenton et al. 2000, Penko et al. 2005) and radiation-induced PTC (Elisei et al. 2001). The reported prevalence of concomitant RET/PTC rearrangements in sporadic cases was 2% and radiation-exposed was 1% (Fig. 1).

Even if part of these differences can be attributed to geographic variability, the major differences in the prevalence of RET/PTC have been reported in radiation-exposed cases from the Belarus area (Klugbauer et al. 1995, Nikiforov et al. 1997, Thomas et al. 1999, Pisarchik et al. 1998, Rabes et al. 2000, Elisei et al. 2001, Kumagai et al. 2004, Nikiforova et al. 2004, Ricarte-Filho et al. 2013) (Fig. 2). It has been suggested that other factors, probably influenced by ethnic or genetic background, may act independently from or in cooperation with radiations to trigger RET rearrangement (Elisei et al. 2001). It has also been suggested that tumor heterogeneity and the use of different detection methods may contribute to the variability in the reported prevalence of RET/PTC (Zhu et al. 2006, Nikiforov & Nikiforova 2011).

Others have reinforced that tumor latency changes the prevalence and the type of RET/PTC rearrangement. Higher prevalence of RET/PTC3 rearrangements was found in faster developing tumors and in the most heavily contaminated areas (Rabes et al. 2000). Others have also found that RET/PTC3 is preferentially found in radiation-associated pediatric PTC with a short latency period, whereas RET/PTC1 is mainly found in later occurring PTC (Smida et al. 1999).

Regarding the prevalence of different RET/PTC isoforms, RET/PTC1 and RET/PTC3 are by far the most prevalent isoforms identified in tumors from two groups (Fig. 1, Supplementary Tables 1 and 2). RET/PTC1 was found at comparable prevalence in sporadic (20%)}
and radiation-induced pediatric PTC (18%), while the prevalence of RET/PTC3 was higher in radiation-exposed (33%) than in sporadic (10%) pediatric PTC (Fisher exact test; $P=0.01$). Although very few studies have examined the prevalence of RET/PTC2, this isoform was more prevalent in the sporadic group (Nikiforov et al. 1997, Fenton et al. 2000).

In the radiation-induced group, RET/PTC3 fusion oncogene was associated with more aggressive variants such as solid variant and DSPTC, whereas RET/PTC1 was mainly found in classical and FVPTC (Rabes et al. 2000, Elisei et al. 2001).

Even though it was described in a radiation-exposed PTC 28 years ago, it is still not clear whether RET/PTC rearrangement correlated with age or a more aggressive phenotype and histological subtype in sporadic pediatric PTC.

**BRAF V600E mutation**

The BRAF V600E, the T1799A nucleotide transversion that leads to a substitution of valine to glutamic acid, is the most common and specific genetic alteration found in PTC of adults (Kimura et al. 2003, Xing 2005, Frasca et al. 2008, Oler & Cerutti 2009, The Cancer Genome Atlas Research Network 2014).

This review of the literature and appraisal of the overall prevalence of BRAF V600E in the pediatric population shows that the prevalence of BRAF V600E is lower in radiation-exposed tumors (3%) than in sporadic cases (13%), although the observed differences did not reach statistical significance. In the sporadic group, the prevalence ranges from 0% to 37%, while in the radiation-exposed group, the prevalence ranges from 0% to 8% (Fig. 2).

Although patient age was not specified in all series, none of the patients with BRAF mutation were younger than 10 years (Lima et al. 2004, Sassolas et al. 2012, Ricarte-Filho et al. 2013, Givens et al. 2014). The lack of the BRAF V600E mutation in children and a lower prevalence of mutation in adolescents suggest that the prevalence of BRAF V600E increases with age and that BRAF V600E may not play a major role in pediatric tumors.

Recently, a group reported a high prevalence (63%) of BRAF V600E mutation in pediatric PTC (Henke et al. 2014). The median age of patients enrolled in this study was 18.6 years and the number of patients younger than 10 years old and their BRAF mutation status were not mentioned. As the methodology used to detected BRAF V600E was PCR-RFLP, instead of PCR-sequencing, this study was not included in overall analysis.

All together, the prevalence of BRAF V600E is significantly lower than RET/PTC in both sporadic and radiation-exposed pediatric groups (Fisher exact test; $P=0.0055$).

**RAS point mutations**

Activating mutation in codons 12, 13 or 61 of RAS genes (NRAS, KRAS and HRAS) has also been described in PTC. According to the catalogue of somatic mutations in cancer (http://sanger.ac.uk/cosmic), NRAS is the most frequently mutated RAS isoform in PTC. The highest rates of mutation were found in exon 2 of NRAS (13%). The Q61K mutation results in substitution from a glutamine (Q) to a lysine (K), at position 61. Recently, NRAS was also reported as the second most common mutation found in PTC by the TCGA study (The Cancer Genome Atlas Research Network 2014).

A strong association has been found between the presence of RAS mutations and histology in PTC of adults, with RAS mutations characterizing FVPTC (Zhu et al. 2003, Adeniran et al. 2006, Rivera et al. 2010, Park et al. 2013, The Cancer Genome Atlas Research Network 2014). High prevalence of mutations in the RAS gene has been described in FTC (18–57%) and follicular thyroid adenoma (FTA) (24–53%) (Fukahori et al. 2012). This mutation is also found in poorly differentiated and anaplastic carcinomas (18–31%) (Pita et al. 2014).

Relatively few studies have evaluated the occurrence of RAS point mutation in pediatric DTC and the incidence rates range from 0% to 7% in sporadic tumors (Kumagai et al. 2004, Sassolas et al. 2012, Ricarte-Filho et al. 2013) and 0% in radiation-exposed tumors (Suchy et al. 1998, Kumagai et al. 2004, Ricarte-Filho et al. 2013). In these studies only mutations at codon Q61 of NRAS were described. Although Suchy et al. (1998) found mutations at codons 14 and 15 of HRAS, these were silent mutations or did not interfere with GTPase activity or protein binding capacity, respectively. Thus, different from adults, RAS mutations exert a minor role in the pathogenesis of pediatric PTC.

**ETV6-NTRK3 fusions transcripts**

The ETV6-NTRK3 is a new fusion oncogene recently described in 7% of pediatric radiation-exposed PTC (Ricarte-Filho et al. 2013). The ETV6-NTRK3 fusion results from an interchromosomal translocation, which
juxtaposes exons 1–4 of ETV6 to exons 12–18 of NTRK3. The chimeric transcript is able to activate MAPK and PI3K signaling pathways and promotes cell growth of NIH-3T3 cells as well as colony formation in soft agar (Ricarte-Filho et al. 2013). Further validation analysis showed that 7% of sporadic pediatric PTC from the Ukraine area had ETV6-NTRK3 fusion (Ricarte-Filho et al. 2013). The authors found that pathological characteristic of both radiation-exposed tumors and sporadic cases appeared to correlate with the nature of underlying drive mutations, i.e., ETV6-NTRK3 was mainly found in FVPTC. Finally, all tumors with ETV6-NTRK3 fusion were from patients older than 13 years of age at surgery.

ETV6-NTRK3 was later detected in 14.5% post-Chernobyl PTCs (age range from 14 to 32 years) and in 2% of sporadic (age range from 15 to 97 years) (Leeman-Neill et al. 2014). ETV6-NTRK3 was the second most common rearrangement, after RET/PTC, in radiation-induced PTCs. One of the tumors with ETV6-NTRK3 was from a patient who was aged 1 year at the time of the Chernobyl accident and another tumor was from a patient who was aged 10 years at the time of exposure. All radiation-induced PTCs in which ETV6-NTRK3 fusion was identified had some component of a solid growth pattern and most were classified as FVPTC (Leeman-Neill et al. 2014). Importantly, the authors demonstrated that the presence of ETV6-NTRK3 rearrangement, as well as RET/PTC and PAX8-PPARγ positive tumors, was significantly more common in tumors associated with higher dose exposure to 131I than tumors that had point mutations (NRAS, HRAS and BRAF).

The prevalence of ETV6-NTRK3 in pediatric sporadic PTC, its prognosis significance and whether in pediatric cases it is associated with older age (>10–18 years old) remains uncertain.

**Other fusions transcripts**

Other less prevalent fusion transcripts have been described in pediatric radiation-exposed PTC. The overall prevalence of these other fusion transcripts was 6% in a pediatric radiation-exposed PTC range from 3% to 19% (Ciampi et al. 2005, Sassolas et al. 2012, Ricarte-Filho et al. 2013) and 0% in sporadic (Ricarte-Filho et al. 2013).

The PAX8-PPARG and CREB3L2-PPARG fusions were previously identified in follicular thyroid cancer (Kroll et al. 2000, Lui et al. 2008). PAX8-PPARG rearrangement is predominantly identified in FTC and less often in FVPTC (Placzkowski et al. 2008). In adults, the PAX8-PPARG rearrangement occurs in up to 45–55% of FTC (Sahin et al. 2005, Castro et al. 2006), whereas the occurrence in follicular variant of PTC ranges from 0% to 35% (Zhu et al. 2003, Castro et al. 2006). In pediatric patients, the occurrence of PAX8-PPARG rearrangement was assessed only in one cohort of sporadic and radiation-exposed PTC patients. The authors did not find PAX8-PPARG in the sporadic group, whereas its prevalence was nearly 4% in the radiation-exposed group (Ricarte-Filho et al. 2013).

**BRAF** fusions have also been described in post-Chernobyl thyroid cancer, suggesting that this is a new mechanism of BRAF activation in human cancers (Ciampi et al. 2005, Ricarte-Filho et al. 2013). As far as we known, AGK-BRAF fusion was described in a tumor from one radiation-exposed PTC case who was 13 years old at surgery (Ricarte-Filho et al. 2013), while AKAP9-BRAF was identified in three tumors from radiation-exposed patients. Functional analyses revealed that both fusion oncogenes are able to activate the MAPK pathway. None of the pediatric sporadic PTC evaluated presented the AGK-BRAF fusion transcript (Ricarte-Filho et al. 2013).

**Is the expression of iodine uptake and metabolism proteins higher in pediatric DTC than in adults?**

It is well known that iodine uptake is a result of an active transport mechanism mediated by the sodium iodide symporter (NIS) protein, which is found in the basolateral membrane of thyroid follicular cells. It has served as an effective means for therapeutic doses of radioiodine to target and destroy cancer cells in which endogenous NIS is functionally expressed (Dadachova & Carrasco 2004). However, NIS-mediated radioiodine accumulation is often reduced in thyroid cancers due to decreased NIS expression/function (Liu et al. 2012, Xing 2013).

An important difference between pediatric and adult DTC is the high prevalence of functional metastases and the greater differentiation and radioiodine responsiveness in pediatric DTC. Accordingly, it has been suggested that the expression of NIS, as well as other proteins involved in iodine uptake and metabolism in pediatric patients, is higher than their expression in adults (Patel et al. 2002, Faggiano et al. 2004, Espadinha et al. 2009). Nonetheless, in some series, there is a higher prevalence of extrathyroidal extension, regional lymph node involvement and distant metastases in younger children than in adolescents (Alessandri et al. 2000, Jarzab et al. 2005, Dinauer et al. 2008, Lazar et al. 2009, O’Gorman et al. 2010, Rivkees et al. 2011, Vaisman et al. 2011, Francis et al. 2015). Therefore, one could postulate that the expression of NIS in children
is lower than its expression in adolescents and, therefore, treatment of pediatric DTC should be stratified into more than one group.

In fact, the hypothesis that DTC from pediatric patients usually has a higher expression of iodine-metabolizing genes than DTC from adults and older patients has little support in the available literature, especially for young children (<0 years old). Either younger children were commonly underrepresented and/or patients over the age of 18 years at diagnosis were also included into the pediatric group. Moreover, only two studies specifically addressed the expression of iodine-metabolizing genes in pediatric patients (Patel et al. 2002, Espadinha et al. 2009). The former study assessed the expression of NIS in the malignant tumor and compared to benign lesions as a substitute of normal thyroid. The authors did not find a significant difference between benign and malignant thyroid lesions (Patel et al. 2002). Because the overall recurrence risk was increased for those tumors that had undetectable NIS expression, the authors suggested that NIS expression is a favorable prognostic indicator for DTC in children and adolescents (Patel et al. 2002). Additionally, the authors studied patients up to 21 years of age and only two cases under the age of 10. No comparison was made between children and adolescents. The subsequent study suggested that the expression of PDS, TPO and TSHR mRNA is higher in the pediatric group compared to adult (22–59 years) and elderly patients (>60 years). Nevertheless, among the 15 pediatric patients, only three cases were under 10 years of age, and there was no specific information regarding the expression of iodine-metabolizing genes in these patients (Espadinha et al. 2009).

Finally, it has been suggested that overactivation of the MAPK pathway, mainly through BRAF V600E mutation, leads to tumor dedifferentiation and, hence, reduced expression of proteins involved in iodine uptake and metabolism in PTC of adults (Romei et al. 2008, The Cancer Genome Atlas Research Network 2014, Zhang et al. 2014). However, it is becoming clear that the BRAF V600E-mutated group consists of distinct subgroups with variable degrees of thyroid differentiation (The Cancer Genome Atlas Research Network 2014), which suggests that additional genetic events may be associated with dedifferentiation status of the thyroid.

Of note the prevalence of BRAF V600E mutation in pediatric PTC is much lower than the prevalence observed in adults (Figs 1 and 2). Whether other genetic alteration that activates the MAPK pathway may modulate the expression of NIS in pediatric groups is still uncertain.

Therefore, the data are unclear as to whether younger age indicates a greater risk for extensive disease or recurrence, and the hypothesis of a greater expression of genes such as NIS, TPO and other proteins associated with iodine metabolism in pediatric patients would be associated with greater radioiodine responsiveness and over-activation of the MAPK pathways needs further evaluation.

Future plans

After the identification of new driver genes that are altered in radiation-exposed pediatric PTC cases lacking known genetic events (RET/PTC, RAS, BRAF mutations, AKAP9-BRAF, TPR-NTRK1 and PAX8-PPARG), significantly reduced the so-called dark matter. Nearly 84% had fusion, most oncoproteins activate MAPK pathways, suggesting that pediatric PTC are also MAPK-driver cancer. Conversely, the prevalence of drive fusion oncogenes in sporadic pediatric PTC was much lower. Nearly 30% of cases are negative for the fusion events and/or point mutations found in radiation-induced pediatric cohort (Ricarte-Filho et al. 2013). As the risk factor to the development of sporadic pediatric thyroid carcinoma is not known and the landscape of sporadic pediatric cancer likely differs significantly from the landscape of the radiation-exposed pediatric cases, it is expected that sporadic cases might have higher prevalence of point mutations than radiation-induced pediatric thyroid carcinomas. Further in-depth genome analysis of sporadic pediatric thyroid carcinoma is necessary to address and clarify this issue. Furthermore, such analysis may also help define whether pediatric tumors from children and adolescents represent different molecular subgroups.

The use of molecular diagnostic testing in thyroid nodules became a reality and aims to improve the accurate diagnosis in cytologically indeterminate thyroid nodules and, consequently, to avoid unnecessary surgical procedures. Although the evaluation and treatment of thyroid nodules in children should be the same as in adults (Francis et al. 2015), the molecular tests that are available for indeterminate thyroid nodules have not been validated in the pediatric patients. Although two studies have suggested a molecular test might improve the diagnosis of an indeterminate cytology in pediatric patients (Monaco et al. 2012, Buryk et al. 2013), it is still uncertain its usefulness. Although positive results may be associated with malignancy, the insufficient data associated with the fact that the ‘dark matter’ of sporadic pediatric thyroid carcinomas has not yet been well
characterized that this is too early to rely on negative genetic tests to exclude malignancy. The in-depth genome analysis of the sporadic pediatric cases that had no known driver mutations will help define a panel of mutations/fusions that may be better applied to the diagnosis of pediatric thyroid nodules.

In conclusion, most of the efforts to determine the landscape of pediatric cases have been focused in radiation-exposed pediatric thyroid cancer, while most routine cases of thyroid nodules/cancer are indeed sporadic cases. As PTC is the most prevalent histological type of pediatric thyroid carcinoma, further efforts should be undertaken to define the genomic landscape of pediatric sporadic PTC.

Regarding treatment, although children with DTC have high rates of regional lymph node involvement and distant metastasis, the overall survival is good. Therefore, the extent of surgery and proper dose of ¹³¹I should be better defined based on the risk of recurrence. Whether molecular classification will help better classify pediatric thyroid carcinomas into subgroups and, therefore, refine diagnosis, prognosis and treatment, it is still a ‘dark matter.’

Supplementary data
This is linked to the online version of the paper at http://dx.doi.org/10.1530/ERC-15-0381.

Declaration of interest
There is no conflict of interest that could be perceived as prejudicing the impartiality of this review.

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