Different expression of TSH receptor and NIS genes in thyroid cancer: role of epigenetics

Maria D’Agostino*, Marialuisa Sponziello1,*, Cinzia Puppin3, Marilena Celano, Valentina Maggisano, Federica Baldan3, Marco Biffoni2, Stefania Bulotta, Cosimo Durante1, Sebastiano Filetti1, Giuseppe Damante3 and Diego Russo

Department of Health Sciences, University of Catanzaro ‘Magna Graecia’, Campus ‘S. Venuta’, Viale Europa, Germaneto, 88100 Catanzaro, Italy
Departments of 1Internal Medicine and Medical Specialties, and 2Surgical Sciences, University of Roma ‘Sapienza’, 00161 Roma, Italy
3Department of Medical and Biological Sciences, University of Udine, 33100 Udine, Italy
*(M D’Agostino and M Sponziello contributed equally to this work)

Correspondence should be addressed to D Russo
Email d.russo@unicz.it

Abstract

The TSH receptor (TSHR) and sodium/iodide symporter (NIS) are key players in radioiodine-based treatment of differentiated thyroid cancers. While NIS (SLC5A5) expression is diminished/lost in most thyroid tumors, TSHR is usually preserved. To examine the mechanisms that regulate the expression of NIS and TSHR genes in thyroid tumor cells, we analyzed their expression after inhibition of ras–BRAF–MAPK and PI3K–Akt–mTOR pathways and the epigenetic control occurring at the gene promoter level in four human thyroid cancer cell lines. Quantitative real-time PCR was used to measure NIS and TSHR mRNA in thyroid cancer cell lines (TPC-1, BCPAP, WRO, and FTC-133). Western blotting was used to assess the levels of total and phosphorylated ERK and Akt. Chromatin immunoprecipitation was performed for investigating histone post-translational modifications of the TSHR and NIS genes. ERK and Akt inhibitors elicited different responses of the cells in terms of TSHR and NIS genes. ERK and Akt inhibitors elicited different responses of the cells in terms of TSHR and NIS mRNA levels. Akt inhibition increased NIS transcript levels and reduced those of TSHR in FTC-133 cells but had no significant effects in BCPAP. ERK inhibition increased the expression of both genes in BCPAP cells but had no effects in FTC-133. Histone post-translational modifications observed in the basal state of the four cell lines as well as in BCPAP treated with ERK inhibitor and FTC-133 treated with Akt inhibitor show cell- and gene-specific differences. In conclusion, our data indicate that in thyroid cancer cells the expression of TSHR and NIS genes is differently controlled by multiple mechanisms, including epigenetic events elicited by major signaling pathways involved in thyroid tumorigenesis.

Key Words

- NIS
- TSH receptor
- thyroid cancer
- MAPK
- Akt
- epigenetics

Introduction

Loss of differentiation is a common feature of thyroid cancers, and it has important prognostic implications. Radioactive iodine is the most effective method for managing recurrent and metastatic disease in these patients, but it requires adequate tumor tissue expression of genes that play key roles in iodine metabolism, in particular those encoding the thyroid-stimulating hormone receptor (TSHR) and the sodium/iodide...
symporter (NIS) (Schlumberger et al. 2007, Wartofsky & Van Nostrand 2012). Many studies have demonstrated losses/reductions in NIS (SLC5A5) expression and function in primary and metastatic thyroid cancer cells as a result of oncogenic activation (Trapasso et al. 1999, Arturi et al. 2000, Puxeddu et al. 2008, Kogai & Brent 2012). Alterations involving the ras–RAF–MAPK and PI3K–Akt–mTOR signal transduction pathways have been shown to play major roles in these changes (Xing 2010). Important contributions are also made by epigenetic events, such as changes in the methylation and acetylation of histones at the level of gene promoters (Russo et al. 2011, Galrão et al. 2013). For this reason, histone deacetylase inhibitors are being investigated as a potential means for restoring NIS expression and function in thyroid cancer cells (Puppin et al. 2005, Russo et al. 2013). As far as TSHR is concerned, early studies found that the expression of this gene in most thyroid cancers is similar to or slightly lower than that found in normal thyrocytes (Brabant et al. 1991, Ohta et al. 1991, Lazar et al. 1999, Sheils & Sweeney 1999, Tanaka et al. 2000, Gérard et al. 2003, Durante et al. 2007). Few data are available on the molecular mechanisms underlying the regulation of TSHR expression in thyroid cancer cells. Indeed, at variance with the reports in tumor tissues, loss of TSHR expression has been described in most of human thyroid cancer cells (Pilli et al. 2009; Sponziello M, Durante C, Russo D & Filetti S, 2013, unpublished observations). However, hypermethylation of the TSHR promoter has been documented in a series of thyroid cancer tissues (Xing et al. 2003).

Different mechanisms thus seem to govern the expression of these fundamental markers of differentiation in thyroid cancers. Elucidation of these mechanisms might reveal important clues for the development of more effective therapeutic options for thyroid malignancies that are unresponsive to radioiodine. To this end, we examined the effects of specific MAPK and Akt pathway inhibitors on the expression of these two genes in thyroid cancer cell lines characterized by different basal levels of NIS/TSHR expression and the role played by post-translational histone modifications in the changes in NIS and TSHR expression in the cells treated with these inhibitors.

**Subjects and methods**

**Cell cultures**

We obtained human papillary thyroid carcinoma cells (TPC-1 and BCPAP) from Dr E Puxeddu of the University of Perugia. Follicular thyroid cancer cells were supplied by Dr P E Goretzki of the Tumor Center Neuss-Düsseldorf (FTC-133 cells) and Dr A Fusco of the University of Naples (WRO cells). The thyroid origins of all cell lines were confirmed by genotype analysis (Schweppé et al. 2008). The cells cultured as described previously (Arturi et al. 2001), were treated with the MEK inhibitor U0126 (10 μM in DMSO) and Akt inhibitor IV (B2311; 0.5 μM in DMSO) (both from Sigma–Aldrich; Hou et al. 2009). Control cells were exposed to DMSO alone at the same concentration used in U0126- and B2311-treated cultures.

**3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assays**

Cellular viability was evaluated with the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) method. Briefly, cells were seeded into 96-well plates (density, 3.5 × 10^4 cells/well for FTC-133 and 6 × 10^3 cells/well for BCPAP). The next day, the medium was replaced with a fresh medium, DMSO alone (controls) or containing U0126 (10 μM) or B2311 (0.5 μM). After 24 and 48 h of incubation, the medium was replaced with phenol red-free medium containing MTT (0.5 mg/ml; Sigma–Aldrich). Four hours later, the solubilized formazan product was quantified with a microplate spectrophotometer (xMark Spectrophotometer Microplate, Bio-Rad) at a wavelength of 540–690 nm.

**RNA extraction and real-time PCR**

The TRIzol method (Invitrogen) was used to extract total RNA from thyroid cancer cells (untreated or treated with U0126 or B2311). TSHR and NIS levels were determined with real-time quantitative RT-PCR, as described previously (D’Agostino et al. 2012, Celano et al. 2013). The same reaction was performed for the evaluation of the transcript levels of thyroglobulin (Tg), thyroperoxidase (TPO), PAX8, NKX2.1, and FOXE1 genes. Two micrograms of RNA were reverse transcribed in a 20 μl reaction volume using the High Capacity cDNA Kit (Applied Biosystems). The cDNAs were then diluted 1:5 in nuclelease-free H₂O (Gibco) and then amplified in an Applied Biosystems 7900HT fast real-time PCR Sequence Detection System (Applied Biosystems) using fast quantitative PCR thermal cycler parameters. A 20 μl reaction contained 1 μl of cDNA, 10 μl TaqMan Fast Universal PCR Master Mix (Applied Biosystems), and 1 μl of a primer/probe mixture for each gene evaluated. The β-actin gene was used as an endogenous reference. All amplification reactions were performed in triplicate, and the threshold cycles...
(identified with Applied Biosystems Software, SDS version 2.2.1) of the three reactions were averaged. Results were obtained by the $2^{-\Delta\Delta C_t}$ method (Livak & Schmittgen 2001) and normalized to a sample of control (untreated) cells.

**Protein extraction and western blotting**

Total proteins were extracted from the cells treated with U0126 or B2311, as described previously (D’Agostino et al. 2012). The cell lysates were quantified spectrophotometrically using the Bradford method. The samples (20 µg) were loaded onto a 12% SDS–polyacrylamide gel and subjected to electrophoresis at a constant voltage (120 V). The resolved proteins were transferred to Hybond-P ECL nitrocellulose membranes (GE Healthcare, Milan, Italy) and blocked for 1 h at room temperature with TTBS/milk (TBS, 1% Tween 20, 5% nonfat dry milk). The membranes were then incubated overnight at 4 °C with the following primary antibodies (in TTBS/milk): polyclonal anti-Akt (1:1000) and anti-phospho-Akt antibodies (1:500), both from Cell Signaling Technology (Danvers, MA, USA); polyclonal anti-ERK1,2 (1:2000) and monoclonal anti-phospho-ERK1,2 (1:1000) antibodies (Santa Cruz Biotech.). After one 15-min and two 5-min washes in TTBS, the membranes were incubated with HRP-conjugated secondary antibodies (Transduction Laboratories, Lexington, TX, USA; 1:110 000) in TTBS/milk, and the proteins were visualized with ECL Prime Reagent (GE Healthcare).

Global histone modifications were analyzed after histone acidic extraction. Briefly, the cell pellet was suspended in HCl 0.5 M added with phenylmethyl-sulphonyl fluoride and a Protease Inhibitor Cocktail (Sigma–Aldrich). Then the lysate was sonicated for 10 s three times and centrifuged at 2500 g, 10 min, 4 °C. The supernatant was collected and processed twice as described earlier. The total supernatant of the three extractions was precipitated with ten volumes of cold acetone, at $-20^\circ$C overnight. The sample was then centrifuged at 2500 g, 15 min, 4 °C; the supernatant was discarded and the pellet was resuspended in water. For western blot analysis, 15 µg protein extracts were electrophoresed on 18% SDS–PAGE. Proteins were then transferred to nitrocellulose membranes and were saturated by incubating for 1 h with 5% nonfat dry milk in PBS/0.1% Tween 20. The membranes were then incubated overnight with rabbit polyclonal anti-acetyl-histone H3 antibody (Millipore Corporation, Billerica, MA, USA), histone H3 trimethyl Lys4 antibody (Active Motif, Carlsbad, CA, USA), histone H3 trimethyl Lys27 antibody (Active Motif), or rabbit polyclonal anti H3 antibody (BioVision, Inc. Headquarters, Milpitas, CA, USA). After three washes with PBS 0.1% Tween 20, the membranes were incubated with anti-rabbit immunoglobulin coupled with peroxidase (Sigma–Aldrich). After 2 h of incubation, the membranes were washed three times with PBS 0.1% Tween 20, and the blots were developed using Chemidoc XRS (Bio-Rad) with the chemiluminescence procedure (GE Healthcare).

**Chromatin immunoprecipitation**

Cross-linkage of control and test substance-treated TPC-1, WRO, BCPAP, and FTC-133 cells was produced by exposure to formaldehyde (final concentration, 1%) at 37 °C for 10 min before harvesting. The cells were then washed twice with ice-cold PBS, scraped into 1 ml of ice-cold PBS supplemented with protease inhibitors, and centrifuged for 5 min at 3500 g (4 °C). The cell pellets were suspended in the cell lysis buffer (1% SDS, 10 mM EDTA, 50 mM Tris–HCl, pH 8.1, and protease inhibitors) and incubated on ice for 10 min. The lysed samples were sonicated to generate chromatin fragments with an average length of ~200–600 bp. After centrifugation at 11 000 g for 10 min at 4 °C, the supernatants were collected, and the samples were diluted tenfold with dilution buffer (0.01% SDS, 1.1% Triton X-100, 1.2 mM EDTA, 16.7 mM Tris–HCl, pH 8.1, and 167 mM NaCl). An aliquot (10%) saved as ‘total input chromatin’ was processed with the eluted immunoprecipitates, beginning with the cross-link reversal step. The samples were incubated (30 min, 4 °C, on a rotating platform) for preclearing with 80 µl of salmon sperm DNA/protein-A–agarose beads. The beads were then centrifuged (1 min in 3500 g), and the supernatant fractions were collected and immunoprecipitated overnight at 4 °C with 10 µg of anti-H3 acetylated polyclonal rabbit antibody (cat no. 06-599, Upstate, Millipore Corporation, Lake Placid, NY, USA); H3K4 trimethyl polyclonal rabbit antibody (cat no. 39159, Active Motif); or H3K27 trimethyl polyclonal rabbit antibody (cat no. 39155, Active Motif). All of these antibodies are appropriate for chromatin immunoprecipitation (ChIP) assays, as demonstrated in previous studies (Braunstein et al. 1996, Ieda et al. 2010, Lavarone et al. 2013). The samples and negative controls were incubated with 60 µl of salmon sperm DNA/protein-A–agarose beads for 1 h at 4 °C. The beads were pelleted by centrifugation and washed for 5 min on a rotating platform with 1 ml of each of the following buffers: low salt (0.1% SDS, 1% Triton X-100, 2 mM EDTA, 20 mM Tris–HCl, pH 8.1, and

DOI: 10.1530/JME-13-0160 Printed in Great Britain

Published by Bioscientifica Ltd.
Table 1  Primers used for readout of ChIP assays

<table>
<thead>
<tr>
<th>Primer</th>
<th>Primer forward</th>
<th>Primer reverse</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIS</td>
<td>TGCCCTCTCTG-AGCCTCAAT</td>
<td>CGTGACTCCTGT-CACTGCTT</td>
<td>TCCCCAAGGTC-CTCCCTC</td>
</tr>
<tr>
<td>TSHR</td>
<td>CCACAGGTGGT-GAGGTCACA</td>
<td>GTACCCCGAGG-CAAAAGGA</td>
<td>CTGTCGAGG-CCTCCCTC</td>
</tr>
</tbody>
</table>

150 mM NaCl); high salt (0.1% SDS, 1% Triton X-100, 2 mM EDTA, 20 mM Tris–HCl, pH 8.1, and 500 mM NaCl); LiCl wash buffer (0.25 M LiCl, 1% NP40, 1% deoxycholate, 1 mM EDTA, 10 mM Tris–HCl, and pH 8.1); and TE buffer (10 mM Tris–HCl, 1 mM EDTA, and pH 8.0). After each wash, samples were centrifuged at 4°C for 1 min at 500 g and the supernatant was discarded. Immune complexes were eluted from beads with elution buffer (1% SDS and 0.1 M NaHCO3), and cross-linkage was reversed by incubation at 65°C for 4 h. After the addition of proteinase K, Tris–HCl pH 6.5, and EDTA 0.5 M, the samples were incubated for 1 h at 45°C. DNA was purified with phenol/chloroform extraction followed by ethanol precipitation and used as a template in quantitative absolute PCR with the reaction primers listed in Table 1. After PCRs, acetylated or methylated H3 levels were measured and expressed as ratios of signals recorded after and before (input) immunoprecipitation.

Statistical analysis

TSHR and NIS mRNA levels were expressed as means ± s.d., and differences were analyzed with the Tukey–Kramer multiple comparisons test performed with GrafPAD Software for Science (San Diego, CA, USA). FOXE1, NXX2.1, Tg, and PAX8 mRNA levels were expressed as means ± s.d., and the significance of differences was assessed with the t-test. P values < 0.05 were regarded as statistically significant. Data analysis was performed by using StatView 5.0.1 software (SAS Institute, Inc., Cary, NC, USA).

Results

TSHR and NIS gene expression and regulation in thyroid cancer cell lines

Our first goal was to identify the regulatory mechanisms responsible for the NIS and TSHR mRNA expression patterns described in thyroid tumors. In vitro experiments were conducted in four human thyroid cancer cell lines characterized by different NIS and TSHR expression profiles. As shown in Fig. 1A, TSHR mRNA was detectable (i.e. present after fewer than 38 cycles of amplification) in BCPAP cells but not in TPC-1 cells (both of which are PTC-derived). The highest levels (appearance after 30 cycles of amplification) were observed in FTC-133 cells, and no TSHR transcript was detected in the second follicular cell line, WRO. In contrast, NIS mRNA was detected only in WRO and BCPAP cells (threshold cycles: 36.0 and 36.7 for WRO and BCPAP respectively, 37.8 for FTC-133 cells; Fig. 1A).

To determine whether these patterns reflect cell-line-specific forms of epigenetic control of gene expression, we performed ChIP experiments using primers specific for the minimal promoter sequences of TSHR and NIS (Fig. 1B). We evaluated the presence of histone H3 marks associated with active transcription (i.e. acetylation of lysines 9 and 14 (H3K9K14ac), trimethylation of lysine 4 (H3K4me3); Barsky et al. 1997, Santos-Rosa et al. 2002, Pokholok et al. 2005, Rando 2007) or with transcriptional repression (i.e. trimethylation of lysine 27 (H3K27me3); Barsky et al. 1997, Füllgrabe et al. 2011). In experiments focusing on the TSHR promoter, FTC-133 cells displayed the highest levels of H3K9K14ac and H3K4me3 (transcription-permissive) and the lowest levels of H3K27me3 (transcription-repressive), whereas BCPAP, TPC-1, and WRO cells all had very high levels of H3K27me3 (Fig. 1B). As for the NIS gene promoter, the post-translational H3 modifications we analyzed showed no correlation with NIS mRNA levels observed in the cell lines. Indeed, H3K27me3 levels were highest in WRO cells, which had exhibited the highest levels of NIS mRNA (Fig. 1B).

These data clearly indicate that TSHR and NIS transcript levels in FTC-133 cells are subjected to different forms of epigenetic control. In the context of current models of epigenetic regulation of gene expression (Barsky et al. 1997, Santos-Rosa et al. 2002, Pokholok et al. 2005, Rando 2007, Füllgrabe et al. 2011), the post-translational H3 modifications in the TSHR promoter region are fully consistent with the TSHR mRNA levels observed in the same cell lines, but this is not true for the NIS gene (Barsky et al. 1997, Santos-Rosa et al. 2002, Pokholok et al. 2005, Rando 2007, Füllgrabe et al. 2011).

Modulation of two major signal transduction pathways involved in thyroid tumorigenesis

In the next set of experiments, we exposed FTC-133 and BCPAP cells (the two lines with detectable levels of TSHR mRNA) to the MEK inhibitor U0126 (10 μM) and the
Akt inhibitor B2311 (0.5 μM). Both have been shown to induce NIS expression and function in other models of thyroid and non-thyroid cancer cells (Kogai et al. 2008, Hou et al. 2010, Liu et al. 2012).

As shown in Fig. 2A, western blotting showed that, at the doses used, U0126 and B2311 clearly reduced the phosphorylation of ERK or Akt respectively in both cell lines. However, the effects of inhibitors on NIS and TSHR mRNA levels were both gene- and cell line-specific (Fig. 2B). After 30 h of exposure to B2311, FTC-133 cells exhibited upregulated NIS transcription (~2.5-fold increases over control levels, P < 0.01) and downregulated expression of TSHR (approximately fivefold reductions compared with controls, P < 0.01), but no significant changes in the expression of either gene were detected in BCPAP cells. In contrast, MEK inhibition with U0126 significantly increased the expression of both NIS and TSHR in BCPAP cells but had no effects in FTC-133 cells (Fig. 2B). In addition to NIS and TSHR, effects of U0126 and B2311 on the expression of PAX8, NKK2.1, FOXE1, Tg, and TPO genes were evaluated in FTC-133 and BCPAP cells. Both in the basal and in stimulated states TPO was never detectable in all these cell lines. As shown in Fig. 3, the general profile of thyroid-specific gene expression after ERK and Akt inhibition appears to be gene- and cell line-specific.

To determine whether post-translational modifications of histone H3 were involved in the changes in TSHR and NIS expression induced by the two inhibitors, we performed ChIP assays on BCPAP cells treated for 24 h with U0126 and on FTC-133 cells exposed for 24 h to B2311. The results are shown in Fig. 4A. In FTC-133 cells, B2311-mediated AKT inhibition reduced H3K9K14ac and H3K4me3 levels (transcription activation marks) and increased levels of H3K27me3 (transcription repression) at the level of the TSHR promoter, findings that were consistent with the TSHR transcript levels shown in Fig. 2B. In contrast, at the NIS gene, instead, the same treatment decreased H3K9K14ac and H3K4me3 levels and increased levels of H3K27me3. In BCPAP cells, where MEK inhibition had increased NIS and TSHR mRNA levels (Fig. 2B), U0126 increased transcriptional activation marks (H3K9K14ac and H3K4me3) at the TSHR promoter, but had no effect on that of the NIS gene (Fig. 4A).
In order to test whether the effects induced by B2311 and UO126 on histone post-translational modifications are specific for NIS or TSHR genes, the effects on global histone levels were investigated by western blot. As shown in Fig. 4B, histone recovery was lower in FTC-133 than in BCPAP. Nevertheless, it is clear that the only significant effect that we were able to detect was the inhibitory effect of U0126 in BCPAP on H3K4me3 levels. These data indicate that most effects induced by B2311 on FTC-133 and U0126 on BCPAP at the level of histone post-translational modifications of NIS and TSHR promoter are gene-specific and not related to global effects.

These data clearly demonstrate that in thyroid cancer cell lines post-translational histone H3 modifications at TSHR and NIS are regulated by MEK and Akt signaling pathways. The effects of this regulation on the TSHR gene are fully consistent with current models of epigenetic modulation of transcription. However, this is not true for
inhibitors significantly reduced the viability of FTC-133 cells (reductions vs controls of ~20% with U0126 and 30% with B2311, after 48 h of exposure). In BCPAP cells, both inhibitors also reduced viability, but the effects were already highly significant (P<0.001) after 24 h of exposure (reductions of 30% with U0126 and 20% with B2311), and the reductions observed at 48 h were larger than those seen in FTC-133 cells (e.g. 35% with U1026 and 45% with B2311) (Fig. 5).

Discussion

Differential alteration of NIS and TSHR expression in thyroid cancer has been frequently reported. Using an in vivo model of normal human thyroid cells, we previously demonstrated that TSH suppression affects NIS mRNA levels but not those of TSHR (Bruno et al. 2005). Characterization of the elements that regulate TSHR (Kakinuma et al. 1996) and NIS (Chieffari et al. 2002) expression has stimulated/facilitated attempts to identify the roles these genes play in human thyroid cancer. Most studies have found that NIS expression in thyroid cancers is reduced or absent (except for some cases with defective membrane transport) (Kogai & Brent 2012), whereas TSHR expression in these tumors is often preserved (Brabant et al. 1991, Ohta et al. 1991, Lazar et al. 1999, Sheils & Sweeney 1999, Tanaka et al. 2000, Durante et al. 2007; Sponziello, Durante, C, Russo D & Filetti S, 2013, unpublished observations). The latter property of most thyroid cancers, combined with the TSH stimulation of NIS expression and function, has been and is currently exploited for the TSH-induced radiiodine conventional treatment of differentiated thyroid malignancies (Schlumberger et al. 2007, Wartofsky & Van Nostrand 2012).

In this study, striking differences were noted between the NIS/TSHR expression patterns observed in the various thyroid cancer cell lines we investigated, under basal conditions and after suppression of tumorigenic signaling pathways. Responses to MEK and Akt inhibitors were influenced in part by the genotypic alterations found in these cell lines. In BCPAP cells, for example, which are characterized by activating BRAF mutation (Schweppe et al. 2008), inhibition of ERK phosphorylation with U0126 upregulated the expression of NIS and TSHR. Phosphorylation of ERK has been implicated as a major mechanism underlying the BRAF-dependent loss of differentiation reported in many studies (Knauf & Fagin 2009), and our findings are thus consistent with the proposed use of inhibitors like U0126 to treat thyroid cancer (Puxeddu et al. 2011). The TSHR and NIS expression patterns were quite different in FTC-133 cells, which
Our hypothesis that the expression of NIS and TSHR is differentially regulated is also supported by our epigenetic data, especially the results of experiments conducted with FTC-133 cells. In this cell line, under basal conditions and after treatment with the Akt inhibitor, the correlation between TSHR mRNA levels and post-translation modifications of histone H3 was in accordance with current knowledge on the effects on gene expression of specific histone modifications (Füllgrabe et al. 2011). FTC-133 cells exhibited increased levels of H3K27me3 (which indicates transcriptional silencing) and reduced levels of H3K9K14ac and H3K4me3 (which are transcription-activating marks). In contrast, this is not true for expression of the NIS gene (decrease in H3K9K14ac and H3K4me3 levels and increase in H3K27me3 after treatment with the Akt inhibitor). In addition, even in BCPAP cells, H3 histone post-translational modifications resulted partially coherent with the current models of how these epigenetic marks control transcription only in the case of TSHR. However, our epigenetic data regarding both TSHR and NIS indicate that each cell line possesses its own profile, highlighting the extreme variability of this phenotype.
activity have all been shown to induce NIS expression and radioiodine uptake even in certain non-thyroid human cancer cells (Liu & Xing 2012). Finally, in our cell lines, such modifications appear when the expected effects on the cell growth are still limited to an ~30% inhibition of proliferation rate.

As epigenetic marks play major roles in the control of gene expression, further studies are needed to understand how Akt and MEK, as well as other signaling pathways, regulate gene-specific histone post-translational modifications may provide new hints for a better knowledge of mechanisms underlying thyroid tumorigenesis.

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

**Funding**
This work was supported by Fondazione ‘Umberto Di Mario’ ONLUS, Banca d’Italia, Ministero dell’istruzione, Universita e Ricerca Scientifica (MIUR-PRIN 2009) and Associazione Italiana Ricerca Cancro (AIRC), grant number IG 10296.

**Acknowledgements**
The authors thank Marian E Kent for the language revision of the manuscript.

---

**Figure 5**
Effects of MEK and Akt inhibitors on FTC-133 and BCPAP cell viability. BCPAP and FTC-133 were treated for 24 and 48 h with U0126 (10 μM) or B2311 (0.5 μM), and MTT assays were performed as described in ‘Subjects and methods’ section. Bars indicate the percentage of viable cells vs controls (untreated cells) and represent means ±1.s.d. of three experiments. ***P<0.001.

Thus, a major finding of our study is that in thyroid cancer cells MEK and Akt signaling pathways control post-translational modifications of histones at specific genes. Regulation of these epigenetic marks by signaling pathways important in cancer is an emerging notion. Studies conducted in neural stem cells, for example, have shown that MEK pathway activation modifies the effects of retinoic acid on H3K4me3 levels of various genes (Ekici et al. 2008), and the activation of the Akt pathway in MCF-7 breast cancer cells reduces the levels of H3K27me3 through phosphorylation of EZH2 (Bredfeldt et al. 2010).

Thus far, the correlation between tumor aggressiveness and histone modifications has been investigated exclusively at the overall only for global (and not gene-specific) histone modifications (Puppin et al. 2011). Our data clearly indicate that signaling through the MEK and Akt pathways in thyroid cancer cells exerts a contemporary control on distinct post-translational histone modifications, so that their ultimate effects are gene-specific. It is also important to recall that suppression of the MAPK and PI3K/Akt pathways and inhibition of histone deacetylase

---

**References**
Bredfeldt TG, Greathouse KL, Safe SH, Hung MC, Bedford MT & Walker C 2010 Xenooestrogen-induced regulation of EZH2 and histone
methylation via estrogen receptor signaling to PI3K/AKT. Molecular Endocrinology 24 993–1006. (doi:10.1210/me.2009-0438)
DOI: 10.1530/JME-13-0160 Printed in Great Britain


Received in final form 4 December 2013
Accepted 10 December 2013
Accepted Preprint published online 18 December 2013