High-mobility group A2 gene expression is frequently induced in non-functioning pituitary adenomas (NFPAs), even in the absence of chromosome 12 polysomy

Giovanna Maria Pierantoni1*, Palma Finelli2,3*, Emanuele Valtorta2, Daniela Giardino2, Ornella Rodeschini2,3, Francesco Esposito1, Marco Losa4, Alfredo Fusco1,5 and Lidia Larizza2,3

1Dipartimento di Biologia e Patologia Cellulare e Molecolare, Facoltà di Medicina e Chirurgia, Università degli Studi di Napoli ‘Federico II’, via S. Pansini 5, 80131 Naples, Italy
2Laboratorio di Citogenetica Medica e Genetica Molecolare, Istituto Auxologico Italiano, Milano, Italy
3Dipartimento di Biologia e Genetica per le Scienze Mediche, Università degli Studi di Milano, Italy
4Neurochirurgia, Ospedale San Raffaele, Milano, Italy
5NOGEC (Naples Oncogenomic Center)-CEINGE, Centro di Biotecnologie Avanzate, via Comunale Margherita 482, 80145, Naples, Italy

(Requests for offprints should be addressed to A Fusco; Dipartimento di Biologia e Patologia Cellulare e Molecolare, Facoltà di Medicina e Chirurgia di Napoli, via Pansini 5, 80131 Naples, Italy, and NOGEC (Naples Oncogenomic Center)-CEINGE, Centro di Biotecnologie Avanzate, via Comunale Margherita 482, 80145, Naples, Italy; Email: afusco@napoli.com)

*(G M Pierantoni and P Finelli contributed equally to this work)

Abstract
The high-mobility group A2 (HMGA2) gene has a critical role in benign tumors where it is frequently rearranged, and in malignant tumors, where it is overexpressed in the absence of structural modification of the HMGA2 locus. By previous fluorescence in situ hybridization (FISH) and reverse transcriptase PCR analyses on human prolactin-secreting pituitary adenomas we detected rearrangement of the HMGA2 gene and amplification of its native region associated with activated expression. These data indicated a role for the HMGA2 gene in the development of human pituitary prolactinomas, since they are consistent with the appearance of prolactin/growth hormone adenomas in transgenic mice overexpressing the HMGA2 gene. To assess a more general role for HMGA2 in pituitary oncogenesis, we investigated HMGA2 amplification and expression in a panel of non-functioning pituitary adenomas (NFPAs) which account for 25% of all pituitary adenomas. We provide evidence that out of 18 NFPA tumors tested, 12 expressed HMGA2, but, different from prolactinomas, only in two cases the upregulation of the gene could be associated with amplification and/or rearrangement of the HMGA2 locus. Increased dosage of chromosome 12 was found in the expressing and non-expressing NFPAs, confirming that this sole event is insufficient to drive up activation of the HMGA2 gene. A role for chromosome 12 polysomy to promote structural instability of HMGA2 is confirmed, but the mechanism via trisomy is less prevalent in the frequently hyperdiploid prolactinomas. Micro-rearrangements of HMGA2 gene not detectable by FISH analysis and/or sequence alterations could contribute to upregulation of HMGA2 gene in pituitary adenomas of the NFPA subtype. However, it cannot be excluded that the HMGA2 overexpression may be due, in some NFPA patients, to the same, still mainly unknown, mechanisms responsible for HMGA2 overexpression in malignant neoplasias.

Endocrine-Related Cancer (2005) 12 867–874

Introduction
Pituitary adenomas are common benign, monoclonal neoplasms accounting for approximately 15% of intracranial tumors (Kovacs & Horvath 1986, Monson et al. 2000). Despite benign proliferations of adenohypophysial cells, they cause significant morbidity due to critical location, expanding size and/or inappropriate...
pituitary hormone expression. Various subtypes have been recognized on the basis of clinical presentation, as well as immunocytochemical and ultrastructural characteristics. About one-third of pituitary adenomas are not associated with clinical hypersecretory syndromes, but with symptoms of an intracranial mass such as headaches, hypopituitarism or visual-field disturbances, and are classified as non-functioning pituitary adenomas (NFPAs). The genesis of pituitary tumors is still under investigation since the genetic alterations of the pituicytes themselves, hypothalamic dysregulation and locally produced growth factors have not been integrated in a multistep model of carcinogenesis. According to this model, genetic alterations represent the initializing event that transforms cells, whereas hormones and/or growth factors play a role in promoting cell proliferation. However, apart from activating mutations of GNSA1, which have been associated with 40% of sporadic somatotrophic adenomas and with 10% of NFPAs, none of the candidate cell-cycle, receptor, second-messenger or related genes examined thus far appear to be individually responsible for more than a few percent of sporadic pituitary adenomas. Somatic mutations identified in other malignancies such as MEN1 mutations, commonly found in patients affected by the MEN-1 syndrome, have been rarely found in sporadic pituitary adenomas, although a decreased expression of menin has been demonstrated (Theodoropoulou et al. 2004). Equally, even though p27kip1 and Rb inactivation is associated with the development of pituitary adenomas of the intermediate lobe in mice, no such mutations have been identified in human pituitary adenomas (for a review see Levy & Lightman 2003). Increased expression of pituitary tumor transforming gene (PTTG), encoding a securin protein, has been found in sporadic pituitary adenomas, and the development of multifocal plurihormonal focal pituitary adenomas in male transgenic mice overexpressing PTTG supports its role in pituitary cell proliferation (Levy & Lightman 2003, Abbud et al. 2005).

Recently, our group suggested a critical role for high-mobility group A2 (HMGA2) in pituitary oncogenesis. It has been shown that transgenic mice overexpressing the HMGA2 gene develop growth hormone- and prolactin-secreting adenomas (Fedele et al. 2002). The HMGA protein family consists of a group of small nuclear non-histone chromatinic proteins. They are involved in the regulation of chromatin structure (Fashena et al. 1992) and play an important role in the assembly of a multi-protein transcriptional complex that regulates the transcription of the target genes (Grosschedl et al. 1994).

HMGA proteins play a crucial role in the process of carcinogenesis. In fact, chromosomal translocations of 12q13-15, involving the HMGA2 gene, leading to rearrangements and dysregulated expression of the HMGA2 gene, have been frequently detected in benign human tumors of mesenchymal origin (Ashar et al., 1995, Schoenmakers et al. 1995). Conversely, malignant neoplasias show an abundant expression of the HMGA2 gene that is required for malignant cell transformation (Berlingieri et al. 1995, Giancotti et al. 1985, 1987, Abe et al. 2003). Consistently with the development of prolactin adenomas in HMGA2 transgenic mice, induction of HMGA2 expression was observed in human prolactinomas in association with amplification and/or rearrangement in most of the tumor samples analyzed (Finelli et al. 2002), whereas the HMGA2 gene was not expressed at all in normal pituitary gland.

The aim of the present work has been to assess the putative involvement of the HMGA2 gene in another pituitary adenoma subtype, such as the NFPAs. NFPAs are benign neoplasias that differ from prolactinomas in showing more frequently a normal karyotype and a lower frequency of trisomy 12 when the karyotype is aberrant (Finelli et al. 2000). Therefore, we analyzed HMGA2 gene expression and possible cytogenetic alterations in a representative panel of 18 NFPAs. Results obtained by fluorescence in situ hybridization (FISH) analysis and reverse transcriptase (RT)-PCR expression show that the majority of NFPAs express HMGA2, which, at odds with prolactinomas, is not associated with over-representation of the HMGA2 region, and only in a few cases is driven by rearrangement of the gene.

Materials and methods
Patients and tumor specimens

The NFPAs tissue samples were obtained at transsphenoidal surgery from 18 patients, 11 of whom had undergone surgery for visual defects (pituitary adenomas (PAs) 80, 84, 86, 92, 100, 105, 107, 109, 114, 116 and 120), five for prevention (PAs 82, 93, 99, 103 and 120), five for prevention (PAs 82, 93, 99, 103 and 120), and two for an increase in tumor size (PAs 110 and 112). The non-functioning secreting pituitary adenomas were clinically and hormonally characterized on the basis of standard endocrinological criteria; the tumor subtype was confirmed by routine immunohistochemistry analysis (Table 1). Seven of 18 tumors (PAs 80, 84, 103, 110, 114, 115, 112) presented with invasion of cavernous sinus. Most of the patients had not received any chemotherapy or radiation therapy.
Table 1 Summary of the results obtained from immunohistochemical, cytogenetic interphase FISH (I-FISH) and RT-PCR analyses on a panel of NFPAs

<table>
<thead>
<tr>
<th>NFPA</th>
<th>Immuno-histochemistry</th>
<th>Karyotype</th>
<th>I-FISH of chromosomes αX, 5, 8, 12</th>
<th>HMGA2 I-FISH (% nuclei)</th>
<th>HMGA2 RT-PCR</th>
<th>1-3 ex</th>
<th>1-5 ex</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>negative</td>
<td>46, XY[8]</td>
<td>Tris X</td>
<td>~90</td>
<td>7(2)</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>82(3)</td>
<td>30% FSH, 2% GH</td>
<td>46, XY[4]</td>
<td>Tris 12</td>
<td>&gt;98</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>92</td>
<td>5% LH, 5% TSH</td>
<td>44-46, XY, der(1)ins(11q1p)[3][c p5]</td>
<td>Tris X</td>
<td>&gt;94</td>
<td>+ nd</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>93</td>
<td>30% FSH</td>
<td>45-47, XY, +X[12], +11[2], +17[2] -17[3], -19[3][cp19]</td>
<td>Tris X</td>
<td>&gt;94</td>
<td>+ nd</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>99(5)</td>
<td>60% LH, 40% FSH</td>
<td>53-60, +3n+, XXY, -1[5], -2[6], -5[4], -7[6], -8[5], -13[5], -17[7], -19[5], -22[5], 2mar[cp8]/46, XY[3]</td>
<td>Tris 12</td>
<td>12</td>
<td>74(4)/0</td>
<td>13(6)</td>
<td>+</td>
</tr>
<tr>
<td>100(7)</td>
<td>90% ACTH, 1% PRL</td>
<td>46-50, XY, +9[3], +12[3], +14[2] [cp 4]</td>
<td>Tris 12</td>
<td>&gt;96/0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>103(7)</td>
<td>70% TSH, 1% PRL</td>
<td>nd</td>
<td>Tetra 12</td>
<td>0/70</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>105</td>
<td>80% FSH, 2% LH</td>
<td>47, XX, +8</td>
<td>Tris 8</td>
<td>&gt;90</td>
<td>+ nd</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>107(7)</td>
<td>20% FSH</td>
<td>nd</td>
<td>Tris 12 and X</td>
<td>~90/0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>109</td>
<td>negative</td>
<td>46, XX[3]</td>
<td></td>
<td>&gt;97</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>110</td>
<td>10% LH</td>
<td>46, XY[3]</td>
<td></td>
<td>&gt;97</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>114(7)</td>
<td>40% FSH</td>
<td>nd</td>
<td>Tris 12</td>
<td>~80</td>
<td>~20/0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>115</td>
<td>2% FSH, 2% LH</td>
<td>46, XY[5]</td>
<td></td>
<td>99</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>116</td>
<td>5% FSH, 2% LH</td>
<td>46, XX[5]</td>
<td></td>
<td>&gt;94</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td>46, XX[6]</td>
<td></td>
<td>&gt;98</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>C1</td>
<td></td>
<td>46, XX</td>
<td></td>
<td>&gt;96</td>
<td>2/1</td>
<td>0</td>
<td>nd</td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td>46, XY</td>
<td></td>
<td>&gt;97</td>
<td>1/2</td>
<td>0.3</td>
<td>nd</td>
</tr>
<tr>
<td>C3</td>
<td></td>
<td>46, XX</td>
<td></td>
<td>&gt;98</td>
<td>1/2</td>
<td>0</td>
<td>nd</td>
</tr>
<tr>
<td>C4</td>
<td></td>
<td>46, XY</td>
<td></td>
<td>&gt;97</td>
<td>1/2</td>
<td>0</td>
<td>nd</td>
</tr>
</tbody>
</table>

(1) sp, split red/green signals.
(2) Nuclei with additional signal(s) given by BAC 698i6 targeting the HMGA2 3' region.
(3) Tumors previously studied in Finelli et al. 2002, and studied in this work with centromeric/pericentromeric probes in I-FISH.
(4) In PA 99 we observed a heterogeneous pattern of FISH signals with a major trisomic clone (53%) characterized by three signals of the same intensity of control cells and a trisomic subclone (21%) with one/two HMGA2-specific signals of reduced intensity.
(5) Over-representation of the HMGA2 region as compared to the copy number of chromosome 12 assessed by dual-color FISH of D12Z3 and HMGA2 BACs in 36% of nuclei controlled.
(6) We observed uncoupled signals in 13% of the nuclei in particular 8% of nuclei with one/two signal/s given by the probe covering the HMGA2 5' gene (BAC 669g18) and 5% of nuclei with one/two signal/s given by the probe targeting the HMGA2 3' region (BAC 698i6).
(7) No over-representation of the HMGA2 region as compared to the copy number of chromosome 12 as specified above.
nd, not determined; FSH, follicle-stimulating hormone; GH, growth hormone; LH, luteinizing hormone; PRL, prolactin; TSH, thyroid-stimulating hormone; ACTH, adrenocorticotropic hormone.
before surgery. Histological analysis was performed as described previously (Finelli et al. 2000). PAs 82 and 86 were described previously (Finelli et al. 2002).

Cell cultures and cytogenetic analysis

The primary pituitary cell cultures were set up as described elsewhere (Bettio et al. 1997). The phytohemagglutinin (PHA)-stimulated peripheral blood cultures were set up according to standard procedure. The Q-banding of fluorescence using Quimacrine (QFQ) banding technique was used for cytogenetic analysis, and the International System for Human Cytogenetic Nomenclature was adopted (Mitelman 1995).

FISH studies

FISH analysis on nuclei was performed by using the following alphoid probes: pZ8.4 (D8Z8) and pDMX1 (DXZ1; Archidiacono et al. 1995), and pBR12 (D12Z3; Baldini et al. 1990). YAC 882a10, which maps on chromosome 5p13, was from the CEPH YAC library, as described by Finelli et al. (2000), encompassing the 5′ HMGA2 untranslated region and exons 1–3 and the 3′ (exons 3–5 and the 3′ untranslated region) portions of HMGA2 gene are described in previous works (Finelli et al. 2002, Pierantoni et al. 2003).

The procedure described by Lichter et al. (1990) and Lichter & Cremer (1992), with some modifications, was used for dual-color FISH experiments on interphase nuclei from direct tumor preparations or short-term culture tumor preparations. Briefly, the probes were labeled by nick-end translation with biotin or digoxigenin (Roche Molecular Biochemicals, Germany). For each in situ hybridization experiment, 200 ng labeled alphoid probe and/or 500 ng labeled YAC/BAC probes were used in a 10 μl volume of hybridization solution. The FISH procedure, detection of biotin- and digoxigenin-labeled probes, nuclei/chromosome counterstaining and digital-image analysis are described elsewhere (Finelli et al. 2000). The images were edited using Adobe Photoshop 7 (Adobe System, Mountain View, CA, USA). As described previously, scoring was based on >200 nuclei per each tumor sample and for reference purposes the background percentage of nuclei with more or less than two signals and the percentage of nuclei with a split hybridization signal were calculated. PHA-stimulated lymphocytes from healthy individuals were hybridized in parallel.

RNA extraction and RT-PCR analysis

Pituitary adenomas were dissected rapidly, frozen on dry ice and stored at −80°C. Total RNA was extracted using TRI reagent solution (Molecular Research Center, Cincinnati, OH, USA) according to the manufacturer’s protocol. 5 μg total RNA, digested with RNase-free DNase, were reverse-transcribed using random hexanucleotides as primers (100 mM) and 12 units avian myeloblastosis virus RT (Promega). The cDNA was amplified in a 25 μl reaction mixture containing 0.2 mM dNTP, 1.5 mM MgCl2, 0.4 mM of each primer and 1 unit Taq DNA polymerase (Perkin-Elmer). After a de-naturing step (95°C for 2 min) the cDNA was further amplified in 20 PCR cycles (95°C for 1 min, 58°C for 30 s and 72°C for 30 s). The following primers were used to amplify the HMGA2 transcript: forward primer, 5′-CGAAGGTGCTGGGAGCTCCGG-3′, which maps onto the first exon; reverse primer, 5′-CATTTCTTAGGTCGCTTCTTG-3′, which maps onto the third exon; reverse primer II, 5′-CTAGTCTCTTCCGAGCTC-3′, which maps onto the fifth exon.

Expression of the GAPDH gene was used as an internal control for the amount of cDNA tested. The specific primers were: forward, 5′-ACATGTCAAAATATATTCC-3′; reverse, 5′-TGACCTCCAGACTCA-3′ (corresponding to nucleotides 195–215 and 355–335, respectively). The reaction products were analyzed on a 2% agarose gel, and transferred to GeneScreen plus nylon membranes (Dupont, Boston, MA, USA). The membranes were hybridized with a HMGA2 cDNA probe. cDNA probes obtained by PCR were labeled with [32P]dCTP using random oligonucleotide primers (Ready-To-Go; Pharmacia) at a specific activity equal to or higher than 7 × 106 c.p.m./μg.

Results

Chromosome analysis

Table 1 shows a list of the 18 NFPA samples analyzed in our study. Their immunohistochemical patterns are also specified. All the tumors were examined using conventional cytogenetics, either on direct or short-term culture chromosome preparations, with successful karyotyping of 14 tumors. An abnormal karyotype was found in five adenomas (PAs 92, 93, 99, 100 and 105), while an apparently normal karyotype was observed in the remaining nine tumors (Table 1, third
the 3 was disomic for suggestive of intra-
decreased intensity as well as split signals are highly
green) signal (Fig. 1A and Table 1). Signals of
HMGA2 green) subclones (summing up to 13%) with one regular (red/
specific signals of reduced intensity, and minor disomic
HMGA2 a trisomic subclone (21%), with one/two
by three signals of the same intensity of control cells,
displayed a major trisomic clone (53%), characterized
FISH signals was given by PA 99: in fact, this sample
omy in 20–96% of nuclei. A heterogeneous pattern of
trisomy, and PA 103, which showed
namely PAs 99, 100, 107 and 114, showing
HMGA2-specific probes with a D12Z3-specific alphoid probe. As
probes and different combinations of
HMGA2-reported in Table 1, dual-color FISH of
BAC probes with a D12Z3-specific alphoid probe. As
short-term tumor preparations using
HMGA2-specific probes and different combinations of
HMGA2-specific BAC probes with a D12Z3-specific alphoid probe. As
reported in Table 1, dual-color FISH of
HMGA2-specific BACs showed on 12 out of 18 NFPAs two
pairs of red/green overlapping spots. This pattern
corresponds to that of peripheral blood cells from
healthy individuals (C1–C4 in Table 1) in the great
majority of nuclei (90–99%). Conversely, an increased
dosage of the target region was detected in five tumors,
namely PAs 99, 100, 107 and 114, showing
HMGA2 trisomy, and PA 103, which showed
HMGA2 tetrasomy in 20–96% of nuclei. A heterogeneous pattern of
FISH signals was given by PA 99: in fact, this sample
displayed a major trisomic clone (53%), characterized
by three signals of the same intensity of control cells,
a trisomic subclone (21%), with one/two
HMGA2-specific signals of reduced intensity, and minor disomic
subclones (summing up to 13%) with one regular (red/green) HMGA2 signal and one split (either red or
green) signal (Fig. 1A and Table 1). Signals of
decreased intensity as well as split signals are highly
suggestive of intra-HMGA2 rearrangements. PA 80
was disomic for HMGA2 in most cells but contained a
small subclone (7%) with an additional signal given by
the 3’ HMGA2 BAC (Fig. 1B). FISH results with
HMGA2 BACs on both NFPAs showing subclones with an atypical pattern were confirmed in independent
experiments. Co-hybridization of HMGA2 BACs with
chromosome 12 alphoid-specific probe was then
performed on the two above NFPAs to detect selective
overrepresentation of the HMGA2 region, in addition
to the trisomy of chromosome 12, when present. These
FISH experiments revealed in PA 99 a number of spots
higher than that given by the alphoid probe in about
36% of the nuclei. This percentage derived from the
sum of the trisomic subclone with signals of reduced
intensity (21%) and that of disomic subclones with
split signals (13%).

Interphase FISH
To assess the normal/abnormal chromosomal set of
tumors where cytogenetic analysis failed (PAs 84, 103,
107 and 114) or only a few metaphases could be
analyzed, we performed FISH of centromeric/pericentromeric probes specific to chromosomes
found at increased dosages in previous studies (Finelli
et al. 2000), i.e. chromosomes 5, 8, 12 and X. By this
approach, we observed the presence of trisomy X in
PA 84, trisomy 12 in PA 114, tetrasomy 12 in PA 103
and combined trisomy 12 and X in PA 107, accounting
for the four tumors where conventional cytogenetics
failed. In addition, we could confirm trisomy 8 in PA
105, trisomy X in PA 93, trisomy 12 in PA 100 and
trisomy 12 and X-specific signal in PA 99
(Table 1, fourth column). Based on previous findings in
prolactin-secreting adenomas (Finelli et al. 2002), we
conducted FISH experiments on 16 non-functioning
secreting pituitary adenomas to establish the dosage
and putative rearrangements of HMGA2. Interphase
dual-color FISH was performed on nuclei from direct/
short-term tumor preparations using
HMGA2-specific probes and different combinations of
HMGA2-specific BAC probes with a D12Z3-specific alphoid probe. As
reported in Table 1, dual-color FISH of
HMGA2-specific BACs showed on 12 out of 18 NFPAs two
pairs of red/green overlapping spots. This pattern
corresponds to that of peripheral blood cells from
healthy individuals (C1–C4 in Table 1) in the great
majority of nuclei (90–99%). Conversely, an increased
dosage of the target region was detected in five tumors,
namely PAs 99, 100, 107 and 114, showing
HMGA2 trisomy, and PA 103, which showed
HMGA2 tetrasomy in 20–96% of nuclei. A heterogeneous pattern of
FISH signals was given by PA 99: in fact, this sample
displayed a major trisomic clone (53%), characterized
by three signals of the same intensity of control cells,
a trisomic subclone (21%), with one/two
HMGA2-specific signals of reduced intensity, and minor disomic
subclones (summing up to 13%) with one regular (red/green) HMGA2 signal and one split (either red or
green) signal (Fig. 1A and Table 1). Signals of
decreased intensity as well as split signals are highly
suggestive of intra-HMGA2 rearrangements. PA 80
was disomic for HMGA2 in most cells but contained a
small subclone (7%) with an additional signal given by
the 3’ HMGA2 BAC (Fig. 1B). FISH results with
HMGA2 BACs on both NFPAs showing subclones with an atypical pattern were confirmed in independent
experiments. Co-hybridization of HMGA2 BACs with
chromosome 12 alphoid-specific probe was then
performed on the two above NFPAs to detect selective
overrepresentation of the HMGA2 region, in addition
to the trisomy of chromosome 12, when present. These
FISH experiments revealed in PA 99 a number of spots
higher than that given by the alphoid probe in about
36% of the nuclei. This percentage derived from the
sum of the trisomic subclone with signals of reduced
intensity (21%) and that of disomic subclones with
split signals (13%).

HMGA2 gene overexpression in non-functioning secreting pituitary
adenomas
RT-PCR analysis, using primers specific for exons
1 and 3 of HMGA2 gene, was performed in parallel to
check the HMGA2 expression in the NFPAs evaluated
by cytogenetics and interphase FISH. 15 tumors could
be investigated together with PAs 82 and 86, used as
negative controls in our previous study (Finelli et al.
2002). Insufficient material has been obtained to
evaluate the HMGA2 expression in PA 93. As shown
in Fig. 1C, most tumors (12/15) showed
HMGA2-specific mRNA, whereas only PAs 100, 103 and 109
were negative. Notable differences in the levels of
HMGA2 mRNA could be appreciated among tumors,
with a group that expresses high levels of
HMGA2 mRNA (PAs 112, 114, 115 and 120) and one that
expresses HMGA2 at low levels (PAs 84, 92, 105, 110
and 116). As expected, HMGA2 was not expressed in
normal pituitary gland (Fig. 1C, lane NP; Zhou et al.
1995). To verify the presence of truncated transcripts of
the HMGA2 gene, we evaluated the expression of
the entire HMGA2 transcript in 15 of the NFPAs
tumours. To this end, we have utilized primers specific
for exons 1 and 5 of the HMGA2 gene, which amplify
the entire coding sequence. Eight adenoma samples,
PAs 84, 107, 110, 112, 114, 115, 116 and 120, showed
HMGA2 gene expression, indicating the presence of
a standard-sized transcript, whereas in the other
samples, PAs 80, 82, 86, 99, 100, 103 and 109, no
amplification was observed (Fig. 1D). The results from
PAs 82, 86, 100, 103 and 109 confirm those obtained
by using the other HMGA2 primer pair. The results
obtained for PAs 80 and 99 were consistent with the
FISH results, where we observed a hybridization pattern suggestive of intra-HMGA2 rearrangements.
For all PCR assays the amplification was also
performed with non-reverse-transcribed RNAs to
exclude DNA contamination (data not shown).
Discussion

Previous data from our group suggest an involvement of the *HMGA2* gene in human prolactinomas. In fact, overrepresentation of the genomic region where *HMGA2* resides (12q14) and/or rearrangement of the gene were demonstrated by FISH experiments in association with an increased expression of *HMGA2* gene (Finelli *et al.* 2002). A causal role of HMGA2 in prolactinomas was supported by the appearance of prolactin/growth hormone adenomas in transgenic *HMGA2* mice (Fedele *et al.* 2002), and by data indicating an oncogenic role for this protein (Fedele *et al.* 1998). Here, we extended the analysis of the *HMGA2* gene to a sample of 18 NFPAs to assess its putative involvement by increased dosage and rearrangement in this common pituitary adenoma subtype. Results obtained by FISH analysis and RT-PCR show that most NFPAs express HMGA2. However, differently from prolactinomas, HMGA2 expression is not commonly associated with overrepresentation of the *HMGA2* region, and is associated with *HMGA2* rearrangement only in two out of 17 NFPAs. In fact, in both the PA 80 and 99 samples, *HMGA2* rearrangement could be observed, by interphase FISH scoring, in low-represented tumor clones, showing uncoupling of the signals given by BACs monitoring the contiguous 5' and 3' portions of *HMGA2* with loss of either signal in a fraction of cells. Moreover, in PA 99 different rearrangements were triggered by the initial *HMGA2* break, as assessed by the heterogeneity in the intensity of the uncoupled FISH signals and the alternative loss of one of them in different tumor subclones (Fig. 1A).

Despite the fact that *HMGA2* rearrangement was monitored only in a fraction of cells in tumors PAs 80 and 99, RT-PCR analysis showed only aberrant transcripts. This suggests that microrearrangements of the gene or sequence alterations, not detectable by FISH analysis, also affected the majority of tumor cells with apparent integrity of the *HMGA2* region by FISH analysis. Interestingly, one of the two rearranged NFPAs, PA 99, showed a consistent fraction of cells...
trisomic for chromosome 12, which represents likely a primary genetic event that might facilitate the occurrence of further rearrangements. Indeed, evidence has been provided that polysomy promotes structural instability in tumor-cell chromosomes through asynchronous replications and breaks within late-replicating regions (Kost-Alimova et al. 2004). The \textit{HMGA2} region falls within a G-dark band, which likely corresponds to a late-replicating region that may become a preferential site of structural rearrangements in the unstable polysomic chromosome 12. As already demonstrated in a high number of benign tumors of mesenchymal origin (Schoenmakers et al. 1995) and for two cases of prolactinomas (Finelli et al. 2002), the rearrangement of the \textit{HMGA2} gene in PAs 80 and 99 results in a break in the large intervening sequence (IVS3) that separates the third from the fourth exon. This would induce the oncogenic potential of the HMGA2 protein because of the loss of its C-terminal tail, as demonstrated previously (Fedele et al. 1998, Battista et al. 1999).

As demonstrated previously for prolactinomas, the sole trisomy 12 is not sufficient for HMGA2 expression, which is associated with overrepresentation of the \textit{HMGA2} region and/or rearrangement. In fact, PAs 100 and 103 were trisomic and tetrasomic for chromosome 12, but they did not have overrepresentation of the 12q14 region (data not shown) and did not express HMGA2. Since overrepresentation of \textit{HMGA2} region, via trisomy or tetrasomy, is quite common in prolactinomas (Finelli et al. 2002), and rare in NFPAs, we retain that the polysomy rearrangement is a major contributor to \textit{HMGA2} activation in prolactinomas, while it is implicated less in NFPAs, most of which have a diploid karyotype. Since FISH experiments have shown the common lack of an extra chromosome 12 and rearrangements only in a small percentage of cells that would trigger new rearrangement in the polysomic chromosome, and most NFPAs express high levels of \textit{HMGA2} transcript, other mechanisms able to activate HMGA2 expression should occur in human NFPAs. Alternative HMGA2-activating mechanisms, among which sequence alterations or dysregulation by cryptic rearrangements, need further study. In fact, it cannot be excluded that the \textit{HMGA2} overexpression may be due to the same, still mainly unknown, mechanisms responsible for \textit{HMGA2} overexpression in malignant neoplasias.

In conclusion, the findings reported here extend those obtained in prolactinomas by confirming the involvement of HMGA2 in pituitary oncogenesis. Since \textit{HMGA2} transgenic mice never develop NFPAs, and since rearrangements of \textit{HMGA2} are rare in this subtype, we can also hypothesize that whereas in most human prolactinomas \textit{HMGA2} overexpression would represent one of the initial and causal events, in most NFPA subtypes \textit{HMGA2} overexpression might represent a secondary event that occurs independently of the specific initializing event and might be responsible for tumor progression. However, this hypothesis needs to be validated by future work.

**Acknowledgements**

This work was supported by grant from the Ministero della Sanità to Istituto Auxologico Italiano, and from AIRC, the Progetto Finalizzato ‘Biotecnologie’ of the CNR, the MURST projects ‘Terapie antineoplastiche innovative’ and ‘Piani di Potenziamento della Rete Scientifica e Tecnologica’. COST ACTION B19 ‘Molecular Cytogenetics of Solid Tumors’ is acknowledged for stimulating discussion. We thank the Associazione Partenopea per le Ricerche Oncologiche (APRO) for its support. The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

**References**


Berlingieri MT, Manfioletti G, Santoro M, Bandiera A, Visconti R, Giancotti V & Fusco A 1995 Inhibition of
HMGIC protein synthesis suppresses retrovirally induced neoplastic transformation of rat thyroid cells. Molecular and Cellular Biology 15 1545–1553.


