The ovary is the seventh most common site of cancer in women, after cancer of the breast, cervix, colon/rectum, stomach, corpus uteri, and lung. Incidence rates for ovarian cancer show a wide geographic variation. The highest incidence rates are observed in north-western Europe, the USA and Canada, whereas the lowest rates are observed in Asia, Africa and Latin America (Chenet et al., 1992; Lynch et al., 1993). In the USA, it was estimated that in 1999, 25 200 new cases would be diagnosed with ovarian cancer and that 14 500 women would die of this disease (Partridge and Barnes, 1999). In the UK, the incidence of ovarian cancer is over 5000 new cases every year and it accounts for 4275 deaths per year (Changet al., 1994). Patients with early-stage ovarian cancer, in whom the disease is confined to one or both ovaries (stage I), have good prognoses with a 5 year survival rate > 80%. The prognosis of patients with advanced disease, in whom the tumour is confined to one or both ovaries (stage I), have good prognoses with a 5 year survival rate > 80%. The prognosis of patients with advanced disease, in whom the tumour has spread within or beyond the abdominal cavity (stage III and stage IV) have a significantly worse prognosis, with only 20% of patients surviving 5 years (Friedlander, 1998). The overall survival rate in ovarian cancer is as low as 30% as most (70–80%) patients present with advanced disease (Pecorelli et al., 1999). Any method that enables the early detection of ovarian cancer would lead to a significant decrease in mortality.

Ovarian cancer encompasses a broad range of lesions: from localized benign tumours and tumours of borderline malignant potential, to invasive malignant adenocarcinomas. Histologically, most (85–90%) malignant ovarian tumours are of the epithelial type, which can be further grouped into histological types as: serous cystadenocarcinoma (42%), mucinous cystadenocarcinoma (12%), endometrioid carcinoma (15%), undifferentiated carcinoma (17%) and clear cell carcinoma (6%). Approximately 5–10% of ovarian cancer is hereditary. It is clear now that most hereditary ovarian carcinoma cases (breast-ovarian cancer syndrome and site-specific ovarian cancer) occur in women with germline mutations in the BRCA1 (for ‘breast cancer 1’) gene (Miki et al., 1994) or the BRCA2 (for ‘breast cancer 2’) gene (Wooster et al., 1995). Women harbouring such mutations are at a 27–60% risk of developing this disease in their life (Ford et al., 1998). Ovarian cancer associated with the hereditary nonpolyposis colon cancer syndrome (Lynch syndrome type II) is the result of mutations in one of the four known DNA mismatch repair genes: hMSH2 (chromosome 2p), hMLH1 (chromosome 3p), hPMS1 (chromosome 2q) and hPMS2 (chromosome 7p) (Aaltonen and Peltomaki, 1994). It was initially anticipated that somatic mutations in BRCA1, BRCA2 and mismatch repair genes would be as important in the development of sporadic epithelial ovarian cancer as in the case of the Rb1 gene, which contributes to the tumorigenesis of both hereditary and sporadic retinoblastoma. Surprisingly, very few mutations in BRCA1 (Takahashi et al., 1995), BRCA2 (Lancaster et al., 1996) and mismatch repair genes have been identified in sporadic cases, indicating a genetic difference between hereditary and sporadic ovarian cancer.

Epithelial ovarian cancer has a clonal origin (for a review, see Shelling et al., 1995), and multiple genetic alterations must occur during the malignant transformation of a single ovarian surface epithelial cell (Godwin et al., 1992). The genes that may contribute to the tumorigenesis of sporadic ovarian cancer fall into two categories: oncogenes and tumour suppressors. Oncogenes are dominant transforming genes as their activation can be caused by an alteration in a single allele. Activation of oncogenes can occur through a variety of mechanisms such as point mutation, amplification, overexpression and translocation. The normal counterpart of oncogenes, proto-oncogenes, are involved in the control of cell proliferation and differentiation. More than 60 oncogenes have been discovered and several, such as cKRAS, cERB2, cFMS, cMYC and AKT2, have been studied.

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in ovarian cancer (Godwin et al., 1997). Although oncogenes may influence ovarian cancer, little is known about how and at what level the oncogenes participate in the malignant transformation of the ovarian surface epithelium (Auersperg et al., 1998). Tumour suppressor genes, unlike oncogenes, act recessively. That is, it is the loss or inactivation of both copies of a tumour suppressor gene that remove normal constraints to cell proliferation (Fig. 1a). Proof that a gene is a tumour suppressor is usually derived from transfection experiments by introduction of its wild type to malignant cells, and analysis of colony formation with a selection marker (Haber and Harlow, 1997). The ultimate proof comes from mouse knockout experiments. Two or more different suppressor genes may be inactivated in the same tumours, and the same suppressors, like the TP53 gene, may be inactivated in different tumour types. Since tumour suppressor genes play an essential role in maintaining normal cell growth, effort has been put into isolation of tumour suppressors involved in the pathogenesis of ovarian cancer.

Positional cloning has been the main strategy applied to localization and identification of tumour suppressor genes. This strategy has been very successful as is evident from the genes identified in the past decade. The main approaches involved in this strategy are: (i) cytogenetic studies to identify chromosomal alterations in patients with cancer; (ii) DNA linkage techniques to localize genes involved in inherited predisposition to cancer; and (iii) examination for loss of heterozygosity (LOH) or allele loss studies in sporadic tumours. In the ideal case, a region with a homozygous deletion is a hallmark for the location of a tumour suppressor gene, as both of the alleles are lost, such as in the case of the BRCA2 gene. This review focuses primarily on identified or potential tumour suppressor genes implicated in sporadic ovarian cancer.

**Cytogenetic changes in sporadic ovarian cancer**

Techniques applied in cytogenetics commonly include chromosome banding, microdissection and fluorescent in situ hybridization (FISH). In addition to these traditional methods, new methods have been developed to allow easier identification of genomic amplifications or deletions. Comparative genomic in situ hybridization (CGH) allows fluorescent identification of chromosome gain and loss in human cancers within a single experiment. This method does not require mitotic cells, cell culture, or prior knowledge of regions of abnormality, and can be performed with small amounts of DNA (Iwabuchi et al., 1995). For example, studies using CGH have revealed the number of copies of one region at 3q26, where PIK3CA (PI3-kinase) that encodes the p110alpha catalytic subunit of phosphatidylinositol 3-kinase is located, as having increased in approximately 40% of ovarian and other cancers. The association between the number of copies of PIK3CA and PI3-kinase activity makes PIK3CA a candidate oncogene, because a broad range of normal cellular functions have been associated with PI3-kinase-mediated signalling. Further study has indeed proved that PIK3CA is an oncogene and plays an important role in ovarian cancer (Shayesteh et al., 1999). Spectral karyotyping (SKY) is another FISH-related method in which all the chromosomes on a metaphase spread are hybridized in a single FISH reaction with a mixture of differentially labelled DNA from each human chromosome using a combination of five fluorochromes in different ratios (Chang and Mark, 1997). The FISH signals obtained can be integrated and transformed into a different colour for each chromosome using a fluorescent image system (Schrock et al., 1996). This method has been very successful in the diagnosis of complicated translocations in cancer cell lines (Veldman et al., 1997).

Cytogenetic analysis of ovarian carcinomas indicates that karyotypes in this disease are often very complex. A wide range of numerical and structural abnormalities such as highly fragmented chromosomes, quadiradials, telomeric fusion, and complexly rearranged chromosomes has been described (Heim and Mitelman, 1995). However, non-random chromosome changes have been reported, including deletions in the region of 6q15–21 and the translocation of chromosome 6 with chromosome 14, t(6;14)(q21;q24) (Wake et al., 1980). Although deletion or translocation of chromosome 6 has not been described as the sole primary change, the loss of 6q remains the most common abnormality described in this tumour to date. The frequent chromosomal abnormalities in ovarian cancers are loss of genetic material in several regions, including 3p, 6q, 11p, 17q, and 17p13 (Mitelman, 1995), indicating that putative tumour suppressor genes residing in these regions play an important role in the pathogenesis of ovarian cancer.

**Allele loss studies in sporadic ovarian cancer**

The analysis for LOH is the common approach used for identifying tumour suppressor genes involved in the aetiology of sporadic tumours. The basis for this strategy is the ‘two hit’ hypothesis by which the recessively acting genes are rendered inactive (Knudson, 1993). The first hit is usually a mutation in one of the alleles of the gene, and the second hit may occur by a variety of mechanisms including mutation or deletion. Deletion appears to be the most common mechanism associated with failure to detect heterozygosity of a polymorphic marker in tumour cells, which is, by contrast, present in the individual’s normal DNA at that locus, hence the LOH (Fig. 1b). When a series of polymorphic markers that cover sites throughout the chromosomes are used on DNA from a panel of ovarian tumours and matching normal samples, the frequency of LOH in the specific region of the genome is determined. Southern blot analysis to detect restriction fragment length polymorphisms (RFLPs) was used initially to evaluate LOH, but amplification of polymorphic microsatellite repeat markers by polymerase chain reaction (PCR) has become the method of choice. Conventional autoradiographic procedures for analysing amplified microsatellites are prone to reading errors as a result of polymerase slippage. More recently, microsatellite repeat PCR products amplified by fluorescently labelled primers can be analysed on 373
sequencer (PE Applied Biosystems) with the accompanying GENESCAN software. This fluorescence-based genotyping is as accurate as the standard radiolabelling technique (Schwengele et al., 1994) and has been widely applied to assess allele loss in tumours (Cooke et al., 1996).

Over 70 papers reporting LOH results in sporadic ovarian tumours have been published to date. However, only two of the studies (termed ‘allelotype studies’) have examined the LOH rates on all the chromosome arms in the same panel of ovarian tumours independently (Sato et al., 1991; Cliby et al., 1993). The first study examined 37 ovarian tumours with 46 polymorphic markers (29 were variable numbers tandem repeat markers, and the remainder were RFLP markers) and reported that chromosomal arms 4p, 6p, 7p, 8q, 12q, 16p,
16q, 17p, 17q and 19q had LOH rates > 30% (Sato et al., 1991). Owing to the poor density of polymorphic markers on each chromosome arm and the relatively low sensitivity of the detection method (Southern analysis), the results from this study are not completely accurate. In the second allele-type study (Cliby et al., 1993), 70 polymorphic markers were tested on the same number of tumours, and PCR was used to detect microsatellite markers. In summarizing the LOH rates from each chromosome arm, the authors did a one-side Student’s t test to calculate the background rate of random chromosomal arm loss, and this was ≈ 35%, which accounted for the high background rate of LOH present in the tumours studied. From this study, frequent allele losses (> 35%) were seen in chromosomal arms 5q, 6q, 7p, 8p, 9q, 13q, 14q, 15q, 17p, 17q, 18q, 21q and 22q.

Most LOH studies on ovarian tumours were focused on one or several chromosome arms and the results were variable, making it difficult to locate clearly a region of interest. These differences may be the result of insufficient numbers of tumours being tested, uninformative loci on the particular chromosome arm, or the varying sensitivities of the methods used. Other causes may be more significant, such as inherent genetic differences in the population studied or the differences in the tumour subtype, stage and grade. In an attempt to adjust for some of these variables, the results of chromosome arm loss from a number of LOH studies have been pooled (Table 1, Fig. 2). Attempts have been made to avoid duplicating data from different studies, and only results from malignant tumours have been included. Chromosomal regions where potential tumour suppressor genes have been studied are discussed in detail below.

**Chromosome 1**

High rates of LOH have been recorded on chromosomal arm 1p (1p31 and 1p36) (Imyanitov et al., 1999; Peng et al., 2000). The p73 gene, the homologue of TP53, has been isolated and mapped to 1p36, making it a candidate tumour suppressor gene. However, RT–PCR and western blot analyses revealed strong expression of p73 in ovarian adenocarcinoma cell lines but very low or undetectable expression in normal ovarian surface epithelial cells. There was no association between 1p36 LOH and p73 expression in ovarian tumours, nor between p73 and p53 expression (Imyanitov et al., 1999). These findings indicate that p73 is not the target of allele loss at 1p36. The ARHI (NOEY2) gene, located at 1p31 (Yu et al., 1999; Peng et al., 2000) is a maternally imprinted putative tumour-suppressor gene in ovarian and breast cancers with high homology to ras and rap (Yu et al., 1999) identified by differential display PCR. In most of the tumour samples with loss of heterozygosity at this region, the non-imprinted functional allele was deleted. Re-expression of ARHI through transfection suppresses clonogenic growth of breast and ovarian cancer cell lines. The growth suppression was associated with downregulation of the cyclin D1 promoter activity and induction of p21WAF1/CIP1 (Yu et al., 1999). Therefore, ARHI appears to be an imprinted tumour suppressor gene but its role in the pathogenesis of ovarian cancer remains to be determined.

**Chromosome 5**

The search for a tumour suppressor gene on chromosome 5 was stimulated by studies showing a high percentage loss on 5q (46%) (Cliby et al., 1993; Allan et al., 1994; Tavassoli et al., 1996). Because the adenomatous polyposis coli (APC) gene is located at 5q21–22, mutation analysis was performed on those tumours demonstrating LOH. However, no mutation was detected in these samples, leading to the conclusion that another tumour suppressor gene of relevance to ovarian cancer is located on 5q, probably at 5q13.1–21 (Tavassoli et al., 1996).

There is a relatively low frequency of LOH on chromosome 5p. Nevertheless, the tumour suppressor gene Dab2/DOC2 (for ‘disabled-2/differentially expressed in ovarian carcinoma 2’) was isolated independently by two groups using the differential expression display method (chromosome 5p13) (Xu et al., 1995a; Mok et al., 1998). Dab2 functions in the mitogenic signal transduction pathway and is frequently inactivated by homozygous gene deletion in tumours (Xu et al., 1998). The expression of Dab2 was absent in all ovarian carcinoma cell lines and tissues examined, but was present in normal ovarian epithelial cell lines and tissues (Mok et al., 1994). It has also been demonstrated that loss of Dab2 expression is an early event in ovarian malignancies (Fazili et al., 1999). Furthermore, when DOC-2 was trans-fected into the ovarian carcinoma cell line SKOV3, the stable transfectants showed significantly reduced growth rate and ability to form tumours in nude mice (Mok et al., 1998). These data indicate that downregulation of Dab2/DOC-2 may play an important role in ovarian pathogenesis.

**Chromosome 6**

Allele loss of up to 62% (Cooke et al., 1996) has been reported frequently (average 48%; Table 1) on the long arm of chromosome 6. The allele loss at 6q was observed in all types of epithelial ovarian cancer. Three common allele loss regions at 6q21–23, 6q25 and 6q27 have been identified (for a review, see Shelling et al., 1995). Chromosomal regions at 6q14–21 (Sandhu et al., 1996) and 6q24–25 (Wan et al., 1999) suppress tumorigenicity in the ovarian cell lines.

The human homologue of the rat Lot1 gene, LOT1 (localized to 6q25) was identified through analysis of differential gene expression in normal and malignant rat ovarian surface epithelial cells. Both the human and rat ovarian carcinoma cell lines exhibited loss or decreased expression of this gene. Furthermore, upon transfection into ovarian cancer cell lines, it suppressed the growth of the cells (Abdollahi et al., 1999). LOT1 may be a novel target of growth factor signalling pathways and it may regulate the growth promoting signals as a zinc-finger motif-containing nuclear transcription factor (Abdollahi et al., 1999).
Therefore, LOT1, is a putative tumour suppressor gene and further research is required to characterize this gene.

Among the several common allele loss regions on the long arm of chromosome 6, 6q27 has been reported most frequently (Saito et al., 1992, 1996; Cooke et al., 1996; Tibiletti et al., 1996, 1998; Suzuki et al., 1998). The D6S149–D6S193 region at 6q27 was altered in all samples analysed by FISH studies using yeast artificial chromosomes (YACs) on direct metaphase spreads from fresh ovarian tumours, indicating that this change might be important even in early ovarian tumours (Tibiletti et al., 1996, 1998). The analysis of 70 malignant ovarian tumours using cosmids

### Table 1. Allele loss in sporadic ovarian cancer

<table>
<thead>
<tr>
<th>Chromosome arm</th>
<th>Allele loss (%)</th>
<th>Minimal allele loss region</th>
<th>Gene(s) studied</th>
</tr>
</thead>
<tbody>
<tr>
<td>5q</td>
<td>41/114 (36)</td>
<td>D5S424–D5S644</td>
<td>APC, Dab2/DOC2</td>
</tr>
<tr>
<td>6p</td>
<td>60/171 (35)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6q</td>
<td>218/453 (48)</td>
<td>6q14–16, 6q21–23, 6q25–27</td>
<td>LOT1</td>
</tr>
<tr>
<td>9p</td>
<td>70/206 (34)</td>
<td>9p21</td>
<td>CDKN2A</td>
</tr>
<tr>
<td>10q</td>
<td>19/121 (16)</td>
<td>10q23</td>
<td>PTEN</td>
</tr>
<tr>
<td>11p</td>
<td>188/542 (35)</td>
<td>11p15</td>
<td>WT1, TSG101</td>
</tr>
<tr>
<td>11q</td>
<td>108/245 (43)</td>
<td>11q23-qter</td>
<td>ATM</td>
</tr>
<tr>
<td>13q</td>
<td>105/260 (40)</td>
<td>13q14, 13q12–13</td>
<td>RB1, BCA2</td>
</tr>
<tr>
<td>14q</td>
<td>67/188 (36)</td>
<td>14q12–13, 14q32</td>
<td></td>
</tr>
<tr>
<td>17p</td>
<td>407/667 (61)</td>
<td>17p13</td>
<td>TP53, OVCA1, OVCA2, HIC1</td>
</tr>
<tr>
<td>17q</td>
<td>499/860 (58)</td>
<td>17q25, or whole arm loss</td>
<td>NF1, BCA1, septin</td>
</tr>
<tr>
<td>18q</td>
<td>75/179 (42)</td>
<td>18q21, 18q23</td>
<td>SMAD4, DCC</td>
</tr>
<tr>
<td>19p</td>
<td>53/181 (30)</td>
<td>19p13.3</td>
<td>LKB1</td>
</tr>
<tr>
<td>22q</td>
<td>111/224 (49)</td>
<td>22q12, D22S284–CYP2D</td>
<td>NF2</td>
</tr>
<tr>
<td>Xp</td>
<td>30/78 (38)</td>
<td>Xp21.1–p11.4</td>
<td>GPC3</td>
</tr>
<tr>
<td>Xq</td>
<td>38/116 (34)</td>
<td>Xq11.2–12</td>
<td></td>
</tr>
</tbody>
</table>

Data summarized from: Shelling et al. (1995); Bryan et al. (1996); Cooke et al. (1996); Davis et al. (1996); Kerr et al. (1996); Phillips et al. (1996); Saito et al. (1996); Tangir et al. (1996); Tavassoli et al. (1996); Tibiletti et al. (1996, 1998); Wertheim et al. (1996); Bandera et al. (1997); Choi et al. (1997); Koike et al. (1997); Roy et al. (1997); Shih et al. (1997, 1998); Colitti et al. (1998); Edelson et al. (1998); Launonen et al. (1998); Suzuki et al. (1998, 2000); Watson et al. (1998); Brown et al. (1999); Fullwood et al. (1999); Huang et al. (1999); Imyanitov et al. (1999); Lin et al. (1999); Niederacher et al. (1999); Nishioka et al. (1999); Shridhar et al. (1999); Dion et al. (2000); Peng et al. (2000); Veugelers et al. (2000).

Fig. 2. Frequency of allele loss on each chromosome arm (taken as total number of markers lost in an individual chromosome arm per total number of tumours analysed). □: short (p) arm; ■: long (q) arm. Horizontal line indicates the average loss of heterozygosity (35%) in all the chromosome arms analysed.

Therefore, LOT1, is a putative tumour suppressor gene and further research is required to characterize this gene.

Among the several common allele loss regions on the long arm of chromosome 6, 6q27 has been reported most frequently (Saito et al., 1992, 1996; Cooke et al., 1996; Tibiletti et al., 1996, 1998; Suzuki et al., 1998). The D6S149–D6S193 region at 6q27 was altered in all samples analysed by FISH studies using yeast artificial chromosomes (YACs) on direct metaphase spreads from fresh ovarian tumours, indicating that this change might be important even in early ovarian tumours (Tibiletti et al., 1996, 1998). The analysis of 70 malignant ovarian tumours using cosmids
mapping to chromosomal arm 6q initially defined a minimal region of allele loss between D6S149 and D6S193 (1.9 cM) in one tumour (Saito et al., 1992, 1996). Subsequent studies have shown increased frequency of allele loss on 6q around the same region, although a minimal region was not defined (Wan et al., 1994; Orphanos et al., 1995). On the basis of analysis of 56 malignant ovarian tumours, the minimum region of allele loss on 6q27 is between D6S297 and D6S264 (3 cM) (Cooke et al., 1996; Chenex-Trench et al., 1997). The maximum frequency of allele loss occurred at D6S193 (62%) and D6S297 (52%). Three tumours showed loss of D6S193 only, while retaining flanking markers, thus indicating that the putative tumour suppressor gene is close to D6S193. Taking into account the two previous allele loss studies, we suggest that the putative gene lies within the region between D6S264 and D6S149 (approximately 4.9 cM). A positional cloning approach was undertaken involving isolation of YACs, cosmids, P1-derived artificial chromosomes (PACs), bacterial artificial chromosomes (BACs) and construction of a physical and transcript map around the key polymorphic markers. Seven genes have been identified in the interval between D6S264 and D6S149 (Liu et al., 2002). Expression and mutation analysis of these genes are being carried out to identify the putative tumour suppressor gene.

**Chromosome 9**

The overall allele loss in chromosome 9p is 34% (Table 1). The tumour suppressor gene CDKN2A (p16, MTS1, CDK4I mapped to 9p21), which encodes a cell cycle regulatory protein, was initially found to be homozygously deleted in gliomas (Kamb et al., 1994) or, alternatively, hypermethylated in the promoter region in some gliomas with an intact CDKN2A gene (Herman et al., 1995). Both of these events led to the loss of expression of this gene. In ovarian tumours, although 21% of tumours did not express p21, methylation deletions or mutations were not found (Shih et al., 1997).

**Chromosome 10**

PTEN/MMAC1 (for ‘phosphatase and tensin homologue mutated in multiple advanced cancers’) on chromosome 10q23 is a recently identified tumour suppressor gene, which is frequently mutated in a wide range of tumours including glioma, prostate cancer, renal cancer, melanoma and endometrial cancer (Li et al., 1997). In ovarian cancer, mutations of PTEN have been found in only 20% of endometrioid type, but not in serous or mucinous types, of epithelial ovarian tumours (Obata et al., 1998). When immunohistochemistry and mutation analysis are combined, PTEN can be inactivated in other subtypes of ovarian cancer (Kurose et al., 2001).

**Chromosome 11**

Somatic mutations have not been identified in the coding region of the WT1 (maps to 11p13) gene in a panel of ovarian tumours in which LOH at 11p13 has been observed (Bruning et al., 1993; Viel et al., 1994; Shimizu et al., 2000). A tumour suppressor gene termed TSG101 (for ‘tumour susceptibility gene 101’) is located at 11p15, where 40–50% ovarian cancers have deletions (Lu et al., 1997). In examining three ovarian cancer cell lines and 27 primary advanced stage epithelial ovarian cancers, the full length TSG101 transcript was detected in all the samples by RT–PCR and northern blot analysis.

On the long arm of chromosome 11, two regions of allele loss (11q22–23.3 and 11q23.3–24.3) have been defined by LOH studies. Allele loss at the 11q23.3–24.3 region is significantly associated with poor survival (Gabra et al., 1996). The ataxia-telangiectasia mutated (ATM) gene, which is responsible for a multisystem recessive disease ataxia-telangiectasia, is located at 11q23 (Lavin, 1999). LOH in the ATM gene occurred in 44% of informative cases, but no somatic alterations of the ATM gene were found in these ovarian cancer samples, including those with LOH present in the ATM gene (Koike et al., 1999). BARX2, a gene encoding a transcription factor that is homologous with the Drosophila homeobox-domain-containing proteins, was identified and mapped to 11q25, and shown to be a tumour suppressor gene by functional analysis (Sellar et al., 2001). However, it is unclear if BARX2 is the cause of the high LOH rate at 11q23.3–24.3.

**Chromosome 13**

The chromosomal arm 13q shows frequent LOH in ovarian cancer, in particular in high grade tumours (Sato et al., 1991; Kim et al., 1994). Initially, the retinoblastoma gene (RB1), located at 13q14, was examined and functional RB protein was shown to be present in ovarian carcinomas despite LOH at the RB locus (Dodson et al., 1994; Kim et al., 1994). BRCA2, a gene predisposing for familial breast cancer (Wooster et al., 1995), has been mapped to 13q12–13. BRCA2 is rarely mutated in sporadic ovarian tumours despite the relatively high frequency of LOH detected in sporadic cases (Lancaster et al., 1996), indicating that a tumour suppressor gene or genes other than RB1 or BRCA2 on chromosome 13q must be involved in the progression of ovarian cancer.

**Chromosome 16**

Although the overall LOH rates on chromosome 16 arms are beneath the threshold of 34%, a 700 kb region at chromosome 16q23.2 was shown to be homozygously deleted in an ovarian tumour. The WWOX (WW domain containing oxidoreductase) gene, encoding a protein with two WW domains and a short-chain dehydrogenase domain, has been mapped to this region. Homozygous deletions of WWOX exons have been reported in one ovarian cancer cell line and one primary ovarian tumour (Paige et al., 2000, 2001).
Chromosome 17

Allele loss occurs frequently on both arms of chromosome 17 (17p, 53%; 17q, 57%) (Table 1). On the short arm, the tumour suppressor gene TP53 is located on chromosome 17p13.1 (McBride et al., 1986). Mutant p53 protein has been the most frequently encountered genetic abnormality in human malignancy (Harris and Hollstein, 1993). TP53 mutation is not a common feature of benign or borderline tumours. Furthermore, the TP53 mutation appears to be less common in localized tumours than in advanced stage tumours (Shelling et al., 1995). Patients with tumours with a mutant p53 have a poor survival rate. It remains unclear whether mutation of the TP53 gene is an independent prognostic factor, and studies with larger numbers of cases are required (Katso et al., 1997). It is possible to suppress the growth of an ovarian cancer cell line using recombinant adenovirus carrying a wild-type TP53 gene (AxCAp53) in the presence of cisplatin (Kigawa and Terakawa, 2000). Another recombinant adenovirus carrying a wild-type TP53 (Avp53) effectively suppressed the growth of peritoneal tumours in vivo in nude mice and prolonged the survival of the treated group, especially when the tumour burden was less (Kim et al., 1999).

Up to 80% (39 of 49) of allelic loss has been observed at 17p13.3 (Phillips et al., 1996). Chromosome 17p13.3 loss may precede TP53 region deletion, because allele loss was observed in early stage ovarian cancers at this region and the alterations in TP53 have been found only in advanced stages (Phillips et al., 1996; Wiper et al., 1998). Three tumour suppressor genes, HIC-1 (for ‘hypermethylated in cancer’), OVCA1 and OVCA2 (for ‘ovarian cancer genes’ 1 and 2), have been identified in this region. HIC-1 was identified by analysis of a DNA site hypermethylated in tumour DNA (Wales et al., 1995) and is a new zinc-finger transcription factor gene that is ubiquitously expressed in normal tissues, but absent in different tumour cells, in which it is hypermethylated. The suppression of the neomycin selectability of cultured brain, breast and colon cancer cells after transfection of HIC-1 make HIC-1 a strong candidate for a tumour suppressor (Wales et al., 1995). OVCA1 and OVCA2 were identified at 17p13.3 by positional cloning (Schrock et al., 1996), are ubiquitously expressed and encode proteins of 443 and 227 amino acids, respectively, with no known functional motifs. Northern blot analysis revealed that OVCA1 and OVCA2 mRNA was expressed in the normal surface epithelial cells of the ovary, but that expression of this transcript was significantly reduced or was undetectable in 92% (11/12) of the ovarian tumours and tumour cell lines analysed (Schultz et al., 1996). Western blot analysis of extracts prepared from breast and ovarian carcinomas revealed reduced expression of OVCA1 compared with extracts from normal epithelial cells from these tissues (Bruening et al., 1999). Reduction of colony formation was also demonstrated in ovarian cancer cell lines transfected with plasmids expressing OVCA1 compared with appropriate controls. As no mutation was identified in the tumour and cell lines that have LOH at 17q13.3, haploinsufficiency, which was observed in the mouse gene p27kip and the PTEN genes when they lost their tumour suppression ability, may be the mechanism silencing the gene (Di Cristofano et al., 1998; Fero et al., 1998). However, as the methylation status of OVCA1 in samples that have allele loss at 17q13.3 has not been studied, the mechanism of inactivation of this gene needs further research.

On the long arm of chromosome 17, at least three distinct commonly deleted regions at 17q12.2 (the NF1 locus), 17q21 (including the BRCA1 locus), and from 17q25.1 to 17qter have been identified in ovarian cancers. No mutation has been identified in the NF1 gene (Foulkes et al., 1994; Iyengar et al., 1999) and very few mutations have been found in the BRCA1 gene in sporadic ovarian cancers (Takahashi et al., 1995). However, expression of BRCA1 may be silenced by hypermethylation in its promoter region (Mancini et al., 1998). As the region between 17q25.1 and 17qter has a much higher frequency of LOH (Eccles et al., 1990; Russell et al., 1990), effort has been put into mapping this region and a human septin gene has been identified at 17q25 (Russell et al., 2000). Given that the septins are a family of genes involved in cytokinesis and cell cycle control, and that this human septin gene is expressed widely in human adult and fetal tissues (including the ovary) (Kalikin et al., 2000), the human septin gene merits further investigation as an attractive candidate tumour suppressor in sporadic ovarian cancer.

Chromosome 18

Overall, 42% of tumours showed LOH on 18q (Table 1). The allele loss between D18S5 and D18S11 at 18q23 was detected more frequently in stage III and IV tumours than in stage I and II tumours, implying that this allele loss may represent a late event in the progression of ovarian cancers (Chenevix-Trench et al., 1997). SMAD4 (DPC4), deleted in colorectal carcinoma, is located at 18q21. Allele loss was detected at the D18S46 (31%) and D18S474 (36%) loci, which are adjacent to the SMAD4 gene. Missense mutations were detected in 2/42 ovarian tumours and 3/8 ovarian cancers cell lines, whereas a silent mutation was detected in 1/42 primary ovarian cancers (Takahura et al., 1999).

Chromosome 19

LOH has been reported in about 30% of ovarian cancers on 19p13.3 (Table 1). Germline mutations in the LKB1 (STK11) gene (chromosome 19p13.3) cause characteristic hamartomas and pigmentation in patients with Peutz-Jeghers syndrome. Peutz-Jeghers syndrome carries an increased risk of benign and malignant ovarian tumours, particularly granulosa cell tumours. However, like those of the BRCA1 and BRCA2 genes, LKB1 mutations can cause
### Table 2. Tumour suppressor genes implicated in the pathogenesis of only sporadic epithelial ovarian cancer

<table>
<thead>
<tr>
<th>Gene</th>
<th>Position</th>
<th>Protein</th>
<th>Function</th>
<th>Location</th>
<th>Strategy</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP53</td>
<td>17q13.1</td>
<td>Nuclear protein P53</td>
<td>Multiple (for example, transcription factor, DNA damage response, apoptosis, angiogenesis)</td>
<td>Nucleus</td>
<td>Virus transformation study</td>
<td>Mutation</td>
</tr>
<tr>
<td>PTEN</td>
<td>10q23</td>
<td>Phosphatase with homology to tensin and auxilin</td>
<td>Negative regulation of P13K/PKB/Akt signalling pathway</td>
<td>Cytoplasm</td>
<td>Positional cloning</td>
<td>Mutation</td>
</tr>
<tr>
<td>ARHI/NOEY2</td>
<td>1p31</td>
<td>Ras family protein</td>
<td>May truncate Ras/mitogen signalling</td>
<td>Cell membrane</td>
<td>Differential display</td>
<td>Imprinting</td>
</tr>
<tr>
<td>Dab2/DOC2</td>
<td>5p13</td>
<td>Phosphoprotein</td>
<td>Mitogen signal transduction pathway</td>
<td>Cytoplasm</td>
<td>Differential display</td>
<td>Homozygous deletion</td>
</tr>
<tr>
<td>LOT1</td>
<td>6q25</td>
<td>Nuclear protein</td>
<td>Transcription factor</td>
<td>Nucleus</td>
<td>Differential display</td>
<td>Unknown</td>
</tr>
<tr>
<td>CDKN2A</td>
<td>9p21</td>
<td>P16</td>
<td>Binds to the cyclin–CDK4 complex</td>
<td>Nucleus</td>
<td>Positional cloning</td>
<td>Homozygous deletion, hypermethylation in the promoter region</td>
</tr>
<tr>
<td>BRAX2</td>
<td>Homeobox-domain-containing protein</td>
<td>Transcription factor that mediates ras/ral dependent transcription of the calcitonin gene</td>
<td>Nucleus</td>
<td>11q25</td>
<td>DNA affinity cloning</td>
<td>Unknown</td>
</tr>
<tr>
<td>WWOX</td>
<td>16q23.2</td>
<td>WW domain containing oxidoreductase</td>
<td>Mediator of apoptosis</td>
<td>Unknown</td>
<td>Differential display</td>
<td>Deletion and mutation</td>
</tr>
<tr>
<td>HIC-1</td>
<td>17p13</td>
<td>Nuclear zinc-finger protein</td>
<td>Transcription factor</td>
<td>Nucleus</td>
<td>Positional cloning</td>
<td>Hypermethylation in the promoter region</td>
</tr>
<tr>
<td>OVCA1</td>
<td>17p13</td>
<td>Protein with unknown functional motifs</td>
<td>Unknown</td>
<td>Throughout cell</td>
<td>Positional cloning</td>
<td>Halopinsufficiency or hypermethylation?</td>
</tr>
<tr>
<td>SMAD4/DPC4</td>
<td>18q21</td>
<td>Protein homologous to mad family</td>
<td>TGF-β signalling</td>
<td>Cytoplasm</td>
<td>Positional cloning</td>
<td>Mutation</td>
</tr>
<tr>
<td>GPC3</td>
<td>Xq26</td>
<td>Glypican integral membrane protein</td>
<td>Regulate interactions between growth factors and their receptors</td>
<td>Cell membrane</td>
<td>Differential display</td>
<td>Hypermethylation in the promoter region</td>
</tr>
<tr>
<td>BRCA1</td>
<td>17q25</td>
<td>Transcription factor</td>
<td>DNA repair</td>
<td>Nucleus</td>
<td>Positional cloning</td>
<td>Methylation</td>
</tr>
</tbody>
</table>
ovarian tumours when present in the germline, but occur rarely in the somatic tissue (Nishioka et al., 1999; Wang et al., 1999). Therefore, the LKB1 gene may play a limited role in the development of ovarian carcinomas.

**Chromosome X**

High allele loss rate has been reported on both chromosomal arm Xp (38%) and Xq (34%) (Table 1). A region located at Xq26 (Xq11.2–12) is frequently deleted in advanced ovarian cancer (Choi et al., 1997). The GPC3 gene, located at Xq26, encodes a glypican integral membrane protein and is mutated in patients with Simpson–Golabi–Behmel syndrome (Pilia et al., 1996). No mutations were found in GPC3, but its expression was lost in four (31%) of the cell lines analysed (Lin et al., 1999). In all of the cases in which GPC3 expression was lost, the GPC3 promoter was hypermethylated. Expression of GPC3 was restored by treatment of the cells with the demethylating agent 5-aza-2’-deoxycytidine. A colony-forming assay confirmed that ectopic GPC3 expression inhibited the growth of ovarian cancer cell lines. These results show that GPC3, a gene involved in the control of organ growth, is frequently inactivated in a subset of ovarian cancers, indicating that it may function as a tumour suppressor in the ovary.

**Other strategies**

The sequencing of the human genome (http://genome.cse.ucsc.edu/) is likely to accelerate the identification of important genes in the pathogenesis of cancer. One possibility is to search the database of proteins predicted from the draft human genome for paralogues of known tumour suppressor genes, although no novel genes have been identified by this method so far (Futreal et al., 2001). Another impact of the sequencing of the human genome has been the identification of 1.42 million single nucleotide polymorphisms (SNPs), which provides an average density on the available sequence of one SNP for every 1.9 kilobases (kb) (International SNP Map Working Group, 2001). With this information, a more precise analysis of LOH and delineation of minimal intervals of allele loss can be performed. The LOH status of a single gene in tumour samples can also be evaluated, as 60 000 SNPs fall within exons (coding and untranslated regions) and 85% of exons are within 5 kb of the nearest SNP (International SNP Map Working Group, 2001). In addition, when a positional cloning investigation points to a genomic segment, any gene located in that region becomes a candidate gene. Therefore, in future, the ‘positional candidate gene’ approach will be the method used to identify tumour suppressor genes. The availability of the human genome sequence accelerates the determination of whether a candidate gene is mutated in sporadic ovarian tumours.

The Human Genome Project has also answered questions about genetic evolution. Only 94 of 1278 protein families in the human genome appear to be specific to vertebrates (Baltimore, 2001) and the number of genes contained in the human genome (30 000–40 000) is only about twice the number needed to make a fruitfly, worm or plant (Rubin, 2001). In the past decade, 50 tumour suppressor genes have been discovered in *Drosophila* and at least nine show clear homology to mammalian genes (Watson et al., 1994), for example, the LAT51 gene, the human homologue of *lats* (for ‘large tumour suppressor’) in *Drosophila*. The deletions in *lats* lead to over-proliferation and tumours in multiple tissues in flies (Xu et al., 1995b) and the human homologue protein Lat1 binds to the crucial cell-cycle regulator CDC2 in a cell-cycle-dependent manner (Tao et al., 1999). Furthermore, re-expression of human *LAT51* in flies completely suppressed tumour growth and rescued the ‘aberrant’ phenotype (Tao et al., 1999). In the meantime, *Lats1* mice were prone to soft-tissue sarcomas, ovarian tumours and pituitary dysfunction (St John et al., 1999). Although it has yet to be determined whether LAT51 is a human tumour suppressor gene, it is clear that the use of model organisms, even invertebrates, is a valid approach that may lead to the identification of novel human cancer genes (Kemp, 1999).

The transgenic mouse has been a very good genetic model in characterizing known genes as tumour suppressors. For example in the study of inhibin-deficient mice, both male and female inhibin-deficient mice generated by embryo stem cell (ES) technology were found to be viable, but developed sex cord stromal tumours with almost complete penetrance (Matzuk et al., 1994). However, the heterozygous mice developed normally, without any tumour formation. Since inhibins are secreted proteins, this observation is not surprising, as heterozygous cells would continue to receive the protein from the surrounding cells, thereby preventing any tumour formation. The above findings have resulted in the identification of the first secreted tumour suppressor protein. This approach can also be used to identify novel tumour suppressor genes. By deleting the region of a mouse chromosome that is syntenic to the human chromosome region with high allele loss, the tumour susceptibility of the mouse carrying the deletion can be observed (Zhang et al., 1994).

**Future developments**

The advances in isolating and characterizing putative tumour suppressor genes have been impressive during the past 5 years, and the current focus is on the functional analysis of the candidate genes. Besides the traditional approaches of positional cloning and knockout mouse strategies, methods such as differential expression display by means of the PCR have been successful in identifying tumour suppressors, for example the NOEY2, *LOT1*, *Dab/DOC2* and GPC3 genes (Table 2). Nevertheless, allele loss studies have provided information about where to look for tumour suppressors. The completion of sequencing genomes in humans and other species will be of great benefit to the search for tumour suppressor genes.
The mechanisms involved in silencing a tumour suppressor gene are mutation, deletion, rearrangement in its coding region, or hypermethylation in its promoter region. Methylation, as an ‘epigenetic’ gene silencing mechanism, is increasingly recognized as a common mechanism by which cancer-related genes are inactivated (Baylin et al., 1998; Jones and Laird, 1999). One example is the abnormal methylation of the promoter of the P14ARF gene, which results in the downregulation of the gene and the degradation of p53, disabling the p53-mediated suicide pathway (Robertson and Jones, 1998). The results of a study of melanomas showed that the Apaf-1 gene is switched off, rather than deleted or mutated, by methylation, and can be activated again by treatment with 5-aza-2‘-deoxycytidine (Soengas et al., 2001). This finding has clinical implications in that the search for ways to reactivate the genes subject to this epigenetic downregulation may be much more straightforward than previously thought. The mechanism of inactivation of potential tumour suppressor genes involved in sporadic ovarian cancer (Table 2) indicates that hypermethylation of the promoter region may be particularly significant in ovarian cancer.

An array of tumour suppressor genes has been implicated in sporadic ovarian cancer and the current knowledge is summarized (Table 2). With the exception of TP53 and PTEN, most of these genes have not been analysed in large numbers of ovarian tumours or cell lines, and their biochemical properties and exact role in the cause of sporadic ovarian cancer need further research. Taken as a group, the many presumed functions for the other known tumour suppressor genes support the notion that these genes control critical points in a wide range of cellular pathways that regulate proliferation, differentiation, apoptosis and response to genetic damage (Haber and Harlow, 1997) (Table 2). It is possible that delineation of the genetic and functional characteristics of tumour suppressor genes will enable us to diagnose and manage patients with ovarian cancer more precisely and effectively.

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References

Key references are identified by asterisks.


Abdollahi A, Bao R and Hamilton TC (1999) LOT1 is a growth suppressor gene downregulated by the epidermal growth factor receptor ligands and encodes a nuclear zinc-finger protein Oncogene 18 6477–6487

Allan GJ, Cottrell S, Trowsdale J and Foulkes WD (1994) Loss of heterozygosity on chromosome 5 in sporadic ovarian carcinoma is a late event and is not associated with mutations in APC in 5q21–22 Human Mutation 3 283–291


Bryan EJ, Watson RH, Davis M, Hitchcock A, Foulkes WD and Campbell IG (1996) Localization of an ovarian cancer tumor suppressor gene to a 0.5-cM region between D22S284 and CYP2D, on chromosome 22q Cancer Research 56 719–721


Chang SS and Mark HF (1997) Emerging molecular cytogenetic technologies Cytobios 90 7–22


Cooke KE, Shelling AN, Le Meuth VG, Charnock ML and Ganesan TS (1996) Allele loss on chromosome arm 6q and fine mapping of the region at 6q27 in epithelial ovarian cancer Genes, Chromosomes and Cancer 15 223–233


Edelson ML, Lai CC, Colitti CV, Welch WR, Bell DA, Berkowitz RS and Mok SC (1998) A one centimorgan deletion unit on chromosome Xq12 is commonly lost in borderline and invasive epithelial ovarian tumors Oncogene 16 197–202


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Haber D and Harlow E (1997) Tumor-suppressor genes: evolving definitions in the genomic age Nature Genetics 16 320–322


Imyanitov EN, Birrell GW, Filippovich I et al. (1999) Frequent loss of heterozygosity at 1p36 in ovarian adenocarcinomas but the gene encoding p73 is unlikely to be the target Oncogene 18 4640–4642


Iyengar TD, Ng S, Lau CC, Welch WR, Bell DA, Berkowitz RS and Mok SC (1997) A novel 4-cM minimally deleted region on chromosome 11p15.1 in ovarian adenocarcinomas: two critical regions and a rearrangement of chromosome 6q27, the minimal region of allele loss in sporadic ovarian cancer. Heterogeneity in age at onset Cancer 92 605–609


Kamata K, Zhou XP, Araki T, Cannistra SA, Mahers ER and Eng C (2001) Frequent loss of PTEN expression is linked to elevated phosphorylated Akt levels, but not associated with p27 and cyclin D1 expression, in primary epithelial ovarian carcinomas American Journal of Pathology 158 2097–2106

Kancer JM, Wooster R, Mangion J et al. (1996) BRCA2 mutations in primary breast and ovarian cancers Nature Genetics 13 238–240


Mancini DN, Rodenhiser DI, Ainsworth PJ, O'Malley FP, Singh SM, Xing W and Archer TK (1998) CpG methylation within the 5' regulatory region of the BRCA1 gene is tumor specific and includes a putative CREB binding site Oncogene 16 1161–1169


Miki Y, Swensen J, Shattuck-Eidens D et al. (1994) A strong candidate for the breast and ovarian cancer susceptibility gene BRCA1 Science 266 66–71


Mok SC, Wong KK, Chan RK, Lau CC, Tsao SW, Knapp RC and Berkowitz RS

*Mok SC, Chan WY, Wong KK et al. (1998) DOC-2, a candidate tumor suppressor gene in human epithelial ovarian cancer Oncogene 16 2381–2387


Peng H, Xu F, Pershad R et al. (2000) ARHIL is the center of allelic deletion on chromosome 1p31 in ovarian and breast cancers International Journal of Cancer 86 690–694


Robertson KD and Jones PA (1998) The human ARF cell cycle regulatory gene promoter is a CpG island which can be silenced by DNA methylation and downregulated by wild-type p53 Molecular and Cellular Biology 18 6457–6473


Russell SE, Mellhatton MA, Burrows JF et al. (2000) Isolation and mapping of a human septin gene to a region on chromosome 17q, commonly deleted in sporadic epithelial ovarian tumors Cancer Research 60 4729–4734


Sellari GC, Li L, Watt KP et al. (2001) BARX2 induces cadherin 6 expression and is a functional suppressor of ovarian cancer progression Cancer Research 61 6977–6981

Shayesteh L, Yu K, Luo W et al. (1999) PIK3CA is implicated as an oncogene in ovarian cancer Nature Genetics 21 99–102


Tangir J, Muto MG, Berkowitz RS, Welch BW, Bell DA and Mok SC (1996) A 400 kb novel deletion unit centromeric to the BRCA1 gene in sporadic epithelial ovarian cancer Oncogene 12 735–740


Tavassoli M, Steinngirimdottil H, Pierce E, Jiang X, Alagcoz M, Farzaneh F and Campbell IG (1996) Loss of heterozygosity on chromosome 5q in ovarian cancer is frequently accompanied by TP53 mutation and identifies a tumour suppressor gene locus at 5q31.3–21 British Journal of Cancer 74 115–119


chromosome abnormalities in haematological malignancies detected by multicolour spectral karyotyping Nature Genetics 15 406–410


Watson RH, Neville PJ, Roy WJ, Jr, Hitchcock A and Campbell IG (1998) Loss of heterozygosity on chromosomes 7p, 7q, 9p and 11q is an early event in ovarian tumorigenesis Oncogene 17 207–212


Xu XX, Yi T, Tang B and Lambeth JD (1998) Disabled-2 (Dab2) is an SH3 domain-binding partner of Grb2 Oncogene 16 1561–1569


Zhang H, Hasty P and Bradley A (1994) Targeting frequency for deletion vectors in embryonic stem cells Molecular and Cellular Biology 14 2404–2410