



**SAPIENZA**  
UNIVERSITÀ DI ROMA

# Utilizzo di scores multiparametrici nella caratterizzazione del rischio stimato di malignita' di noduli tiroidei sottoposti a citologia per ago sottile

**Dottorato di Ricerca in Tecnologie Biomediche in Medicina Clinica**

**XXXI Ciclo**

**Dott. Giorgio Grani**

**Matricola 939973**

Relatore

Prof. Cosimo Durante

A.A. 2017-2018

## Outline

Background.....	3
Thyroid ultrasonography .....	4
Cytology.....	9
Molecular testing.....	12
Aims .....	16
Sonographic evaluation .....	17
Methods .....	17
Definition of sonographic features and interobserver reliability.....	17
Prospective cohort enrollment.....	22
Pre-FNAB ultrasound examination of the nodules.....	23
Classification of nodules using five sonographic risk-stratification systems.....	23
Reference standard diagnosis .....	24
Results .....	25
Discussion .....	31
Molecular evaluation.....	33
Methods .....	33
Sample collection .....	33
Molecular Analysis through targeted Next-Generation Sequencing .....	33
Data analysis.....	34
Digital PCR quantification of microRNA.....	34
Reference standard .....	36
Results .....	37
Discussion .....	44
Conclusions.....	46
References.....	51

## Background

Thyroid nodules are defined as discrete lesions within the thyroid gland, radiologically distinct from surrounding thyroid parenchyma. Their diagnosis is increasingly frequent in clinical practice (Durante, et al. 2018).

With neck palpation, thyroid nodule prevalence in iodine sufficient populations has been estimated to about 5%, depending on age and sex (Mazzaferri 1993). Nowadays, however, clinicians are asked to manage a much higher rate of asymptomatic patients with “occult” thyroid nodules (up to 68% of the general population) (Guth, et al. 2009). This is largely due to the incidental discovery of asymptomatic nodules, mainly during diagnostic imaging test for other purposes (so-called “thyroid incidentalomas”). The prevalence is reported about 15% with computed tomography (CT) or magnetic resonance imaging (MRI), and 1-2% with 18-fluorodeoxyglucose (FDG) positron emission tomography (PET) (Russ, et al. 2014). The risk of malignancy in case of ultrasound (US), CT or MRI incidentalomas ranges between 5 and 13%, while in case of focal FDG uptake, the expected malignancy rate may increase up to 55% (Russ et al. 2014; Sharma, et al. 2015). Recognized risk factors for malignancy are head and neck and whole body irradiation (Aldrink, et al. 2016; Cahoon, et al. 2017), exposure to ionizing radiation from fallout in young age (Land, et al. 2015), hereditary syndromes that include thyroid cancer (e.g., multiple endocrine neoplasia syndrome type 2, familial adenomatous polyposis). Clinical features such as rapid nodule growth and hoarseness also increase the probability of malignancy (Haugen, et al. 2016).

The main clinical goal is the detection of the clinically relevant nodules (mainly those harboring a clinically significant malignancy) among their sizable number in the general population: in fact, the majority of nodules are benign, and so remain during long-term follow-up. Currently used diagnostic tools are: ultrasonography, cytology, and molecular testing.

## Thyroid ultrasonography

Thyroid sonography is the main tool used for initial cancer risk stratification of thyroid nodules. It is the preferred imaging modality: high frequency linear matrix probes (12 MHz) provide excellent image resolution, because the thyroid is a superficial gland, with its posterior border generally situated at less than 4 cm depth from the cutaneous surface. For this reason, if a thyroid nodule is incidentally detected on another radiologic study, a sonographic re-evaluation is suggested (Durante et al. 2018; Haugen et al. 2016). A complete diagnostic ultrasound examination should include description of the background thyroid parenchyma, nodule location and size (in 3 dimensions), and a survey of the cervical lymph nodes (AIUM 2013). Individual sonographic features may help stratifying the risk of malignancy of thyroid nodules, because some of them are associated with thyroid cancer (e.g. solid composition, hypoechogenicity, irregular margins, and microcalcifications) while others are more likely to indicate benignity (cystic content, “spongiform” appearance) (Brito, et al. 2014; Campanella, et al. 2014; Moon, et al. 2012). The cancer risk is also low (<5-10%) for solid noncalcified smoothly marginated nodules that are either iso- or hyperechoic (same or lighter greyscale imaging compared to normal thyroid) (Moon, et al. 2008).

The American Thyroid Association (ATA) (Haugen et al. 2016) and multiple other professional groups (Gharib, et al. 2016; Russ, et al. 2017; Shin, et al. 2016; Tessler, et al. 2017) have devised similar, even if not identical systems, aiming to classify nodules by patterns/combinations of sonographic features, according to their cancer risk, and then to recommend graduated size cut-offs for fine-needle aspiration biopsy (FNAB) (Table 1). Guidelines from endocrinology societies have generally focused on nodule pattern identification (Gharib et al. 2016; Haugen et al. 2016; Russ et al. 2017), accompanied by figures illustrating these patterns, with correlation of each pattern to an estimated cancer risk. Recently, the American College of Radiology (ACR) (Tessler et al. 2017) has recommended a point scale for systematic assessment of

imaging for thyroid nodules (TIRADS, Thyroid Imaging Reporting and Data System), similar to the approach used by radiologists for other organs. Points are assigned based upon 5 ultrasound features and the sum determines the TIRADS classification of the nodule, its estimated cancer risk, and recommendations for either FNAB or surveillance. Malignancy risk estimates based upon sonographic appearance is generally very similar among all 4 classification systems; however, there are some differences in FNAB recommended cutoff sizes.

The sonographic features included in each classification system tiers are listed in Table 1.

**Table 1. An overview of the standardized sonographic scoring systems proposed or endorsed by international practice guidelines for risk-based guidance in planning FNAB of thyroid nodules. Modified from (Durante et al. 2018)**

<b>AACE/ACE/AME</b> (Gharib et al. 2016)	<b>ATA</b> (Haugen et al. 2016)	<b>EU-TIRADS</b> (Russ et al. 2017)	<b>ACR TIRADS</b> (Tessler et al. 2017)	<b>K-TIRADS</b> (Shin et al. 2016)
<p><b>Low-risk</b> <i>Risk of malignancy 1%</i> <i>FNAB &gt;20 mm (selective)<sup>a</sup></i></p> <p>Cysts (fluid component &gt;80%). Mostly cystic nodules with reverberating artifacts and not associated with suspicious US signs. Isoechoic spongiform nodules, either confluent or with regular halo.</p>	<p><b>Benign</b> <i>Risk of malignancy &lt;1%</i> <i>FNAB is not indicated</i></p> <p>Purely cystic nodules (no solid component)</p>	<p><b>Benign (EU-TIRADS 2)</b> <i>Risk of malignancy ≈ 0%</i> <i>FNAB is not indicated</i></p> <p>Pure, anechoic cysts; Entirely spongiform nodules</p>	<p><b>TR1 Benign</b> <i>Risk of malignancy 2%</i> <i>FNAB is not indicated</i></p> <p>Spongiform Pure cyst</p> <p><b>TR2 Not suspicious</b> <i>Risk of malignancy 2%</i> <i>FNAB is not indicated</i></p> <p>Mixed cystic or solid noncalcified nodules with smooth margins and oval shape</p>	<p><b>Benign</b> <i>ROM &lt;1-3%</i> <i>FNAB ≥20 mm</i></p> <p>Spongiform Partially cystic nodule with comet-tail artifact Pure cyst</p>
	<p><b>Very low suspicion</b> <i>Risk of malignancy &lt;3%</i> <i>FNAB ≥20 mm or observation</i></p> <p>Spongiform or partially cystic nodules without any of the US features defining low-, intermediate- or high-suspicion patterns</p>	<p><b>Low-Risk (EU-TIRADS 3)</b> <i>Risk of malignancy 2-4%</i> <i>FNAB &gt;20 mm</i></p> <p>Oval shape, smooth margins, isoechoic or hyperechoic, without any feature of high risk</p>	<p><b>TR3 Mildly suspicious</b> <i>Risk of malignancy 3%</i> <i>FNAB ≥25mm</i></p> <p>Isoechoic solid or hypoechoic cystic noncalcified nodules with smooth margins and oval shape</p>	<p><b>Low suspicion</b> <i>ROM 3-15%</i> <i>FNAB ≥ 15 mm</i></p> <p>Partially cystic or isohyperechoic nodule without any of 3 suspicious US features</p>
	<p><b>Low suspicion</b> <i>Risk of malignancy 5-10%</i> <i>FNAB ≥15 mm</i></p>			

	Isoechoic or hyperechoic solid nodule, or partially cystic nodule with eccentric solid area <u>without</u> : microcalcifications, irregular margin, extrathyroidal extension, taller than wide shape.			
<p><b>Intermediate-risk</b> Risk of malignancy 5-15% FNAB: &gt;20mm</p> <p>Slightly hypoechoic (vs. thyroid tissue) or isoechoic nodules, with ovoid-to-round shape, smooth or ill-defined margins May be present:</p> <ul style="list-style-type: none"> <li>• Intranodular vascularization</li> <li>• Elevated stiffness at elastography,</li> <li>• Macro or continuous rim calcifications</li> <li>• Indeterminate hyperechoic spots</li> </ul>	<p><b>Intermediate suspicion</b> Risk of malignancy 10-20% FNAB ≥10 mm</p> <p>Hypoechoic solid nodule with smooth margins <u>without</u>: microcalcifications, extrathyroidal extension or taller than wide shape</p>	<p><b>Intermediate-Risk (EU-TIRADS 4)</b> Risk of malignancy 6-17% FNAB &gt;15 mm</p> <p>Oval shape, smooth margins, mildly hypoechoic, without any feature of high risk</p>	<p><b>TR4 Moderately Suspicious</b> Risk of malignancy 5-20% FNAB &gt;15mm</p> <p>Hypoechoic solid noncalcified nodules with oval shape and either smooth or irregular or lobulated margins</p> <p>Isoechoic solid or mixed noncalcified nodules with either nonparallel orientation (taller than wide) or punctate echogenic foci</p>	<p><b>Intermediate suspicion</b> ROM 15–50% FNAB ≥10 mm</p> <p>Solid hypoechoic nodule without any suspicious US feature or partially cystic or isohyperechoic nodule with any of the following: microcalcification, nonparallel orientation (taller-than-wide), spiculated/microlobulated margin</p>
<p><b>High-risk</b> Risk of malignancy 50-90%<sup>b</sup> FNAB ≥10 mm (5 mm, selective<sup>c</sup>) Nodules with <u>≥1</u> of the following:</p> <ul style="list-style-type: none"> <li>• Marked hypoechoogenicity (vs. prethyroid muscles)</li> </ul>	<p><b>High suspicion</b> Risk of malignancy &gt;70-90% FNAB ≥10 mm</p> <p>Solid hypoechoic nodule or solid hypoechoic component of partially cystic nodule <u>with</u> <u>≥1</u> of the following:</p>	<p><b>High-Risk (EU-TIRADS 5)</b> Risk of malignancy 26-87% FNAB &gt;10 mm</p> <p>Nodules <u>with</u> <u>≥1</u> of the following:</p> <ul style="list-style-type: none"> <li>• Non-oval shape</li> <li>• Irregular margins</li> <li>• Microcalcifications</li> <li>• Marked hypoechoogenicity</li> </ul>	<p><b>TR5 Suspicious</b> Risk of malignancy “at least 20%” FNAB &gt;10mm</p> <p>Hypoechoic solid nodule with any of the following:</p> <ul style="list-style-type: none"> <li>• Nonparallel orientation (taller-than-wide)</li> </ul>	<p><b>High suspicion</b> ROM &gt;60% FNAB ≥10 mm (&gt;5 mm, selective<sup>d</sup>) Solid hypoechoic nodule with any of the following:</p> <ul style="list-style-type: none"> <li>• Microcalcification</li> <li>• Nonparallel orientation (taller-than-wide)</li> </ul>

<ul style="list-style-type: none"> <li>• Spiculated or lobulated margins</li> <li>• Microcalcifications</li> <li>• Taller-than-wide shape (AP&gt;TR)</li> <li>• Extrathyroidal growth</li> <li>• Pathologic adenopathy</li> </ul>	<ul style="list-style-type: none"> <li>• Irregular margins (infiltrative, microlobulated)</li> <li>• Microcalcifications</li> <li>• Taller than wide shape</li> <li>• Rim calcifications with small extrusive soft tissue</li> <li>• Extrathyroidal extension</li> </ul>		<ul style="list-style-type: none"> <li>• Extrathyroidal extension</li> <li>• Punctate echogenic foci</li> </ul> <p>Isoechoic solid nodule with irregular or lobulated margins and either peripheral rim calcifications or punctate echogenic foci</p>	<ul style="list-style-type: none"> <li>• Spiculated/microlobulated margin</li> </ul>
---	--	--	---	--

Abbreviations. AACE/ACE/AME: American Association of Clinical Endocrinologists, American College of Endocrinology, and Associazione Medici Endocrinologi; ACR: American College of Radiologists; ATA: American Thyroid Association. EU-TIRADS: European Thyroid Imaging Reporting and Data System; FNAB: fine-needle aspiration; TR: American College of Radiologists Thyroid Imaging Reporting and Data System. FNAB indicates the size above which a fine-needle aspiration cytology is recommended.

<sup>a</sup> Growing nodule, high-risk history, before surgery or local therapies.

<sup>b</sup> In accordance with the presence of 1 or more suspicious findings.

<sup>c</sup> FNAB is recommended for smaller nodules in the following cases: subcapsular or paratracheal lesions; suspicious lymph nodes or extrathyroid spread; personal or family history of thyroid cancer; history of head and neck irradiation; coexistent suspicious clinical findings (e.g., dysphonia).

## Cytology

Cytology usually provides the most definitive diagnostic information for the evaluation of thyroid nodules (Haugen et al. 2016). FNAB is simple, safe, and reliable, and is usually performed under ultrasound guidance. In the United States and much of the world, thyroid cytologic results reporting is stratified using the Bethesda classification system which provides six diagnostic categories (Table 2). An updated version of the Bethesda system was recently published including minor changes in the nomenclature and the revision of the estimated malignancy risk for each class (Baloch, et al. 2017; Pusztaszeri, et al. 2016). Category 1 is "nondiagnostic" or "insufficient", category 2 is "benign", and categories 5 and 6 are "suspicious for malignancy" and "malignant", respectively. Despite interobserver differences in cytologic interpretation (Cibas, et al. 2013), Bethesda categories 2, 5, and 6 provide high enough predictive values for definite clinical decisions. However, categories 3, and 4, comprising about 20-30% of all biopsies, are "indeterminate" or "suspicious" readings, and usually require additional evaluation. In the U.S., the dominant strategy is the avoidance of surgery, because the majority of nodules in these three categories are benign (Bongiovanni, et al. 2012; Strickland, et al. 2015).

The revised version of the Italian Consensus for Reporting Thyroid Cytopathology published in 2014 (Nardi, et al. 2014), is a six-tiered system almost comparable to the Bethesda system. The original TIR3 category was splitted in two subcategories: TIR3A, which comprises specimens with increased cellularity with follicular pattern, or oxyphilic cells, is similar to the Bethesda category 3, while TIR3B resembles Bethesda category 4 and includes lesions with high cellularity characterized by a repetitive microfollicular or trabecular pattern but also those with mild-focal nuclear alterations suggestive of papillary carcinoma.

**Table 2. Bethesda System and Italian Consensus for Reporting Thyroid Cytopathology**

**synopsis: estimated risk of malignancy and suggestions for clinical management.**

<b>The Bethesda System for Reporting Thyroid Cytopathology (Cibas and Ali 2017)</b>	<b>Risk of malignancy (%)</b>	<b>The Italian Consensus for Reporting Thyroid Cytopathology</b>	<b>Usual management</b> (other factors may influence management)
Nondiagnostic or Unsatisfactory  Cyst fluid only  Virtually acellular specimen  Obscuring blood, artifacts.	0-5  (risk of malignancy varies with the type/structure of the nodule)	TIR 1 (Nondiagnostic)	Repeat FNAB with ultrasound guidance
Benign  Benign follicular nodule (e.g., adenomatoid nodule, colloid nodule)  Chronic lymphocytic (Hashimoto) thyroiditis  Granulomatous (subacute) thyroiditis	0–3 <sup>a</sup>	TIR 2 (benign)	Clinical and sonographic follow-up
Atypia of Undetermined Significance or Follicular Lesion of Undetermined Significance	~10–30 <sup>b</sup>	TIR 3A (low-risk indeterminate lesion)  <i>[estimated risk &lt;10%; published data 17%]</i>	Repeat FNAB, molecular testing, or lobectomy
Follicular Neoplasm or Suspicious for a Follicular Neoplasm <sup>f</sup>  Specify if oncocytic (Hürthle cell) type	25-40 <sup>c</sup>	TIR 3B (high-risk indeterminate lesion)  <i>[estimated risk 15-30%; published data 47%]</i>	Molecular testing, lobectomy
Suspicious for Malignancy  Suspicious for papillary thyroid carcinoma	50–75	TIR4 (suspicious for malignancy)	Near-total thyroidectomy or lobectomy  <i>Some studies have recommended molecular</i>

<p>Suspicious for medullary thyroid carcinoma</p> <p>Suspicious for metastatic carcinoma</p> <p>Suspicious for lymphoma</p>			<p><i>analysis to assess the type of surgical procedure (lobectomy vs. total thyroidectomy).</i></p>
<p>Malignant</p> <p>Papillary thyroid carcinoma</p> <p>Poorly differentiated carcinoma</p> <p>Medullary thyroid carcinoma</p> <p>Undifferentiated (anaplastic) carcinoma</p> <p>Squamous cell carcinoma</p> <p>Carcinoma with mixed features</p>	97–99	TIR 5 (malignant)	<p>Near-total thyroidectomy</p> <p><i>(surgery may not be indicated in case of metastatic tumors; lobectomy is appropriate for papillary thyroid cancers &lt; 4 cm without other high-risk features)</i></p>

a) Estimate extrapolated from studies showing correlation between biopsied nodule and surgical pathology follow-up.

b) Estimates extrapolated from histopathologic data from large case cohorts (including repeat atypical FNAs) and meta-analysis of the post 2007 literature

c) Estimates extrapolated from histopathologic data from large case cohorts and meta-analysis of the post 2007 literature

d) The measured malignancy rates for the Italian Consensus indeterminate cytology reports were derived by two recent systematic reviews and meta-analyses (Trimboli, et al. 2018a; Trimboli, et al. 2018b)

## Molecular testing

Over the last years, our knowledge of the genetic mechanisms of thyroid cancer has expanded dramatically. A recent study from the Cancer Genome Atlas (Cancer Genome Atlas Research Network 2014) provided comprehensive genetic characterization of papillary thyroid carcinoma (PTC), the most common type of thyroid cancer, identified two main classes of PTC, the “*BRAF* V600E-like” and “RAS-like,” each with its own biologic and clinical characteristics. The first class is characterized by classic papillary or tall-cell histology and reduced expression of differentiation markers such as thyroglobulin, thyroid peroxidase, and Na/I symporter; the second one is driven by RAS and similar mutations and gene fusions and characterized by follicular morphology and preserved expression of differentiation markers (Nikiforov 2017). Furthermore, novel genomic data were published about follicular thyroid cancer (Fagin and Wells 2016), Hürthle cell carcinoma (Ganly, et al. 2018), poorly differentiated, and anaplastic thyroid cancer (Landa, et al. 2016). Mutations occur principally in genes coding for proteins in the MAP kinase pathway that regulates cellular proliferation and differentiation. A mutation in the *BRAF* gene (V600E) is found in approximately 40% of PTC, as well as in some poorly differentiated and anaplastic cancers arising from PTC (Nikiforova, et al. 2003). Mutations in the RAS gene family are found in some PTC (usually follicular variant), follicular thyroid cancers, in benign follicular adenomas, as well as in NIFTP. The *RET/PTC* fusion gene, in which the *RET* gene is fused with the *PTC* gene is associated with radiation-related PTC, while another fusion gene (between the *PAX8* and the *PPAR $\gamma$*  gene) is seen in some follicular thyroid cancers, in some follicular adenomas, and in follicular variant PTC. Mutations in *TERT* and *TP53* tumor suppressor genes have also been observed in some thyroid cancers and confer aggressive behavior.

This knowledge provides the basis for clinical use of molecular markers in diagnosis and individualized management of patients with thyroid nodules. Molecular testing of FNAB specimens is now a popular (Burch, et al. 2016) and potentially practice changing approach (Duick, et al.

2012) to the issue of cytologically indeterminate nodules. The two most popular molecular testing strategies are “*mutational analysis*” and “*gene expression analysis*”, in which genetic information is can be derived from the same material obtained in the original FNAB sample. **Mutational analysis** involves isolating DNA from thyroid follicular cells in the specimen and performing gene sequencing, focusing on possible mutations in relevant genes, as well for the presence of fusion genes (Nikiforov 2017). Mutational testing has been initially considered as “rule in test”, since if a known drive mutation is found, or if fusion genes are present, thyroid cancer is almost always present (Eszlinger, et al. 2017). However, mutations in *RAS* genes are seen in the full spectrum of thyroid pathology, from non-malignant thyroid neoplasms (adenomas) to invasive cancers and have less diagnostic utility. Furthermore, if no mutations are found, a thyroid malignancy with a mutation that was not assessed could still be present, and therefore mutational testing may lead to both false negative and false positive results (the latter especially if *RAS* and *RAS*-like mutations are found).

In a single institution study of 239 patients with Bethesda category 3 and 4 cytology, the mutational testing strategy (with an expanded number of genes tested; ThyroSeq v.2), yielded a negative predictive value (NPV) when a mutation was not found of about 96%, and a positive predictive value (PPV) of approximately 80%.(Nikiforov, et al. 2015) In a second single institution study of 182 patients with 190 Bethesda category 3 and 4 cytologies, the NPV was 91% (82-97%) and the PPV was 42% (25-61%).(Valderrabano, et al. 2017) A new version of ThyroSeq (v.3), including additional mutations and fusions, was developed and assessed in a multicenter trial (Steward, et al. 2018): it demonstrated a 94% (95% CI, 86%-98%) sensitivity and 82% (95% CI, 75%-87%) specificity in Bethesda III and IV nodules combined, with a NPV of 97% and a PPV of 66%.

The second type of molecular testing, “*gene expression analysis*” or “*gene expression classifier*” (GEC) uses a proprietary algorithm (derived by machine learning protocols) to analyze the expression of specific genes in a 142-gene panel. Nodules are classified as “benign” or “suspicious”, and the test is designed to be a “rule out test” with high NPV. In a pooled analysis of

12 studies involving 1303 nodules, the NPV ranged from 87-96% (95% CI) with a malignancy prevalence rate varying from 29-34%.(Al-Qurayshi, et al. 2017) The GEC has a low positive predictive value, with a risk of malignancy in the range of 30-50% in the context of a "suspicious" GEC result. (Alexander, et al. 2012) The first version of this test is no longer available: a newer version (called *Genomic Sequencing Classifier*, including multiple new components), has a higher specificity (sensitivity of 91% and a specificity of 68%), resulting in a higher positive predictive value (PPV 47%), with a stable NPV of 96% (Patel, et al. 2018).

MicroRNA (miRNA) analysis is a more recent methodology for molecular testing for which there are more limited data (Lithwick-Yanai, et al. 2017) but may prove to be useful in diagnostic decision making. Two commercial diagnostic tests use miRNAs: ThyGenX/ThyraMIR is a combination of a 7-gene mutation panel and a panel of 10 miRNA markers (ThyraMIR), with a combined NPV of 94% and PPV of 74%) (Labourier, et al. 2015), and Rosetta GX Reveal test, based on a panel of 24 miRNA, no more on the market.

Molecular testing is expensive: about \$3000-5000 per test in the United States, depending on the specific testing strategy (Nishino 2016); so, it is unaffordable in many parts of the world. Some studies suggest that molecular testing is cost-effective (Labourier 2016; Lee, et al. 2014; Yip, et al. 2012) since it decreases the number of diagnostic surgeries, and complications, when the test results are benign. However, the results vary depending on the test performance parameters, malignancy rates in the patient population, the health-care setting, among other factors (Eszlinger et al. 2017).

**Table 3: Current commercially available molecular tests, with their main validation study**

	<b>ThyroSeq GC</b>	<b>Afirma GEC</b>	<b>Afirma GSC</b>
	Steward, et al. 2018	Alexander et al. 2012	(Patel et al. 2018)
<b>Study Type</b>	Multicenter, prospective, double-blind	Multicenter, prospective, double-blind	Multicenter, retrospective, double-blind
<b>Nodules</b>	257	210	191
<b>Cancer prevalence</b>	27.5	24.3	23.7
<b>Sensitivity</b>	94.1	90.2	91.2
<b>Specificity</b>	81.6	51.6	68.3
<b>NPV</b>	97.3	94.3	96.1
<b>PPV</b>	65.9	37.4	47.1
<b>Benign call rate</b>	61	41	54
<b>Avoidable surgeries</b>	82	52	68

## Aims

Multiple sonographic systems and molecular tests are now available to guide physicians in the management of thyroid nodules. Independent validation studies for sonographic systems were typically small and demonstrated inconsistencies between the results of different groups. Molecular tests are expensive, currently not commercially available in Italy, and the results of validation studies were usually not replicated in real clinical practice.

The aims of the present project were to:

1. Prospectively validate current sonographic classification systems for the risk evaluation of thyroid nodules;
2. Propose a molecular test strategy for risk refinement in case of indeterminate cytology;
3. Propose an integrated workflow to manage thyroid nodules using sonographic, cytological and molecular data.

## Sonographic evaluation

### Methods

#### Definition of sonographic features and interobserver reliability

First of all, a literature review was performed to retrieve all the sonographic features predictive of malignancy and included in the sonographic classification systems recommendations already available at the time (Grant, et al. 2015; Horvath, et al. 2009; Kwak, et al. 2011; Kwak, et al. 2013; Mohammadi and Hajizadeh 2013; Ozel, et al. 2012; Park, et al. 2009; Russ, et al. 2013; Seo, et al. 2015; Su, et al. 2014). A standardized rating form was designed (**Box 1**) and an electronic database for data collection was developed.

**Box 1: Standardized rating form for sonographic features (an electronic version was used for consistent data collection).**

- Thyroiditis US pattern

**Diameters (mm)** \_\_\_\_\_ x \_\_\_\_\_ x \_\_\_\_\_ [**transverse, anteroposterior, longitudinal**]

- Taller-than-wide (yes/no)

#### **Margins**

- Sharp
- Irregular/Microlobulated
- Ill-defined
- Infiltrating
- Hypoechoogenic halo

#### **Suspected extrathyroidal extension**

- No
- Yes

#### **Internal architecture**

- Cystic nodule
- Solid nodule
- Mixed nodule
  - Spongiform nodule
  - Solid component

- Nodular solid component
  - Eccentric
  - Central
- Non-nodular
- Septate cyst

### Echogenicity

- isoechogenic
- hypoechogenic
- markedly hypoechogenic
- hyperechogenic
- anechogenic

### Hyperechoic foci

- “comet-tail-artifact” foci
- indeterminate foci

### Calcifications

- Microcalcifications ( $\leq 2$  mm, with acoustic shadowing)
- Macrocalcifications (including eggshell calcifications)

### Homogeneity

- homogeneous
- inhomogeneous

### Vascularity

- (1) None detectable
- (2) Peripheral only
- (3) Central only or central and peripheral
  
- **Suspicious lymph nodes**

The definitions of the various sonographic features were based on the current literature and preliminarily shared between the examiners, to ensure consistency (Table 4).

**Table 4: definitions of the various sonographic features**

Feature	Options	Definition
<b>Composition</b>	Solid	almost entirely composed of solid tissue
	Mixed	both cystic and solid portions are present
	Cystic	completely or almost completely anechoic nodule
<b>Spongiform</b>		Small cysts representing at least 50% of the nodule volume
<b>Echogenicity</b>	Marked hypoechogenicity	Hypoechoic relative to adjacent strap muscle
	Mild hypoechogenicity	Hypoechoic relative to thyroid parenchyma

	Isoechogenicity	Same echogenicity of thyroid parenchyma
	Hyperechogenicity	Hyperechoic relative to thyroid parenchyma
<b>Shape</b>	Wider-than-tall	Anteroposterior diameter equal or less than the transverse one
	Taller-than-wide	Anteroposterior diameter greater than the transverse one
<b>Margin</b>	Sharp	Clearly discernible smooth edge
	Irregular/microlobulated	Spiculation, microlobulation, or jagged appearance
	Infiltrative	Digitative soft tissue protrusions into the surrounding tissue
	Ill-defined	Poorly demarcated margin which cannot be clearly distinguished by the surrounding tissue
	Halo	Thin or thick hypoechoic rim surrounding nodule (not described if irregular, microlobulated or infiltrative)
<b>Calcification</b>	Absent	
	Microcalcification	Echogenic foci of 2 mm or less with or without posterior acoustic shadowing within solid portion
	Macrocalcification	Echogenic foci of more than 2 mm with posterior acoustic shadowing, including eggshell calcifications
<b>Other echogenic foci</b>	Absent	
	Comet-tail artifact	Echogenic foci with reverberation artifacts within cystic component
	Indeterminate	Small echogenic foci without acoustic shadowing nor reverberation; small linear foci, including areas of fibrosis
<b>Extrathyroidal extension</b>	No	
	Suspicious	loss of the echogenic thyroid border, abutment, or contour bulging

However, because interobserver variability has been documented during assessments of the single sonographic features of thyroid nodules (Grani, et al. 2015), we preliminarily performed an internal assessment of variability between the two examiners actually involved. We conducted a retrospective analysis of 1055 ultrasound images of thyroid nodules identified in 265 patients (each with less than four nodules). All had originally been classified as benign (those with suspicious US features but benign cytology) or presumably benign (nodules with no suspicious ultrasound features) and managed with active surveillance as long as there was no evidence of malignancy. The images had been acquired in our center at the time of nodule detection and/or during the first

five years thereafter and stored in order to precisely document the main nodule features over time. For the purposes of this analysis, the images of the 1055 nodules (at various follow-up points) were converted to and stored as deidentified bitmap files. The blinded files were then randomly divided into two groups: set 1 (501 nodules) and set 2 (554 nodules).

The selected of each nodule in set 1 was independently reviewed on a single liquid crystal display monitor by two clinicians, each with 6 years of experience in thyroid US imaging, but trained in two different thyroid units. The readers were blinded to the identity of the patient, the date of the scan, and all other clinical information regarding the case. Using the standard form (Box 1) the two readers rated the various US features of each nodule. For each nodule, the ratings of each reader were used to classify the nodule according to the following five systems: American Association of Clinical Endocrinologists/American College of Endocrinology/Associazione Medici Endocrinologi (AACE/ACE/AME); the TIRADS system developed by the American College of Radiologists (ACR); the 2015 ATA Guidelines; the EU-TIRADS system proposed by the European Thyroid Association; and the Korean Society of Thyroid Radiology's K-TIRADS system.

Two weeks after their independent reviews and classification of set 1 images, the two readers jointly reviewed the results and the images of all 501 nodules. Discrepancies between their ratings were discussed and a consensus decision reached for each nodule feature. Four weeks after completion of the training session, the two readers were asked to independently review US images of the 554 nodules of set 2, repeating the above procedure.

For each set of nodules, inter-reader agreement was calculated for single features of the nodule, risk-class assignment based on each of the five US classification system, and the indication of FNAB biopsy based on the risk-class assignments. Agreement on ordinal ratings was assessed with the Krippendorff  $\alpha$  statistic (Hayes and Krippendorff 2007). Values close to 1 indicate high inter-reader agreement, and values above 0.65 are considered an acceptable basis for tentative conclusions. Interobserver agreement on nominal, dichotomic ratings was evaluated using Cohen's kappa statistic. Values less than 0.20 are considered indicative of slight agreement; 0.21 to 0.40, fair

agreement; 0.41 to 0.60, moderate agreement; 0.61 to 0.80, substantial agreement; and 0.81 to 1.00, near-perfect agreement (Landis and Koch 1977).

Table 5 shows the interobserver agreement for the recognition of single US features in Set 1 and Set 2. The agreement improved after the set 1 training and discussion session.

**Table 5: Interobserver agreement for the recognition of single US features** Krippendorff alpha (95% confidence intervals)

	<b>Set #1</b>	<b>Set #2</b>
<i>Nodules</i>	501	554
<b>Echogenicity</b>	0.56 (0.46-0.66)	0.66 (0.59-0.73)
<b>Composition</b>	0.52 (0.34-0.68)	0.5 (0.29-0.68)
<b>Margin</b>	0.51 (0.43-0.58)	0.44 (0.34-0.53)
<b>Calcification</b>	0.8 (0.63-0.93)	0.89 (0.75-1)
<b>Micro-</b>	0.49 (-0.28-1)	0.39 (-0.49-1)
<b>Macro-</b>	0.85 (0.59-1)	0.83 (0.6-1)
<b>Echogenic foci</b>	0.48 (0.3-0.64)	0.35 (0.17-0.52)
<b>Capsule invasion</b>	0.11 (-0.91-1)	0.4 (-1-1)

Table 6 summarizes the data on interobserver agreement nodule risk classification for the five reporting systems tested, and the agreement in the identification of nodules that required FNAB biopsy.

**Table 6. Inter-observer agreement for nodule classification and on indications for FNAB biopsy according to five sonographic classification systems endorsed by scientific societies.**

	Nodule classification <sup>a</sup>		Indication to biopsy <sup>b</sup>	
	Set 1	Set 2	Set 1	Set 2
	(n=501)	(n=554)	(n=501)	(n=554)
<b>AACE/ACE/AME</b>	0.47 (0.35-0.57)	0.61 (0.49-0.72)	0.73 (0.64-0.82)	0.82 (0.75-0.89)
<b>ACR TIRADS</b>	0.49 (0.4-0.57)	0.57 (0.5-0.63)	0.61 (0.5-0.72)	0.73 (0.63-0.82)
<b>ATA</b>	0.49 (0.41-0.57)	0.65 (0.58-0.71)	0.75 (0.67-0.82)	0.82 (0.75-0.89)
<b>EU-TIRADS</b>	0.61 (0.54-0.68)	0.75 (0.69-0.81)	0.68 (0.58-0.79)	0.74 (0.65-0.83)
<b>K-TIRADS</b>	0.53 (0.43-0.62)	0.66 (0.57-0.73)	0.82 (0.76-0.88)	0.91 (0.86-0.95)

a) Krippendorff alpha (95% confidence intervals)

b) Cohen kappa (95% confidence intervals)

On the whole, classification of thyroid nodules using sonographic classification systems produces an higher inter-observer agreement than classification based on single suspicious features. More importantly, identification of nodules that require FNAB biopsy based on these classification systems is associated with substantial to near-perfect agreement. However, there is clearly room for further improvement. Given these results (Grani, et al. 2018b), judgments for the prospective cohort were made jointly in an effort to improve consistency and reliability.

#### Prospective cohort enrollment

All patients consecutively referred to the unit for FNAB cytology of a thyroid nodule between November 1, 2015 and September 10, 2018 were eligible for enrollment. The referring

physicians included primary care physicians and secondary health-care providers (e.g., endocrinologists, surgeons, otolaryngologists, nuclear medicine specialists). The study was conducted with institutional review board approval and written informed patient consent. A first subset of the results has already been published (Grani, et al. 2018a).

#### Pre-FNAB ultrasound examination of the nodules

Prior to each biopsy, each nodule was carefully examined with a HI VISION Avius® ultrasound system (Hitachi Medical Corporation, Inc., Tokyo, Japan) and a 13-MHz linear-array transducer. During this examination, two clinicians experienced in thyroid sonography recorded their consensus judgement on the sonographic features of each nodule on the previously described and internally-developed standardized rating form (**Box 1**) (Grani, et al. 2017)

#### Classification of nodules using five sonographic risk-stratification systems

For each nodule, the consensus ratings of each ultrasound feature were used to classify the risk of malignancy according to five widely used ultrasound risk-stratification systems (Table 1), those published by the AACE/ACE/AME (Gharib et al. 2016); the American College of Radiologists (ACR-TIRADS) (Tessler et al. 2017); the ATA (Haugen et al. 2016); the European Thyroid Association (EU-TIRADS) (Russ, et al. 2017); and the K-TIRADS (Shin, et al. 2016). Since none of these systems routinely recommends the FNAB of sub-centimeter thyroid nodules, the nodules with a maximum diameter less than 1 cm were excluded. Using each system, we identified the nodules for which FNAB was suggested based on the size threshold for the assigned risk class. For this study, nodules that could not be classified according to the ATA Guidelines (e.g. isoechoic nodules with other suspicious features like microcalcification, irregular margins, and

taller-than-wide shape) were considered intermediate-suspicion nodules, since their risk of malignancy is similar (Rosario, et al. 2017; Yoon, et al. 2016).

#### Reference standard diagnosis

The biopsies were done under ultrasound guidance using 23-25-gauge needles. The non-aspiration technique was used in most cases (1-4 needle passes). Direct smears of each specimen were analyzed by experienced thyroid cytopathologists and classified according to the criteria published in the Italian Consensus for Thyroid Cytopathology (Fadda, et al. 2010; Nardi et al. 2014) (Table 2). If surgery had been performed, the reference standard diagnosis was based on histological examination of the resected nodule. If the nodule had been managed non-surgically, the reference standard was FNAB cytology: nodules were considered malignant if they had been classified as TIR4 or TIR5 (suspected malignancy or malignancy), and *benign* if they had been classified as TIR2. Nodules without histologic diagnoses that had been cytologically classified as non-diagnostic, TIR3A, or TIR3B (indeterminate) were excluded from the final analysis, unless a repeat FNAB had yielded conclusive results.

#### Statistical analysis

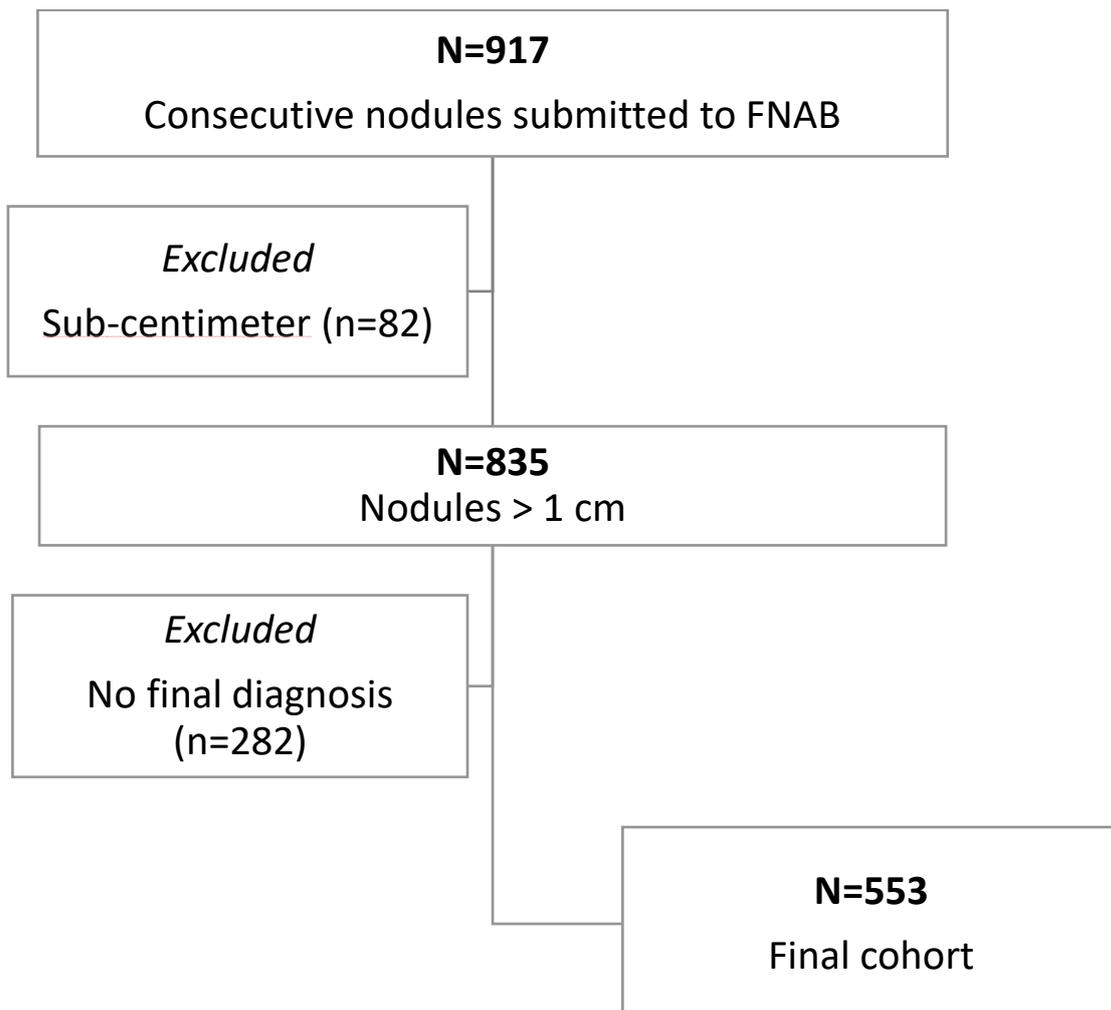
For each classification system, we calculated the number of nodules that did (or did not) meet the criteria for FNAB (test positivity and test negativity, respectively). The sonographic recommendation regarding FNAB was then compared with the reference-standard diagnosis to estimate sensitivity, specificity, PPV, NPV, area under the receiver operating characteristics curve (AUROC), and diagnostic odds ratios (DOR), each with 95% confidence intervals (CIs). The proportions of biopsies that would have spared by the various systems were compared using the McNemar test, and the reliability of these indications was assessed by calculation of the NPV and

FNR. Data were analyzed with the IBM SPSS Statistics package, version 25.0 (IBM Corp., Armonk, NY, US).

## Results

As shown in Figure 1, a total of 917 nodules were sonographically evaluated prior to cytology. The examination identified 82 subcentimeter nodules, which were excluded from our analysis because FNAB is not routinely indicated by international guidelines for nodules smaller than 1 cm. Of the 835 nodules measuring at least 1 cm, 282 were also excluded because their reference-standard diagnosis was inconclusive. The final cohort included 553 nodules, of which 42 (7.6%) were classified as malignant (Tables 7-8), from 524 patients (Table 9).

**Figure 1: Flow-chart of the enrollment of the prospective cohort**



**Table 7. Sonographic features of the 553 nodules included in the final cohort**

		<b>mean±SD</b>	
<b>Diameters (mm)</b>	Anteroposterior	13.59±6.58	
	Transverse	17.32±8.33	
	Longitudinal	22.04±10.09	
	Maximum diameter	22.30±10.06	
		<b>N</b>	<b>%</b>
<b>Location (lobe)</b>	Right	229	41.4
	Left	281	50.8
	Isthmus	43	7.8
<b>Single nodule</b>		177	32.0
<b>Margins</b>	Regular	188	34.0
	Ill-defined	67	12.1
	Irregular/lobulated	34	6.1
	Infiltrating	3	0.5
	Halo	261	47.2
<b>Extrathyroidal extension</b>	Suspicion	5	0.9
<b>Composition</b>	Mostly cystic	8	1.4
	solid	185	33.5
	Mixed	371	65.1
	<i>of which, spongiform</i>	13	2.4
<b>Echogenicity (of the solid component, if any)</b>	Anechoic	3	0.5
	Hyperechoic	2	0.4
	Isoechoic	407	73.6
	Hypoechoic	125	22.6
	Markedly hypoechoic	16	2.9
<b>Echogenic foci</b>	Comet-tail	25	4.5
	Indeterminate	105	19.0
<b>Calcifications</b>	Macrocalcifications	80	14.5
	Microcalcifications	42	7.6
<b>Shape</b>	Taller than wide	94	17.0
<b>Suspicious lymph nodes</b>	Yes	7	1.3

**Table 8. Cytological report of the 553 nodules included in the final cohort**

<b>Italian consensus for reporting thyroid cytology class</b>	TIR 1	1	0.2
	TIR 2	495	89.5
	TIR 3A	9	1.6
	TIR 3B	20	3.6
	TIR 4	13	2.4
	TIR 5	15	2.7

**Table 9. Clinical features of the 524 patients enrolled in the final cohort**

Age	years, median (IQR)	56 (46-67)	
		N	%
<b>Gender</b>	Male	127	24.2
	Female	397	75.8
<b>Chronic thyroiditis</b>	Clinical	35	6.7
	Sonographic appearance	33	6.3
<b>Family history of cancer</b>	Not reported	458	87.4
	Differentiated thyroid cancer	39	7.4
	Colorectal cancer	2	0.4
	Breast cancer	3	0.6
	Prostate cancer	2	0.4
	Lung cancer	5	1.0
	Others	15	2.9
	<b>Personal history of cancer</b>	Not reported	488
Colorectal cancer	3	0.6	
Breast cancer	15	2.9	
Prostate cancer	1	0.2	
Lung cancer	2	0.4	
Others	15	2.9	

Strict application of the five ultrasound systems would have appreciably reduced the number of FNAs performed (**Table 10**). The percentages of avoidable biopsies varied widely (from 16.6% to 51.9%). The most effective system in this cohort was the ACR TIRADS, which would have spared over half the biopsies performed (287, 51.9%), with a false-negative rate of only 2.8% (NPV 97.2%; 95% CI 94.6–98.8%). Except for K-TIRADS, the discriminatory capacities of the systems (as reflected by their AUROC and DOR; Table 11, Figure 2) were similar to that of the ACR TIRADS, but their impact on the number of procedures performed was significantly smaller.

**Table 10: number of avoidable biopsies and diagnostic performance of the five sonographic classification systems.**

	<b>Avoidable biopsies (%)</b>	<b>TP</b>	<b>FP</b>	<b>FN</b>	<b>TN</b>	<b>FNR</b>	<b>Sensitivity</b>	<b>Specificity</b>	<b>PPV</b>	<b>NPV</b>
<b>AACE</b>	189 (34.18%)	36	328	6	183	3.17%	85.71% (71.46-94.57%)	35.81% (31.65-40.14%)	9.89% (7.02-13.43%)	96.83% (93.22-98.83%)
<b>ACR TIRADS</b>	287 (51.90%)	34	232	8	279	2.79%	80.95% (65.88-91.4%)	54.6% (50.17-58.98%)	12.78% (9.02-17.4%)	97.21% (94.58-98.79%)
<b>ATA (modified)</b>	141 (25.50%)	38	374	4	137	2.84%	90.48% (77.38-97.34%)	26.81% (23.02-30.88%)	9.22% (6.61-12.44%)	97.16% (92.9-99.22%)
<b>EU-TIRADS</b>	165 (29.84%)	36	352	6	159	3.64%	85.71% (71.46-94.57%)	31.12% (27.12-35.33%)	9.28% (6.58-12.61%)	96.36% (92.25-98.65%)
<b>K-TIRADS</b>	92 (16.64%)	39	422	3	89	3.26%	92.86% (80.52-98.5%)	17.42% (14.23-20.99%)	8.46% (6.08-11.38%)	96.74% (90.77-99.32%)

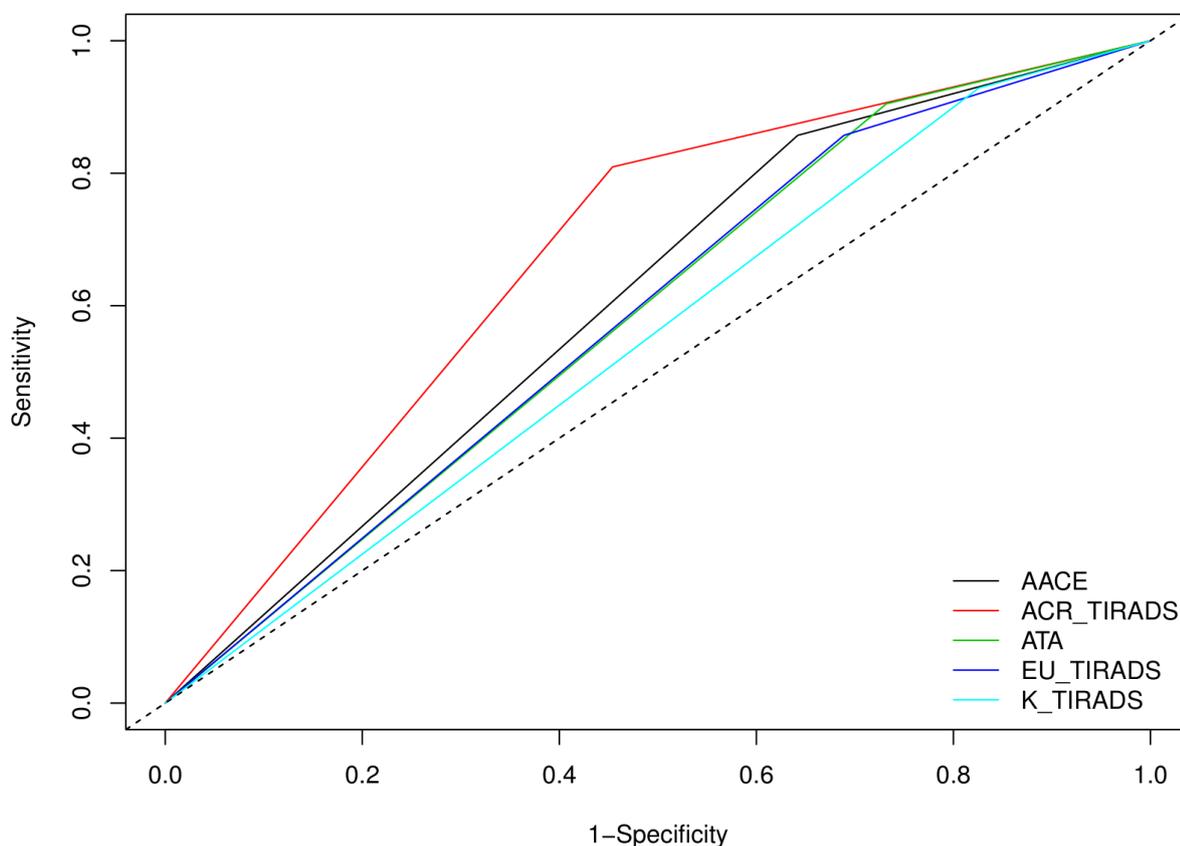
The rate of avoided biopsies is significantly different between the US classification systems (McNemar test; ACR TIRADS vs. ATA,  $p=0.002$ , ATA vs. AACE/ACE/AME,  $p<0.001$ , AACE/ACE/AME vs. EU-TIRADS,  $p<0.001$ ; EU-TIRADS vs. K-TIRADS,  $p<0.001$ ).

**Table 11: Diagnostic odds ratio (DOR) and area under the receiver operating curve (AUROC) of the five sonographic classification systems applied to the same cohort.**

	<b>DOR (95% CI)<sup>a</sup></b>	<b>AUROC (95% CI)<sup>b</sup></b>
<b>AACE/ACE/AME</b>	3.348 (1.384-8.095)	0.608 (0.55-0.665)
<b>ACR TIRADS</b>	5.111(2.320-11.257)	0.678 (0.614-0.742)
<b>ATA</b>	3.480 (1.219-9.932)	0.586 (0.538-0.635)
<b>EU-TIRADS</b>	2.710 (1.119-6.562)	0.584 (0.527-0.641)
<b>K-TIRADS</b>	2.742 (0.829-9.070)	0.551 (0.509-0.594)

- a) the DOR measures the discriminatory power of a diagnostic test as compared with that of the reference standard. The value ranges from 0 to infinity, with higher values indicating better performance;
- b) the multiple comparisons of AUROC were performed using Bonferroni correction; K-TIRADS had a significantly lower diagnostic performance than ACR TIRADS (adj. p=0.01).

**Figure 2: Computed ROC curves (dichotomous test result: biopsy indication) of the five systems.**



The actual malignancy rate was consistent to the predicted risk of malignancy proposed by the systems (Table 12), except for the high-risk classes. In these cases, the estimated malignancy risk was higher than the measured one. Furthermore, the estimates provided by the K-TIRADS classification were higher than the actual risk of malignancy (for all classes).

**Table 12: Malignancy rate and estimated malignancy risk of the various risk classes proposed by five sonographic classification systems.**

		<i>Malignancy rate</i>	<i>Estimated malignancy risk</i>
<b>AACE/ACE/AME</b>	Low	0.0%	1.0%
	Intermediate	3.7%	5-15%
	High	16.8%	50-90%
<b>ACR TIRADS</b>	1	0.0%	2.0%
	2	2.0%	2.0%
	3	1.9%	3.0%
	4	6.4%	5-20%
	5	28.9%	>20%
<b>ATA</b>	Benign	0.0%	<1%
	Very low	1.9%	<3%
	Low	3.5%	5-10%
	Intermediate	16.1%	10-20%
	High	32.2%	>70/80%
	Not classifiable	9.3%	-
<b>EU-TIRADS</b>	2	0.0%	0.0%
	3	2.3%	2-4%
	4	7.7%	6-17%
	5	17.2%	26-87%
<b>K-TIRADS</b>	2	0.0%	<1-3%
	3	2.3%	3-15%
	4	10.6%	15-50%
	5	47.2%	>60%

Eight nodules definitively diagnosed as malignant would have been misclassified as not requiring FNAB by at least one of the TIRADS systems (Table 13): they were all low risk PTC, except for a small medullary thyroid cancer.

**Table 13: Ultrasound features of the malignancies missed by one or more sonographic classification systems**

	<b>Missed by</b>				
	<i>Size (mm)</i>	<i>ACR TIRADS</i>	<i>Modified ATA</i>	<i>K-TIRADS</i>	<i>EU-TIRADS and AACE</i>
hyperechoic solid nodule in thyroiditis (FV-PTC)	13	X	X	X	X
hypoechoic solid nodule (PTC)	13	X			X
isoechoic mixed nodule (suspected PTC)	11	X	X	X	X
isoechoic nodule with irregular margins (PTC)	11	X			
isoechoic mixed nodule (PTC)	15	X	X		X
isoechoic mixed nodule (FV-PTC)	13	X	X	X	X
hypoechoic solid nodule (MTC)	12	X			X
Micro-PTC in the context of a 39-mm follicular adenoma (isoechoic mixed nodule)	-	X			
		<b>8</b>	<b>4</b>	<b>3</b>	<b>6</b>

*Abbreviations:* ACR TIRADS: American College of Radiology Thyroid Imaging Reporting and Data Systems; ATA: American Thyroid Association; EU-TIRADS: European Thyroid Imaging Reporting and Data Systems; MTC: medullary thyroid cancer; PTC: papillary thyroid cancer; K-TIRADS: Korean Thyroid Imaging Reporting and Data Systems

## Discussion

Thyroid cytology used to be the cornerstone of the diagnostic workflow of thyroid nodules. In roughly one third of cases, cytomorphologic analysis of the aspirate yields inconclusive results (Bongiovanni et al. 2012) that prompt repeat biopsies or additional, more expensive testing

(Lamartina, et al. 2016). The sonographic risk-stratification tools are designed as “rule-out” tests, aiming to identify nodules with low risks of malignancy whose cytologic assessment can safely be deferred. The first aim of this project was to prospectively validate current sonographic classification systems for the risk evaluation of thyroid nodules. Four of the five sonographic stratification systems confirmed a statistically significant discriminatory capacity (all except K-TIRADS): the number of biopsies performed would have been reduced applying the internationally-endorsed classification systems. However, the safest and most substantial reduction would have been achieved with the ACR TIRADS: the number of deferred biopsies and its ability to discriminate between benign and malignant nodules were greater than those of the competitors.

The study has some limitations. First, this was a selected cohort of thyroid nodules, all of which had already been flagged for FNAB, and the clinical criteria supporting these indications were not known. The malignancy rate, however, was similar to those reported for unselected nodule series (Durante et al. 2018), and all sonographic risk classes were represented, including low-risk categories. Second, we used a composite reference standard: a benign cytology report was considered sufficient for classification. However, cytology can yield false-negative results, even if uncommonly, with estimated frequencies of 3.7% (Bongiovanni et al. 2012) and even lower (<1%) in prospective series of cytologically benign nodules with no high-suspicion ultrasound features (Durante, et al. 2015). Furthermore, the exclusion of nodules with non-diagnostic or indeterminate cytology reports (and no final histology) may have caused a selection bias: however, the proportion of nodules with these cytological reports is consistent with those reported in other cytological series (Bongiovanni et al. 2012). The major strength of our study is its prospective nature: the US features of each nodule were evaluated during real-time examinations carried out before aspirates were collected. Our results support the use of sonographic classification systems to reduce the number of needed thyroid nodule biopsies. The best overall performance was that of the ACR TIRADS, which classified over half of the requested biopsies as unnecessary.

## Molecular evaluation

A new molecular platform for the refinement of cytologic diagnoses was designed and tested on a retrospective surgical cohort of resected thyroid nodules, for which a cytological examination was previously performed, and the relative material was available for molecular testing.

### Methods

#### Sample collection

A retrospective series of FNAB samples with cytological diagnosis performed from June 2016 to December 2017 and subsequently submitted to thyroid surgery were enrolled. For this reason, the indeterminate, suspicious or malignant reports were more prevalent (Figure 3). At the time of ultrasound-guided FNAB procedure, a liquid-based cytology sample was prepared, to be processed with ThinPrep5000™ system (Hologic Co.). The material remaining after cytological analysis was used for molecular profiling.

Nucleic acids were isolated from each sample using the *AllPrep DNA/RNA Micro Kit* (QIAGEN) which allows the simultaneous purification of genomic DNA and total RNA from the same biological sample. Samples will be accurately measured using the highly sensitive fluorescence-based *Qubit*® dsDNA/RNA High Sensitivity quantification assays (Thermo Fisher Scientific).

#### Molecular Analysis through targeted Next-Generation Sequencing

Genetic analysis was performed on the *Ion S5* system (Thermo Fisher Scientific) using two custom NGS multi-gene panels, which tested for single-nucleotide variants/small indels/copy number amplification (DNA panel) and gene fusions/gene expression (RNA panel) involving well-known thyroid cancer-related genes (e.g., *BRAF*, *RAS*, *EIF1AX*, *TERT*, *RET/PTC*, and *PAX8*/

*PPARG* fusion) and others from our in-house database. Genes for the custom panel were selected based on literature data (Cancer Genome Atlas Research Network 2014; Landa et al. 2016; Nikiforov, et al. 2014) and our in-house database, and custom primers for their targeted amplification were designed with the *Ion AmpliSeq™ Designer* (Thermo Fisher Scientific). Two libraries were created from 20 ng of DNA and 20 ng of RNA. The targeted amplification products were partially digested, phosphorylated, and ligated to *Ion P1 adapter and Ion Xpress™ barcodes* (Thermo Fisher Scientific). Libraries were pooled and clonally amplified on the Ion One Touch2 System. Sequencing was performed using *Ion S5 sequencing solution* on an *Ion 530 chip* (Thermo Fisher Scientific).

#### Data analysis

Data were analyzed with Variant Caller v5.4, annotated with Ion Reporter 5.6 and wANNOVAR software and prioritized on the basis of their population frequency (Minor allele frequency <0.005). Predicted variant deleteriousness was assessed with wANNOVAR (<http://wannovar.wglab.org/>).

SNVs and Indels were called when the position was covered by over 500 reads. The lower detection limits were set at 5% for SNVs and 15% for small indels. CNA will be called when variant will have a confidence level more than 15. The presence of at least 50 high-quality reads crossing the fusion point of the transcript will be required to consider the test positive.

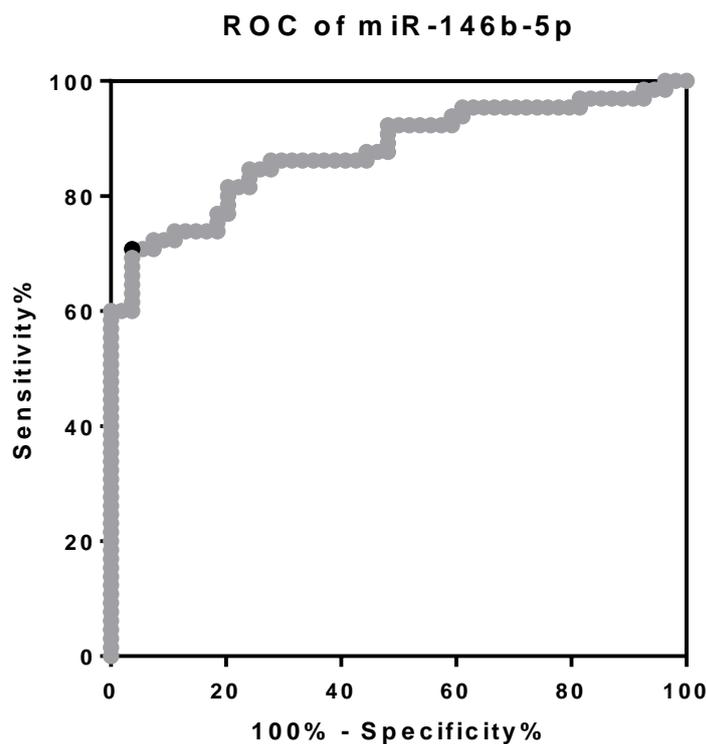
#### Digital PCR quantification of microRNA

Dysregulated miRNA expression has been documented and characterized at the tissue level in many malignancies, including thyroid cancer. We decided to evaluate the expression of a single miR (miR-146b-5p). It was selected because it is specifically expressed in follicular-cell-derived

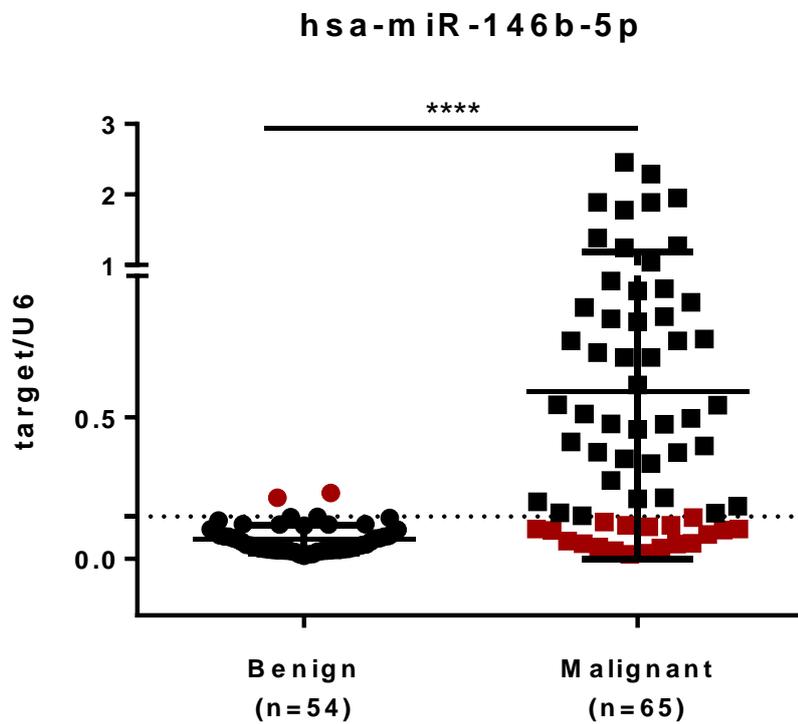
malignant thyroid neoplasms, based on results previously published by our group (Rosignolo, et al. 2017a; Rosignolo, et al. 2017b).

Expression analysis of miR-146b-5p was performed by digital PCR, using a *QuantStudio 3D Digital PCR* equipment (Thermo Fisher Scientific), using 1.25 ng of RNA, with standard procedures. Expression suite software v 1.0.3 (Thermo Fisher Scientific) was used to determine relative miRNA expression, using U6 as an endogenous control. The optimal cutoff level was selected using receiver-operating characteristic (ROC) curve analysis (p-ROC package in R software, version 3.1.1, Figure 3).

**Figure 3: ROC curve analysis of mIR-146b-5p quantification, performed to select the optimal cut-off point (0.1503).**



**Figure 4: Diagnostic performance of mIR-146b-5p/U6 ratio using the cut-off point derived by the ROC curve analysis (specificity 96%, sensitivity 71%).**



#### Reference standard

Surgical histology was used as the reference standard. Noninvasive follicular thyroid neoplasm with papillary-like nuclear features (NIFTP), a recently defined entity (Nikiforov, et al. 2016), previously considered an encapsulated noninvasive follicular-variant papillary thyroid cancer, is to date variably considered as nonmalignant, premalignant, or possibly carcinoma *in situ*. For the purposes of this study, it was considered a lesion with extremely low malignant potential, according to the statement of the ATA expert panel (Haugen, et al. 2017). Furthermore, it cannot be grouped with benign nodules, as it requires surgical management (Nikiforov 2017).

#### Statistical analysis

The NGS test was considered positive if a known driver mutation was found (with any allele frequency) or an unknown mutation in driver genes was found with an allele frequency >10%. The

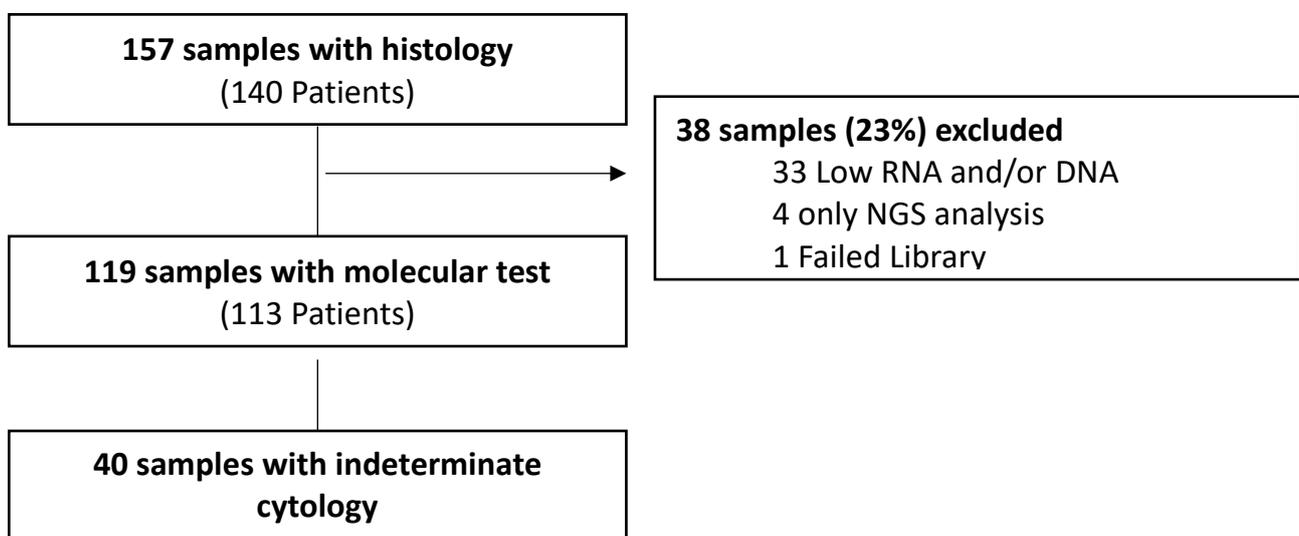
digital PCR test was considered positive if the ratio miR-146b-5p/U6 was  $> 0.1503$  (Figure 4). The combined test was considered positive if one of the two components (NGS or miR-146b-5p) was positive, and negative if both components were negatives.

The test result was then compared with the reference-standard diagnosis to estimate its sensitivity, specificity, positive and negative predictive values (PPV and NPV) and areas under the receiver operating characteristic (AUROC) curve (each with 95% confidence intervals, [CIs]). Data were analyzed with the IBM SPSS Statistics package, version 25.0 (IBM Corp., Armonk, NY, US).

## Results

From the original cohort of 157 samples with histology, from 140 patients, 38 inadequate samples (23%) were excluded: the molecular analysis was then performed in 119 samples from 113 patients (Figure 5; Table 14). Among them, 54 were histologically classified as benign (31 nodular hyperplasia/goiter; 23 adenomas), and 65 as malignant (61 papillary thyroid cancers – including 2 NIFTP, 1 follicular thyroid cancer, 1 poorly differentiated thyroid cancer, 1 anaplastic thyroid cancer, and 1 medullary thyroid cancer).

**Figure 5: Flow-chart of the enrollment of the retrospective cohort**



**Table 14. Demographic features of the patients (whole cohort and indeterminate cytology cohort)**

	<b>All 119 samples</b>	<b>40 indeterminate samples</b>
<b>Age</b>	<b>48.7 (18-91)</b>	<b>52.9 (32-79)</b>
<b>Male</b>	28 (25%)	11 (28%)
<b>Female</b>	85 (75%)	28 (72%)
<b>N</b>	<b>113 patients</b>	<b>39 patients</b>

The NGS panel identified 69 nodules harboring somatic alterations involving a known driver gene, the most common being BRAF, followed by RAS (N-, H-, and K-RAS grouped together) (Table 15).

**Table 15. Driver mutations identified by the NGS panel**

	<b>N</b>	<b>%</b>
<b>None</b>	50	42.0
<b>BRAF</b>	43	36.1
<b>NRAS</b>	6	5.0
<b>EIF1AX</b>	4	3.4
<b>HRAS</b>	4	3.4
<b>RET/PTC1</b>	4	3.4
<b>KRAS</b>	2	1.6
<b>RET</b>	2	1.7
<b>CHEK2</b>	1	0.8
<b>PAX8-PPARG</b>	1	0.8
<b>PTEN233</b>	1	0.8
<b>RET/PTC3</b>	1	0.8

The resulting diagnostic performance is reported in Table 16. The overall sensitivity is 87.69% (95% CI 77.18-94.53%), specificity of 77.78% (64.4-87.96%), PPV 82.61% (71.59-

90.68%) and NPV of 84% (70.89-92.83%). Considering only cytologically indeterminate nodules, the sensitivity is 88.89% (51.75-99.72%), specificity 80.65% (62.53-92.55%), PPV 57.14% (28.86-82.34%), and NPV 96.15% (80.36-99.9%). Thus, 12 false positive cases were found: 5 (41.7%) involving *RAS* genes, 3 (25%) *EIF1AX*, and *BRAF*, *CHEK2*, *PTEN*, and *RET* genes (1 case each; all of them were carefully checked by the pathologists, and the absence of histology features of malignancy was confirmed).

**Table 16: Diagnostic performance of the Next Generation Sequencing panel (overall and according to cytology classes; indeterminate cytology categories are highlighted in gray)**

	<b>TP</b>	<b>FP</b>	<b>FN</b>	<b>TN</b>	<b>n</b>	<b>Sensitivity</b>	<b>Specificity</b>	<b>PPV</b>	<b>NPV</b>
<b>NGS, overall</b>	57	12	8	42	119	87.69% (77.18-94.53%)	77.78% (64.4-87.96%)	82.61% (71.59-90.68%)	84.0% (70.89-92.83%)
<i>According to cytology classes</i>									
<b>TIR 2</b>	0	4	1	16	21	0.0% (0.0-97.5%)	80.0% (56.34-94.27%)	0.0% (0.0-60.24%)	94.12% (71.31-99.85%)
<b>TIR 3A</b>	1	1	0	7	9	100.0% (2.5-100.0%)	87.5% (47.35-99.68%)	50.0% (1.26-98.74%)	100.0% (59.04-100.0%)
<b>TIR 3B</b>	7	5	1	18	31	87.5% (47.35-99.68%)	78.26% (56.3-92.54%)	58.33% (27.67-84.83%)	94.74% (73.97-99.87%)
<b>TIR 3A and B</b>	8	6	1	25	40	88.89% (51.75-99.72%)	80.65% (62.53-92.55%)	57.14% (28.86-82.34%)	96.15% (80.36-99.9%)
<b>TIR 4</b>	19	2	3	0	24	86.36% (65.09-97.09%)	0.0% (0.0-84.19%)	90.48% (69.62-98.83%)	0.0% (0.0-70.76%)
<b>TIR 5</b>	30	0	2	0	32	93.75% (79.19-99.23%)	-	100.0% (88.43-100.0%)	0.0% (0.0-84.19%)

The miR-146b-5p levels were considered positive in 48 cases. The diagnostic performance is reported in Table 17. Since the cutoff level was selected in this same cohort, according to the ROC curve analysis, overestimation of diagnostic values is possible, and the determination in an independent cohort is needed. In the whole cohort, sensitivity was 70.77% (95% CI 58.17-81.4%), specificity 96.3% (87.25-99.55%), PPV 95.83% (85.75-99.49%), and NPV 73.24% (61.41-83.06%). In the subset of indeterminate nodules, sensitivity was 77.78% (39.99-97.19%), specificity 93.55% (78.58-99.21%), PPV 77.78% (39.99-97.19%), and NPV 93.55% (78.58-99.21%).

The combination of the two tests resulted in a sensitivity of 90.77% (80.98-96.54%), specificity 74.07% (60.35-85.04%), PPV 80.82% (69.92-89.1%), and NPV 86.96% (73.74-95.06%) in the entire cohort, and a sensitivity of 100.0% (66.37-100.0%), specificity 74.19% (55.39-88.14%), PPV 52.94% (27.81-77.02%), and NPV 100.0% (85.18-100.0%) in the cytologically indeterminate nodule subset (Table 18). Combining the two tests did not improve the diagnostic performance (assessed according to the AUROC analysis) in the entire cohort: the AUROC for mIR, NGS, and combined test were 0.84 (0.77-0.9), 0.83 (0.76-0.9), and 0.82 (0.76-0.89) respectively. In the subgroup of indeterminate nodules, the AUROC slightly increases, without statistical significance: 0.86 (0.71-1), 0.85 (0.72-0.98), 0.87 (0.79-0.95) for mIR, NGS, and combined test, respectively (Figure 6). However, the combination of the two tests zeroed the false negative number, allowing for a NPV of 100%. A greater sample is probably needed to clarify the better workflow and combination strategy.

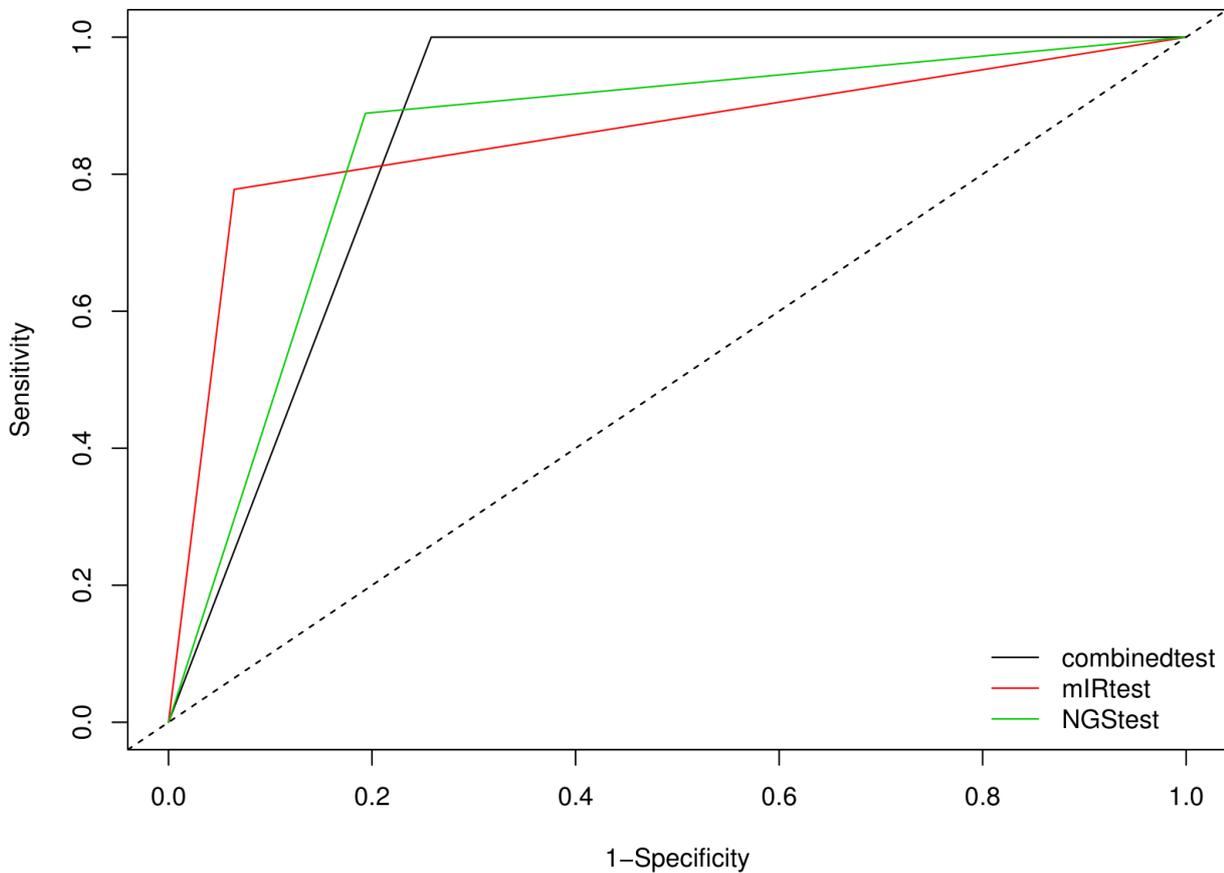
**Table 17: Diagnostic performance of the mIR (overall and according to cytology classes; indeterminate cytology categories are highlighted in gray)**

	<b>TP</b>	<b>FP</b>	<b>FN</b>	<b>TN</b>	<b>n</b>	<b>Sensitivity</b>	<b>Specificity</b>	<b>PPV</b>	<b>NPV</b>
<b>miR</b>	46	2	19	52	119	70.77% (58.17-81.4%)	96.3% (87.25-99.55%)	95.83% (85.75-99.49%)	73.24% (61.41-83.06%)
<i>According to cytology classes</i>									
<b>TIR 2</b>	0	0	1	20	21	0.0% (0.0-97.5%)	100.0% (83.16-100.0%)	-	95.24% (76.18-99.88%)
<b>TIR 3A</b>	1	0	0	8	9	100.0% (2.5-100.0%)	100.0% (63.06-100.0%)	100.0% (2.5-100.0%)	100.0% (63.06-100.0%)
<b>TIR 3B</b>	6	2	2	21	31	75.0% (34.91-96.81%)	91.3% (71.96-98.93%)	75.0% (34.91-96.81%)	91.3% (71.96-98.93%)
<b>TIR 3A and B</b>	7	2	2	29	40	77.78% (39.99-97.19%)	93.55% (78.58-99.21%)	77.78% (39.99-97.19%)	93.55% (78.58-99.21%)
<b>TIR 4</b>	15	0	7	2	24	68.18% (45.13-86.14%)	100.0% (15.81-100.0%)	100.0% (78.2-100.0%)	22.22% (2.81-60.01%)
<b>TIR 5</b>	24	0	8	0	32	75.0% (56.6-88.54%)	-	100.0% (85.75-100.0%)	0.0% (0.0-36.94%)

**Table 18: Diagnostic performance of the combination of mIR and Next Generation Sequencing panel (overall and according to cytology classes; indeterminate cytology categories are highlighted in gray)**

	<b>TP</b>	<b>FP</b>	<b>FN</b>	<b>TN</b>	<b>n</b>	<b>Sensitivity</b>	<b>Specificity</b>	<b>PPV</b>	<b>NPV</b>
<b>Combination</b>	59	14	6	40	119	90.77% (80.98-96.54%)	74.07% (60.35-85.04%)	80.82% (69.92-89.1%)	86.96% (73.74-95.06%)
<i>According to cytology classes</i>									
<b>TIR 2</b>	0	4	1	16	21	0.0% (0.0-97.5%)	80.0% (56.34-94.27%)	0.0% (0.0-60.24%)	94.12% (71.31-99.85%)
<b>TIR 3A</b>	1	1	0	7	9	100.0% (2.5-100.0%)	87.5% (47.35-99.68%)	50.0% (1.26-98.74%)	100.0% (59.04-100.0%)
<b>TIR 3B</b>	8	7	0	16	31	100.0% (63.06-100.0%)	69.57% (47.08-86.79%)	53.33% (26.59-78.73%)	100.0% (79.41-100.0%)
<b>TIR 3A and B</b>	9	8	0	23	40	100.0% (66.37-100.0%)	74.19% (55.39-88.14%)	52.94% (27.81-77.02%)	100.0% (85.18-100.0%)
<b>TIR 4</b>	19	2	3	0	24	86.36% (65.09-97.09%)	0.0% (0.0-84.19%)	90.48% (69.62-98.83%)	0.0% (0.0-70.76%)
<b>TIR 5</b>	31	0	1	0	32	96.88% (83.78-99.92%)	-	100.0% (88.78-100.0%)	0.0% (0.0-97.5%)

**Figure 6: Computed ROC curves of the NGS, miR, and combined test in the subgroup of indeterminate nodules (TIR3A and TIR3B cytology reports)**



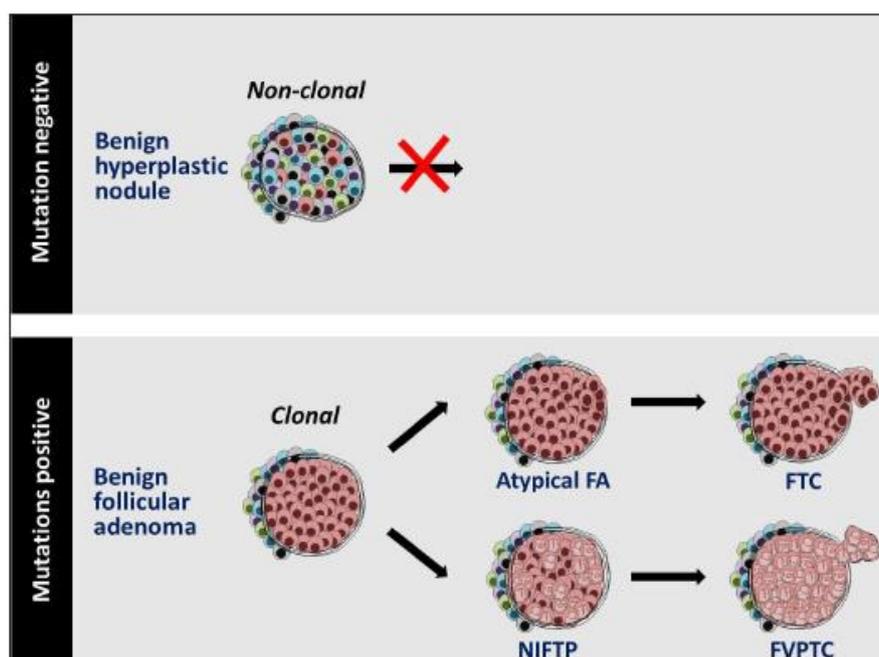
## Discussion

We have developed a combination test with a sensitivity of 100.0% (66.37-100.0%) and specificity of 74.19% (55.39-88.14%) in the cytologically indeterminate nodule subset. With the current prevalence of malignancy (22.5%), it has a PPV of 52.94% (27.81-77.02%) and NPV 100.0% (85.18-100.0%). It is so possible to use it as a “rule out” test in cytologically indeterminate lesions. Furthermore, we have demonstrated that it is possible to have a sufficient amount of nucleic acid from the original cytology sample in at least 77% of the cases; with liquid-based cytology processing, it also does not require the destruction of the original slide used for morphological diagnosis. Finally, the potential availability of mutational data in a pre-surgical setting may help the

personalized surgical planning, providing some risk estimation information before the thyroidectomy, and may help clinicians to refine the treatment of patients. For example, the detection of additional mutations (late genetic events) such as *TERT* may identify thyroid cancers with the highest risk for tumor recurrence and disease specific mortality (Moon, et al. 2017; Song, et al. 2016; Vuong, et al. 2017).

While in this cohort of cytologically indeterminate nodules no false negative were detected, in the whole cohort 6 false negative were detected: all but two of them were correctly identified by cytological examinations. In the 2 cases that resulted false negative both for cytology and for molecular testing, a sampling error may not be excluded (the first case had a non-diagnostic cytology; in the second case a small, 3-mm PTC was probably not the target of the biopsy). On the contrary, some false positives were detected: the majority of them (6/8 in the indeterminate cohort) were due to the detection of driver mutation. In these cases, at least an adenoma was identified: it is a clonal neoplasm, therefore potentially prone to progression (Figure 7).

**Figure 7: Hyperplasia and adenoma and detection of mutations (from Nikiforov, 2017)**



This study has several limitations. First of all, it is based on a surgical cohort: it is prone to selection bias. Furthermore, this study was performed at a single high-volume pathology center with established clinical expertise: the results may vary in other settings. Finally, the threshold for positivity of miR-146b-5p was established according to the ROC curve analysis in this same cohort, thus leading to overestimation of the diagnostic accuracy. An independent validation cohort is needed.

The study reports a high sensitivity and high NPV of our combined test for indeterminate cytology nodules, which together with good specificity may avoid surgeries in a good number of patients (in our cohort 23 patients may have avoided surgery, 57.5%).

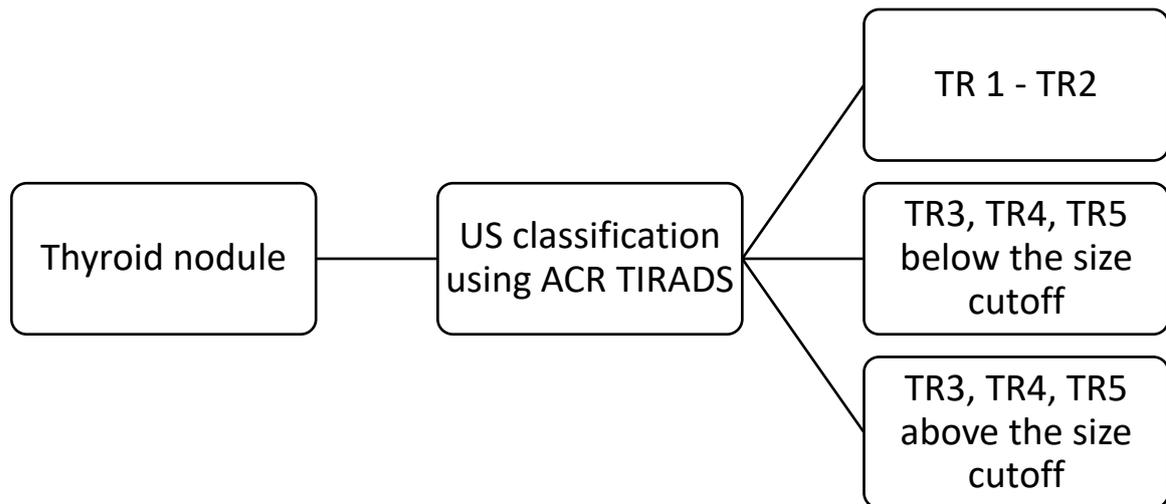
## Conclusions

More than 600'000 thyroid FNABs are performed every year in the United States alone, and the number has been increasing annually by 16% from 2006 to 2011. In the same time frame, The number of thyroid surgeries performed increased by 31%, and total thyroidectomies increased by 12% per year (Sosa, et al. 2013). About 20% of FNAB of thyroid nodules have indeterminate cytology (Bethesda category III and IV) (Durante et al. 2018). The number of diagnostic surgeries can be reduced if the nodules are reliably classified as benign. Over the past decade, molecular testing of thyroid nodules was developed to improve diagnostic accuracy of FNA cytology: development of new test strategies is ongoing, using gene expression profiling, miRNA profiling, broader gene panels of for mutational markers, inclusion of copy number alterations, mitochondrial DNA, and combinations of different markers. However, the role and optimal application of molecular testing is yet to be determined, also considering his high cost.

The final aim of this project was to propose an integrated workflow to manage thyroid nodules using sonographic, cytological and molecular data.

The first step is to better select the nodules that really need further examinations. We have documented that the application of the ACR TIRADS systems may reduce more than a half of the cytological examinations performed at our center, still detecting clinically significant cancers.

**Figure 8: First step of management of newly detected thyroid nodules**

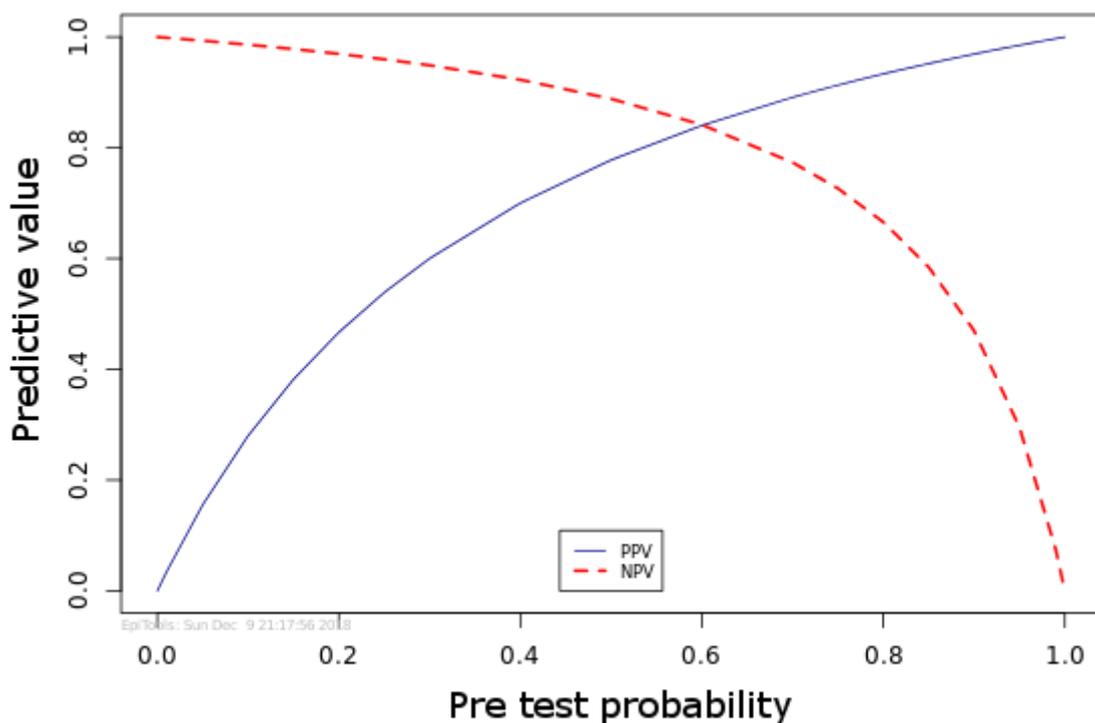


Only nodules classified as ACR TIRADS TR3, TR4, TR5 above the defined size cutoff should be submitted to FNAB (no more than 50% of the nodules greater than 1 cm). It is important to note, however, that the US features being evaluated must also be clearly and unambiguously defined, and the application of TIRADS systems requires specific training and experience (Grani et al. 2018b), appropriate equipment and sufficient time.

About 20% of biopsied nodules are expected to have an indeterminate cytology report. In this group, the application of the molecular test may be considered: however, its performance is heavily dependent on pre-test probability of malignancy. Given the sensitivity and specificity of the molecular test, Bayes theorem can predict the test NPV and PPV along the spectrum of disease prevalence (i.e. the pre-test probability of disease) (Christenson 2007). The plot of the predicted NPV and PPV of our molecular testing approach is reported in Figure 9: the NPV is at least 95% till

to a 30% pre-test probability of disease. From a clinical point of view, it means that a negative test equals the diagnostic performance of a benign cytology report, is a good “rule out” test, and the patient may avoid surgery. In most center, the malignancy risk of Bethesda class 5 (or Italian TIR4) cytology report is > 30%, so that the clinical performance of diagnostic test is not enough to spare surgery.

**Figure 9: Plot of positive and negative predictive values of the developed combined molecular testing according to the pre-test probability of disease. The NPV is  $\geq 95\%$  for a pre-test probability up to 30%.**

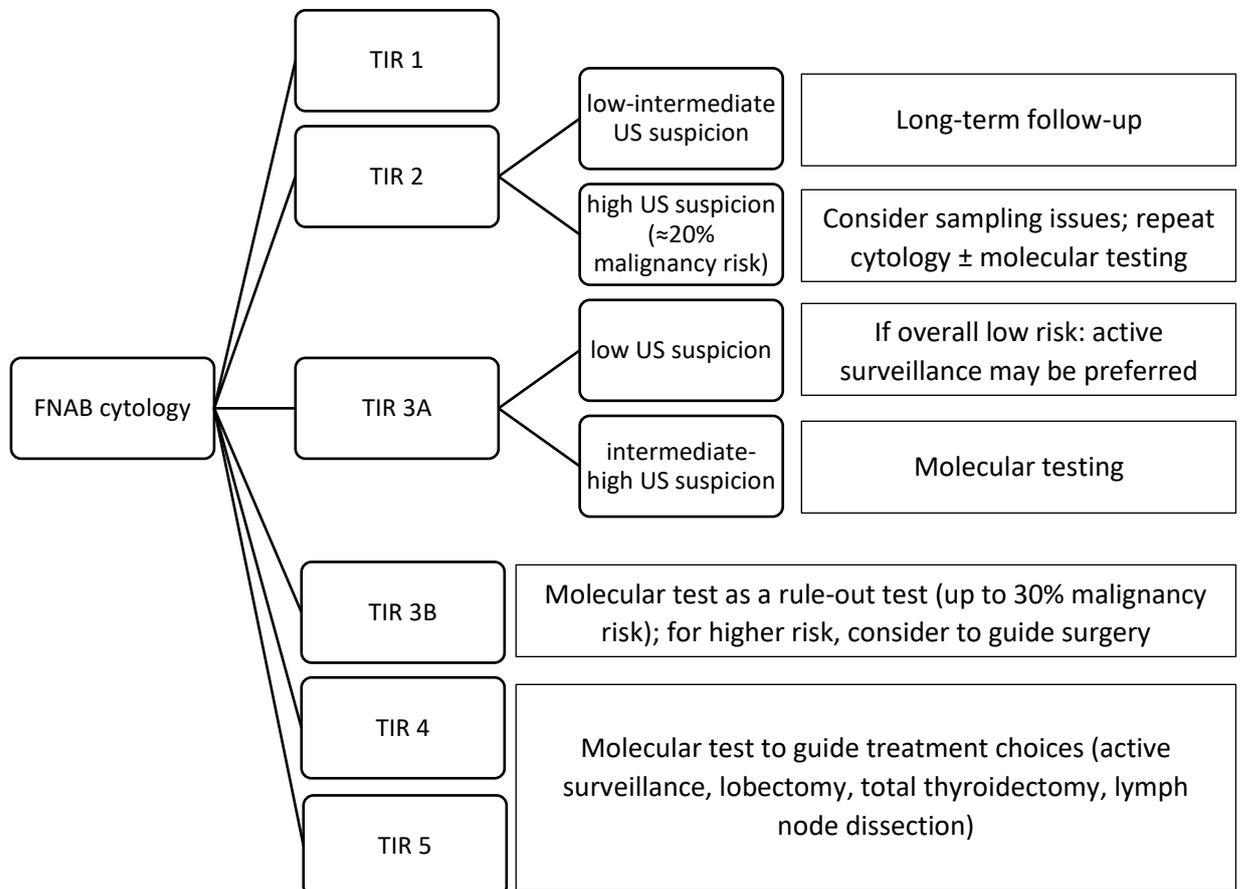


Furthermore, if at a given center, the malignancy rate of Bethesda class 4 (or TIR3B) lesions is >30%, the negative predictive value would be lower than predicted. On the contrary, nodules with non-diagnostic or benign cytology with suspicious sonographic features may have a malignancy risk around 20% (thus similar to the cytologically indeterminate nodules): in these cases, repeat cytology with molecular testing may also be considered. For low-risk indeterminate nodules with no

sonographic suspicion, the predicted malignancy risk may be so low to not justify the cost of molecular testing: it would be possible to directly suggest periodic surveillance.

If the cause of indeterminate cytology is an adenoma, molecular test is also likely to produce false positive results, since the *RAS* and *RAS*-like gene mutations are associated with neoplasia (and frequently reported in adenomas), even if not necessarily with malignancy. Morphologic subgrouping of indeterminate cytology reports may also help in guiding the choice of molecular testing. In high-risk nodules, the molecular test is not to be used not as a “*rule-out*” test: however, it can detect or exclude mutations associated with aggressive features, thus guiding the extent of surgery.

**Figure 10: Management of thyroid nodules submitted to FNAB cytology**



In conclusion, the traditional approach to the thyroid nodule, based on cytology, is changed. Nowadays, the leading examination is the neck sonography, that may be used to spare about the half of previously suggested biopsies. Among the sampled nodules, the cytologically indeterminate lesions may be managed in a more conservative way, sparing a relevant number of diagnostic surgeries, with an appropriate use of molecular tests. In our cohort, half of the surgeries performed for indeterminate nodules could be avoided. Furthermore, the risk estimation provided by both the cytology and the sonographic examination may contribute to the pre-molecular test probability of malignancy, optimizing the diagnostic performance and potentially contributing to the cost-effectiveness, that is yet to be determined in a European public health system such as the Italian one.

## References

2013 AIUM practice guideline for the performance of a thyroid and parathyroid ultrasound examination. *J Ultrasound Med* **32** 1319-1329.

Al-Qurayshi Z, Deniwar A, Thethi T, Mallik T, Srivastav S, Murad F, Bhatia P, Moroz K, Sholl AB & Kandil E 2017 Association of Malignancy Prevalence With Test Properties and Performance of the Gene Expression Classifier in Indeterminate Thyroid Nodules. *JAMA Otolaryngol Head Neck Surg* **143** 403-408.

Aldrink JH, Adler B, Haines J, Watkins D, Matthews M, Lubeley L, Wang W & King DR 2016 Patients exposed to diagnostic head and neck radiation for the management of shunted hydrocephalus have a significant risk of developing thyroid nodules. *Pediatr Surg Int* **32** 565-569.

Alexander EK, Kennedy GC, Baloch ZW, Cibas ES, Chudova D, Diggans J, Friedman L, Kloos RT, LiVolsi VA, Mandel SJ, et al. 2012 Preoperative diagnosis of benign thyroid nodules with indeterminate cytology. *N Engl J Med* **367** 705-715.

Baloch ZW, Cooper DS, Gharib H & Alexander EK 2017 Overview of Diagnostic Terminology and Reporting. In *The Bethesda System for Reporting Thyroid Cytopathology: Definitions, Criteria, and Explanatory Notes* Eds SZ Ali & ES Cibas. New York, NY: Springer.

Bongiovanni M, Spitale A, Faquin WC, Mazzucchelli L & Baloch ZW 2012 The Bethesda System for Reporting Thyroid Cytopathology: a meta-analysis. *Acta Cytol* **56** 333-339.

Brito JP, Gionfriddo MR, Al Nofal A, Boehmer KR, Leppin AL, Reading C, Callstrom M, Elraiyah TA, Prokop LJ, Stan MN, et al. 2014 The accuracy of thyroid nodule ultrasound to predict thyroid cancer: systematic review and meta-analysis. *J Clin Endocrinol Metab* **99** 1253-1263.

Burch HB, Burman KD, Cooper DS, Hennessey JV & Vietor NO 2016 A 2015 Survey of Clinical Practice Patterns in the Management of Thyroid Nodules. *J Clin Endocrinol Metab* **101** 2853-2862.

Cahoon EK, Nadirov EA, Polanskaya ON, Yauseyenko VV, Velalkin IV, Yeudachkova TI, Maskvicheva TI, Minenko VF, Liu W, Drozdovitch V, et al. 2017 Risk of thyroid nodules in residents of Belarus exposed to Chernobyl fallout as children and adolescents. *J Clin Endocrinol Metab* **102** 2207-2217.

Campanella P, Ianni F, Rota CA, Corsello SM & Pontecorvi A 2014 Quantification of cancer risk of each clinical and ultrasonographic suspicious feature of thyroid nodules: a systematic review and meta-analysis. *Eur J Endocrinol* **170** R203-211.

Cancer Genome Atlas Research Network 2014 Integrated genomic characterization of papillary thyroid carcinoma. *Cell* **159** 676-690.

Christenson RH 2007 Evidence-based laboratory medicine - a guide for critical evaluation of in vitro laboratory testing. *Ann Clin Biochem* **44** 111-130.

Cibas ES & Ali SZ 2017 The 2017 Bethesda System for Reporting Thyroid Cytopathology. *Thyroid* **27** 1341-1346.

Cibas ES, Baloch ZW, Fellegara G, LiVolsi VA, Raab SS, Rosai J, Diggans J, Friedman L, Kennedy GC, Kloos RT, et al. 2013 A prospective assessment defining the limitations of thyroid nodule pathologic evaluation. *Ann Intern Med* **159** 325-332.

Duick DS, Klopper JP, Diggans JC, Friedman L, Kennedy GC, Lanman RB & McIver B 2012 The impact of benign gene expression classifier test results on the endocrinologist-patient decision to operate on patients with thyroid nodules with indeterminate fine-needle aspiration cytopathology. *Thyroid* **22** 996-1001.

Durante C, Costante G, Lucisano G, Bruno R, Meringolo D, Paciaroni A, Puxeddu E, Torlontano M, Tumino S, Attard M, et al. 2015 The natural history of benign thyroid nodules. *Jama* **313** 926-935.

Durante C, Grani G, Lamartina L, Filetti S, Mandel SJ & Cooper DS 2018 The Diagnosis and Management of Thyroid Nodules A Review. *Jama-Journal of the American Medical Association* **319** 914-924.

Eszlinger M, Lau L, Ghaznavi S, Symonds C, Chandarana SP, Khalil M & Paschke R 2017 Molecular profiling of thyroid nodule fine-needle aspiration cytology. *Nat Rev Endocrinol* **13** 415-424.

Fadda G, Basolo F, Bondi A, Bussolati G, Crescenzi A, Nappi O, Nardi F, Papotti M, Taddei G & Palombini L 2010 Cytological classification of thyroid nodules. Proposal of the SIAPEC-IAP Italian Consensus Working Group. *Pathologica* **102** 405-408.

Fagin JA & Wells SA, Jr. 2016 Biologic and Clinical Perspectives on Thyroid Cancer. *N Engl J Med* **375** 1054-1067.

Ganly I, Makarov V, Deraje S, Dong Y, Reznik E, Seshan V, Nanjangud G, Eng S, Bose P, Kuo F, et al. 2018 Integrated Genomic Analysis of Hurthle Cell Cancer Reveals Oncogenic Drivers, Recurrent Mitochondrial Mutations, and Unique Chromosomal Landscapes. *Cancer Cell* **34** 256-270.e255.

Gharib H, Papini E, Garber JR, Duick DS, Harrell RM, Hegedüs L, Paschke R, Valcavi R, Vitti P & Nodules AAATFoT 2016 American Association of Clinical Endocrinologists, American College of Endocrinology, and Associazione Medici Endocrinologi medical guidelines for clinical practice for the diagnosis and management of thyroid nodules - 2016 update. *Endocr Pract* **22** 622-639.

Grani G, D'Alessandri M, Carbotta G, Nesca A, Del Sordo M, Alessandrini S, Coccaro C, Rendina R, Bianchini M, Prinzi N, et al. 2015 Grey-Scale Analysis Improves the Ultrasonographic Evaluation of Thyroid Nodules. *Medicine* **94** e1129.

Grani G, Lamartina L, Ascoli V, Bosco D, Biffoni M, Giacomelli L, Maranghi M, Falcone R, Ramundo V, Cantisani V, et al. 2018a Reducing the number of unnecessary thyroid biopsies while improving diagnostic accuracy: towards the "right" TIRADS. *J Clin Endocrinol Metab* **104** 95-102

Grani G, Lamartina L, Ascoli V, Bosco D, Nardi F, D'Ambrosio F, Rubini A, Giacomelli L, Biffoni M, Filetti S, et al. 2017 Ultrasonography scoring systems can rule out malignancy in cytologically indeterminate thyroid nodules. *Endocrine* **57** 256-261.

Grani G, Lamartina L, Cantisani V, Maranghi M, Lucia P & Durante C 2018b Interobserver agreement of various thyroid imaging reporting and data systems. *Endocrine Connections* **7** 1-7.

Grant EG, Tessler FN, Hoang JK, Langer JE, Beland MD, Berland LL, Cronan JJ, Dessler TS, Frates MC, Hamper UM, et al. 2015 Thyroid Ultrasound Reporting Lexicon: White Paper of the ACR Thyroid Imaging, Reporting and Data System (TIRADS) Committee. *J Am Coll Radiol* **12** 1272-1279.

Guth S, Theune U, Aberle J, Galach A & Bamberger CM 2009 Very high prevalence of thyroid nodules detected by high frequency (13 MHz) ultrasound examination. *Eur J Clin Invest* **39** 699-706.

Haugen BR, Alexander EK, Bible KC, Doherty GM, Mandel SJ, Nikiforov YE, Pacini F, Randolph GW, Sawka AM, Schlumberger M, et al. 2016 2015 American Thyroid Association Management Guidelines for Adult Patients with Thyroid Nodules and Differentiated Thyroid Cancer: The American Thyroid Association Guidelines Task Force on Thyroid Nodules and Differentiated Thyroid Cancer. *Thyroid* **26** 1-133.

Haugen BR, Sawka AM, Alexander EK, Bible KC, Caturegli P, Doherty GM, Mandel SJ, Morris JC, Nassar A, Pacini F, et al. 2017 American Thyroid Association Guidelines on the Management of Thyroid Nodules and Differentiated Thyroid Cancer Task Force Review and Recommendation on the Proposed Renaming of Encapsulated Follicular Variant Papillary Thyroid Carcinoma Without Invasion to Noninvasive Follicular Thyroid Neoplasm with Papillary-Like Nuclear Features. *Thyroid* **27** 481-483.

Hayes AF & Krippendorff K 2007 Answering the Call for a Standard Reliability Measure for Coding Data. *Communication Methods and Measures* **1** 77-89.

Horvath E, Majlis S, Rossi R, Franco C, Niedmann JP, Castro A & Dominguez M 2009 An ultrasonogram reporting system for thyroid nodules stratifying cancer risk for clinical management. *J Clin Endocrinol Metab* **94** 1748-1751.

Kwak JY, Han KH, Yoon JH, Moon HJ, Son EJ, Park SH, Jung HK, Choi JS, Kim BM & Kim EK 2011 Thyroid imaging reporting and data system for US features of nodules: a step in establishing better stratification of cancer risk. *Radiology* **260** 892-899.

Kwak JY, Jung I, Baek JH, Baek SM, Choi N, Choi YJ, Jung SL, Kim EK, Kim JA, Kim JH, et al. 2013 Image reporting and characterization system for ultrasound features of thyroid nodules: multicentric Korean retrospective study. *Korean J Radiol* **14** 110-117.

Labourier E 2016 Utility and cost-effectiveness of molecular testing in thyroid nodules with indeterminate cytology. *Clin Endocrinol (Oxf)* **85** 624-631.

Labourier E, Shifrin A, Busseniers AE, Lupo MA, Manganelli ML, Andruss B, Wylie D & Beaudenon-Huibregtse S 2015 Molecular Testing for miRNA, mRNA, and DNA on Fine-Needle Aspiration Improves the Preoperative Diagnosis of Thyroid Nodules With Indeterminate Cytology. *J Clin Endocrinol Metab* **100** 2743-2750.

Lamartina L, Deandreis D, Durante C & Filetti S 2016 ENDOCRINE TUMOURS: Imaging in the follow-up of differentiated thyroid cancer: current evidence and future perspectives for a risk-adapted approach. *Eur J Endocrinol* **175** R185-202.

Land CE, Kwon D, Hoffman FO, Moroz B, Drozdovitch V, Bouville A, Beck H, Luckyanov N, Weinstock RM & Simon SL 2015 Accounting for shared and unshared dosimetric uncertainties in the dose response for ultrasound-detected thyroid nodules after exposure to radioactive fallout. *Radiat Res* **183** 159-173.

Landa I, Ibrahimasic T, Boucai L, Sinha R, Knauf JA, Shah RH, Dogan S, Ricarte-Filho JC, Krishnamoorthy GP, Xu B, et al. 2016 Genomic and transcriptomic hallmarks of poorly differentiated and anaplastic thyroid cancers. *J Clin Invest* **126** 1052-1066.

Landis JR & Koch GG 1977 The measurement of observer agreement for categorical data. *Biometrics* **33** 159-174.

Lee L, How J, Tabah RJ & Mitmaker EJ 2014 Cost-effectiveness of molecular testing for thyroid nodules with atypia of undetermined significance cytology. *J Clin Endocrinol Metab* **99** 2674-2682.

Lithwick-Yanai G, Dromi N, Shtabsky A, Morgenstern S, Strenov Y, Feinmesser M, Kravtsov V, Leon ME, Hajduch M, Ali SZ, et al. 2017 Multicentre validation of a microRNA-based assay for diagnosing indeterminate thyroid nodules utilising fine needle aspirate smears. *J Clin Pathol* **70** 500-507.

Mazzaferri EL 1993 Management of a solitary thyroid nodule. *N Engl J Med* **328** 553-559.

Mohammadi A & Hajizadeh T 2013 Evaluation of diagnostic efficacy of ultrasound scoring system to select thyroid nodules requiring fine needle aspiration biopsy. *Int J Clin Exp Med* **6** 641-648.

Moon HJ, Sung JM, Kim EK, Yoon JH, Youk JH & Kwak JY 2012 Diagnostic performance of gray-scale US and elastography in solid thyroid nodules. *Radiology* **262** 1002-1013.

Moon S, Song YS, Kim YA, Lim JA, Cho SW, Moon JH, Hahn S, Park DJ & Park YJ 2017 Effects of Coexistent BRAF(V600E) and TERT Promoter Mutations on Poor Clinical Outcomes in Papillary Thyroid Cancer: A Meta-Analysis. *Thyroid* **27** 651-660.

Moon WJ, Jung SL, Lee JH, Na DG, Baek JH, Lee YH, Kim J, Kim HS, Byun JS & Lee DH 2008 Benign and malignant thyroid nodules: US differentiation--multicenter retrospective study. *Radiology* **247** 762-770.

Nardi F, Basolo F, Crescenzi A, Fadda G, Frasoldati A, Orlandi F, Palombini L, Papini E, Zini M, Pontecorvi A, et al. 2014 Italian consensus for the classification and reporting of thyroid cytology. *J Endocrinol Invest* **37** 593-599.

Nikiforov YE 2017 Role Of Molecular Markers In Thyroid Nodule Management: Then And Now. *Endocr Pract* **23** 979-988.

Nikiforov YE, Carty SE, Chiosea SI, Coyne C, Duvvuri U, Ferris RL, Gooding WE, Hodak SP, LeBeau SO, Otori NP, et al. 2014 Highly accurate diagnosis of cancer in thyroid nodules with

follicular neoplasm/suspicious for a follicular neoplasm cytology by ThyroSeq v2 next-generation sequencing assay. *Cancer* **120** 3627-3634.

Nikiforov YE, Carty SE, Chiosea SI, Coyne C, Duvvuri U, Ferris RL, Gooding WE, LeBeau SO, Ohori NP, Seethala RR, et al. 2015 Impact of the Multi-Gene ThyroSeq Next-Generation Sequencing Assay on Cancer Diagnosis in Thyroid Nodules with Atypia of Undetermined Significance/Follicular Lesion of Undetermined Significance Cytology. *Thyroid* **25** 1217-1223.

Nikiforov YE, Seethala RR, Tallini G, Baloch ZW, Basolo F, Thompson LD, Barletta JA, Wenig BM, Al Ghuzlan A, Kakudo K, et al. 2016 Nomenclature Revision for Encapsulated Follicular Variant of Papillary Thyroid Carcinoma: A Paradigm Shift to Reduce Overtreatment of Indolent Tumors. *JAMA Oncol* **2** 1023-1029.

Nikiforova MN, Kimura ET, Gandhi M, Biddinger PW, Knauf JA, Basolo F, Zhu Z, Giannini R, Salvatore G, Fusco A, et al. 2003 BRAF mutations in thyroid tumors are restricted to papillary carcinomas and anaplastic or poorly differentiated carcinomas arising from papillary carcinomas. *J Clin Endocrinol Metab* **88** 5399-5404.

Nishino M 2016 Molecular cytopathology for thyroid nodules: A review of methodology and test performance. *Cancer Cytopathol* **124** 14-27.

Ozel A, Erturk SM, Ercan A, Yilmaz B, Basak T, Cantisani V, Basak M & Karpaz Z 2012 The diagnostic efficiency of ultrasound in characterization of thyroid nodules: how many criteria are required to predict malignancy? *Med Ultrason* **14** 24-28.

Park JY, Lee HJ, Jang HW, Kim HK, Yi JH, Lee W & Kim SH 2009 A proposal for a thyroid imaging reporting and data system for ultrasound features of thyroid carcinoma. *Thyroid* **19** 1257-1264.

Patel KN, Angell TE, Babiarz J, Barth NM, Blevins T, Duh QY, Ghossein RA, Harrell RM, Huang J, Kennedy GC, et al. 2018 Performance of a Genomic Sequencing Classifier for the Preoperative Diagnosis of Cytologically Indeterminate Thyroid Nodules. *JAMA Surg* **153** 817-824.

Pusztaszeri M, Rossi ED, Auger M, Baloch Z, Bishop J, Bongiovanni M, Chandra A, Cochand-Priollet B, Fadda G, Hirokawa M, et al. 2016 The Bethesda System for Reporting Thyroid Cytopathology: Proposed Modifications and Updates for the Second Edition from an International Panel. *Acta Cytol* **60** 399-405.

Rosario PW, da Silva AL, Nunes MS, Ribeiro Borges MA, Mourao GF & Calsolari MR 2017 Risk of malignancy in 1502 solid thyroid nodules >1 cm using the new ultrasonographic classification of the American Thyroid Association. *Endocrine* **56** 442-445.

Rosignolo F, Memeo L, Monzani F, Colarossi C, Pecce V, Verrienti A, Durante C, Grani G, Lamartina L, Forte S, et al. 2017a MicroRNA-based molecular classification of papillary thyroid carcinoma. *International Journal of Oncology* **50** 1767-1777.

Rosignolo F, Sponziello M, Giacomelli L, Russo D, Pecce V, Biffoni M, Bellantone R, Lombardi CP, Lamartina L, Grani G, et al. 2017b Identification of Thyroid-Associated Serum microRNA Profiles and Their Potential Use in Thyroid Cancer Follow-Up. *Journal of the Endocrine Society* **1** 3-13.

Russ G, Bonnema SJ, Erdogan MF, Durante C, Ngu R & Leenhardt L 2017 European Thyroid Association Guidelines for Ultrasound Malignancy Risk Stratification of Thyroid Nodules in Adults: The EU-TIRADS. *European Thyroid Journal* **6** 225-237.

Russ G, Leboulleux S, Leenhardt L & Hegedus L 2014 Thyroid incidentalomas: epidemiology, risk stratification with ultrasound and workup. *Eur Thyroid J* **3** 154-163.

Russ G, Royer B, Bigorgne C, Rouxel A, Bienvenu-Perrard M & Leenhardt L 2013 Prospective evaluation of thyroid imaging reporting and data system on 4550 nodules with and without elastography. *Eur J Endocrinol* **168** 649-655.

Seo H, Na DG, Kim JH, Kim KW & Yoon JW 2015 Ultrasound-Based Risk Stratification for Malignancy in Thyroid Nodules: A Four-Tier Categorization System. *Eur Radiol* **25** 2153-2162.

Sharma SD, Jacques T, Smith S & Watters G 2015 Diagnosis of incidental thyroid nodules on 18F-fluorodeoxyglucose positron emission tomography imaging: are these significant? *J Laryngol Otol* **129** 53-56.

Shin JH, Baek JH, Chung J, Ha EJ, Kim JH, Lee YH, Lim HK, Moon WJ, Na DG, Park JS, et al. 2016 Ultrasonography Diagnosis and Imaging-Based Management of Thyroid Nodules: Revised Korean Society of Thyroid Radiology Consensus Statement and Recommendations. *Korean J Radiol* **17** 370-395.

Song YS, Lim JA, Choi H, Won JK, Moon JH, Cho SW, Lee KE, Park YJ, Yi KH, Park DJ, et al. 2016 Prognostic effects of TERT promoter mutations are enhanced by coexistence with BRAF or RAS mutations and strengthen the risk prediction by the ATA or TNM staging system in differentiated thyroid cancer patients. *Cancer* **122** 1370-1379.

Sosa JA, Hanna JW, Robinson KA & Lanman RB 2013 Increases in thyroid nodule fine-needle aspirations, operations, and diagnoses of thyroid cancer in the United States. *Surgery* **154** 1420-1426; discussion 1426-1427.

Steward DL, Carty SE, Sippel RS, Yang SP, Sosa JA, Sipos JA, Figge JJ, Mandel S, Haugen BR, Burman KD, et al. 2018 Performance of a Multigene Genomic Classifier in Thyroid Nodules With Indeterminate Cytology: A Prospective Blinded Multicenter Study. *JAMA Oncol*. doi: 10.1001/jamaoncol.2018.4616

Strickland KC, Howitt BE, Marqusee E, Alexander EK, Cibas ES, Krane JF & Barletta JA 2015 The Impact of Noninvasive Follicular Variant of Papillary Thyroid Carcinoma on Rates of Malignancy for Fine-Needle Aspiration Diagnostic Categories. *Thyroid* **25** 987-992.

Su HK, Dos Reis LL, Lupo MA, Milas M, Orloff LA, Langer JE, Brett EM, Kazam E, Lee SL, Minkowitz G, et al. 2014 Striving toward standardization of reporting of ultrasound features of thyroid nodules and lymph nodes: a multidisciplinary consensus statement. *Thyroid* **24** 1341-1349.

Tessler FN, Middleton WD, Grant EG, Hoang JK, Berland LL, Teefey SA, Cronan JJ, Beland MD, Desser TS, Frates MC, et al. 2017 ACR Thyroid Imaging, Reporting and Data System (TI-RADS): White Paper of the ACR TI-RADS Committee. *J Am Coll Radiol* **14** 587-595.

Trimboli P, Crescenzi A, Castellana M, Giorgino F, Giovanella L & Bongiovanni M 2018a Italian consensus for the classification and reporting of thyroid cytology: the risk of malignancy

between indeterminate lesions at low or high risk. A systematic review and meta-analysis. *Endocrine*. doi: 10.1007/s12020-018-1825-8

Trimboli P, Crescenzi A & Giovanella L 2018b Performance of Italian Consensus for the Classification and Reporting of Thyroid Cytology (ICCRTC) in discriminating indeterminate lesions at low and high risk of malignancy. A systematic review and meta-analysis. *Endocrine* **60** 31-35.

Valderrabano P, Khazai L, Leon ME, Thompson ZJ, Ma Z, Chung CH, Hallanger-Johnson JE, Otto KJ, Rogers KD, Centeno BA, et al. 2017 Evaluation of ThyroSeq v2 performance in thyroid nodules with indeterminate cytology. *Endocr Relat Cancer* **24** 127-136.

Vuong HG, Altibi AMA, Duong UNP & Hassell L 2017 Prognostic implication of BRAF and TERT promoter mutation combination in papillary thyroid carcinoma-A meta-analysis. *Clin Endocrinol (Oxf)* **87** 411-417.

Yip L, Farris C, Kabaker AS, Hodak SP, Nikiforova MN, McCoy KL, Stang MT, Smith KJ, Nikiforov YE & Carty SE 2012 Cost impact of molecular testing for indeterminate thyroid nodule fine-needle aspiration biopsies. *J Clin Endocrinol Metab* **97** 1905-1912.

Yoon JH, Lee HS, Kim EK, Moon HJ & Kwak JY 2016 Malignancy Risk Stratification of Thyroid Nodules: Comparison between the Thyroid Imaging Reporting and Data System and the 2014 American Thyroid Association Management Guidelines. *Radiology* **278** 917-924.