

Review

Applications of microarray technology in breast cancer research

Colin S Cooper

The Institute of Cancer Research, Sutton, Surrey, UK

Correspondence: Colin S Cooper, The Institute of Cancer Research, Haddow Laboratories, Cotswold Road, Sutton, Surrey, SM2 5NG, UK.
E-mail: csc@icr.ac.uk

Received: 8 January 2001

Accepted: 1 February 2001

Published: 20 March 2001

Breast Cancer Res 2001, **3**:158–175

© 2001 BioMed Central Ltd

(Print ISSN 1465-5411; Online ISSN 1465-542X)

Abstract

Microarrays provide a versatile platform for utilizing information from the Human Genome Project to benefit human health. This article reviews the ways in which microarray technology may be used in breast cancer research. Its diverse applications include monitoring chromosome gains and losses, tumour classification, drug discovery and development, DNA resequencing, mutation detection and investigating the mechanism of tumour development.

Keywords: drug discovery, genetic gains and losses, microarrays, microarray design, mutation detection, tumour classification

Introduction

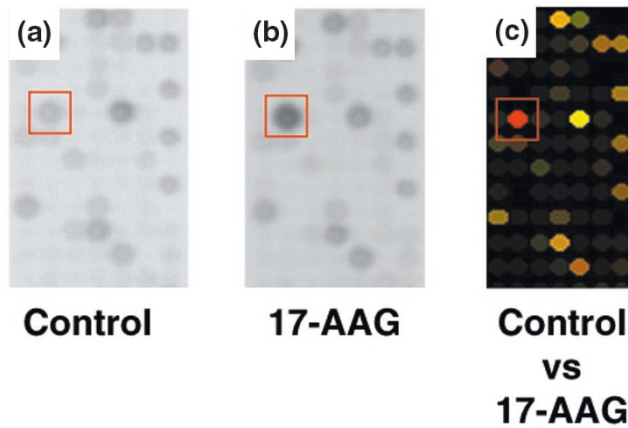
The Human Genome Project, which is nearing completion, is expected to lead to the identification of up to 50,000 human genes. The key question now facing the cancer community is how to use information from this project for the benefit of cancer patients. One of the key technical platforms that has been developed to achieve this is microarray analysis. This review highlights the ways in which DNA microarray technology can be utilised in a wide range of approaches to aid drug discovery and development and to improve our understanding of the mechanism of cancer development. Where possible, the work will focus on breast cancer, but other cancers will be described to illustrate particular approaches that may be of relevance to breast cancer. Many new bioinformatics approaches are being developed to support the analysis of the large amount of data generated by microarray studies. It is not the intention of this review to focus on

bioinformatics, however, as information on this important area can be obtained from a number of sources (see [1]).

Microarray design

A microarray is an orderly arrangement of known or unknown DNA samples attached to a solid support. Each DNA spot on the microarray (called the probe) is usually less than 200 μ m in diameter and an entire array typically contains thousands of spots. Many different design formats are possible [2]. The probes attached to the solid support can be small oligonucleotides, cDNAs or genomic sequences. The array may be formatted by photolithographic synthesis of oligonucleotides *in situ* [3–5], or the DNA samples may be applied directly to the array surface by pins, nibs or inkjet technology [6–8]. Several distinct chemistries may be used to attach the probe to the surface, and hybridisation may be electronically controlled [9]. The target sequence hybridised to probes on the array

5AC = 5-aza-2'-deoxycytidine; 5-FU = 5-fluorouracil; ALL = acute lymphoblastic leukaemia; AML = acute myeloid leukaemia; BAC = bacterial artificial chromosome; bp = base pair; CGH = comparative genomic hybridisation; CsA = cyclosporin A; DLBCL = diffuse large B-cell lymphoma; DPYD = dihydropyrimidine dehydrogenase; ER = oestrogen receptor; EST = expressed sequence tag; FISH = fluorescence *in situ* hybridisation; HIV = human immunodeficiency virus; HNSCC = head and neck squamous cell carcinoma; JNK = Jun N-terminal kinase; LCM = laser capture microdissection; LDR = ligase detection reaction; Mb = megabase (1 million bases); NC160 = National Cancer Institute's set of 60 human cancer cell lines; PCR = polymerase chain reaction; RDA = representational difference analysis; SAPK = stress-activated protein kinase; SSH = suppression subtractive hybridisation; TPA = phorbol ester; Top1 = topoisomerase 1; Top2 = topoisomerase 2.

Figure 1

Filter microarrays hybridised to [α - ^{33}P]-labelled cDNA probes prepared from 50–100 ng of poly(A)⁺ mRNA from a human cell line (a) before and (b) after treatment with 17-allylamino-17-demethoxygeldanamycin (17-AAG). Hybridisation signals were detected by phosphorimaging and a pseudo-coloured intensity output is shown in (c). Red is expression increased by 17-AAG treatment; green, expression decreased by 17-AAG treatment. Figure provided by Paul Clarke.

may be radioactively or fluorescently labelled. Despite the large number of possible permutations, only a small number of formats are in common use.

Filter arrays

Filter arrays are produced by the high-density application of DNA samples, usually cDNAs, to nylon hybridisation membranes such as those used for Southern analysis [10–12]. Filter arrays have the advantage that they are commercially available and require no specialised equipment. Their use may be appropriate if only small RNA samples are available, as a result can be obtained with as little as 50 ng total RNA, which is used in reverse transcription reactions to synthesise a radiolabelled probe (usually with ^{32}P or ^{33}P). There are, however, several major disadvantages to this approach. First, the hybridisation patterns of two different targets can only be compared by comparing the results obtained with duplicate files or following stripping and rehybridisation of the same filter. This system is also generally thought to be less sensitive than other formats, detecting only high- and medium-abundance transcripts. An example of a result obtained with a filter array is shown in Figure 1.

Glass DNA microarrays

Glass DNA microarrays are produced by the robotic application of DNA to a glass surface; cDNAs or genomic clones are usually applied [6,7], although oligonucleotides may also be used [13]. This approach has the advantage that the probe can be covalently attached to an appropriately treated glass surface. Glass is extremely durable and

its non-porous properties mean that both the access of the hybridisation target to attached probes and the washing steps are rapid and highly reproducible. In addition, the transparency and rigidity of glass improves image acquisition, and its low-fluorescence background results in superior sensitivity. As the target or test samples are fluorescently labelled, several targets can be hybridised simultaneously in a single reaction, allowing direct comparison between samples. A disadvantage of glass DNA microarrays is that large target samples are required: probes would typically be prepared from 1–5 μg poly(A)⁺ RNA or 50–200 μg total RNA by reverse transcription under conditions that allow incorporation of one of two fluorescently labelled dyes designated Cy3 (red) and Cy5 (green). Alternatively, if DNA sequences are under investigation, the same dyes may be incorporated into genomic DNA by random priming. Technical details for the fabrication of arrays are provided by Southern *et al* [14], Cheung *et al* [15] and at the websites listed in Table 1.

High-density oligonucleotide arrays

In this format, arrays of oligonucleotides (20–25mers) are synthesised *in situ* on a flat solid support [5,16–19]. Affymetrix achieves this by first attaching linkers containing a photochemically removable protecting group to a glass surface. Selected areas of the surface are then activated by illumination through a photolithographic mask, yielding reactive hydroxyl groups. A given nucleotide (A, G, C or T) is incubated with the surface under conditions that allow attachment of a single nucleotide only to the areas illuminated in the previous step. Repeating this process using a series of photolithographic masks that each direct light to different areas of the surface allows the synthesis of a large number of distinct oligonucleotides (Figure 2). Any set of oligonucleotides of length N can be synthesised in a maximum of $4 \times N$ cycles. This approach has many of the advantages of the glass DNA arrays described above and allows much higher densities of probe. For example, Affymetrix typically produces arrays, called GeneChips, that contain at least 300,000 different oligonucleotides in a 1.28×1.28 cm area. Another advantage of this approach is that the high information density allows the use of probe redundancy to check results and provides an extensive series of controls. Disadvantages of this format are that careful development is required to produce a single reliable microarray, and it is not possible to produce custom-built arrays rapidly. For some applications, hybridisation of only one labelled target to the array is recommended, which prevents direct comparison between two samples in a single experiment. The arrays are also expensive, limiting access by academic institutions.

Image analysis

Filter arrays hybridised to radiolabelled targets can be monitored by phosphorimager systems. Glass DNA arrays and high-density oligonucleotide arrays hybridised

Table 1

Microarray Worldwide Web links

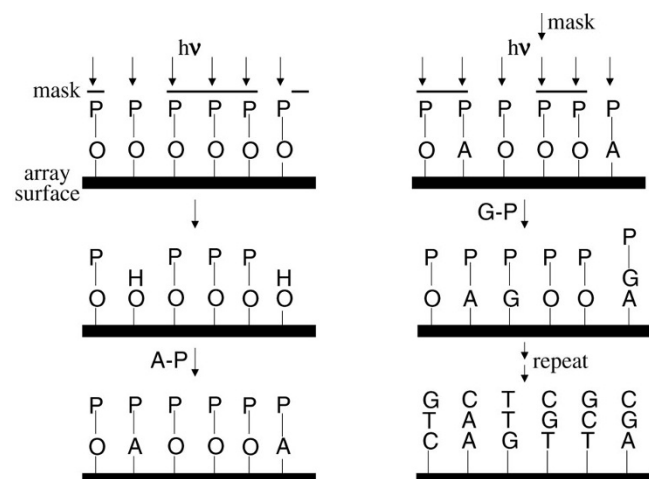
Genes and ESTs	
IMAGE consortium	http://www-bio.llnl.gov/bbrp/image/image.html
Cancer Genome Anatomy Project (CGAP)	http://www.ncbi.nlm.nih.gov/CGAP
CGAP EST database	http://ncbi.nlm.nih.gov/dbEST/index.html
UniGene resources	http://www.ncbi.nlm.nih.gov/UniGene
Purchasing UniGene clones	http://image.llnl.gov/image/html/idistributors.shtml
ESTs identified by the Institute of Genomic Research (TIGR)	http://www.tigr.org
Research Genetics	http://www.resgen.com/index.php3
Incyte	http://www.incyte.com
Ensembl resources	http://www.ensembl.org
Microarray laboratories	
Ed Southern	http://www.bioch.ox.ac.uk/rgroups/rgroupslist.asp
Pat Brown laboratory	http://cmgm.stanford.edu/pbrown/index.html
National Human Genome Research Institute (NHGRI)	http://www.nhgri.nih.gov/DIR/LCG/15K/HTML
Vivian Cheung Laboratory	http://w95vcl.neuro.chop.edu/vcheung
Albert Einstein College of Medicine	http://sequence.aecom.yu.edu/bioinf/funcgenomic.html
Institute of Cancer Research	http://wyvis.icr.ac.uk
Company links	
Affymetrix	http://affymetrix.com
Chroma	http://chroma.mbt.washington.edu/hood-www/
Incyte	http://www.incyte.com
Molecular Dynamics	http://www.mdyn.com
Genometrix	http://www.genometrix.com
Hyseq	http://www.hyseq.com
BioRobotics	http://www.biorobotics.co.uk
General Scanning	http://www.genescan.com
Gene Logic	http://www.genelogic.com
Bioinformatics links	
Stanford Link Page	http://genome-www4.Stanford.EDU/MicroArray/SMD/restech.html

to Cy3- and Cy5-labelled probes are usually monitored by commercial readers that typically use laser confocal fluorescent scanning or computer-controlled digital camera systems (CCD). The highly regular arrangement of probes in an array facilitates extraction of information by digital imaging processing software packages. The software packages usually have facilities for semi-automatic identification of probe spots and several methods for processing and presenting the raw data on the fluorescence intensities obtained for each individual pixel within the spot. Information on some of the currently available systems is provided in [1] and is available at the websites listed in Table 1.

Selection of the gene set

When analysing expression profiles, it is important to select an appropriate gene set. Ideally, all the genes in the genome would be present in the array, but this is currently only possible for certain lower organisms such as the yeast *Saccharomyces cerevisiae*. Only around 7,000 human genes have been identified by conventional approaches to gene discovery, compared to the predicted total of 50,000 genes. An alternative strategy for gene discovery involves the large-scale sequencing of expressed sequence tags (ESTs) randomly selected from cDNA libraries prepared from many different human tissues and cell lines. The IMAGE consor-

Figure 2



Construction of Affymetrix arrays. Modified from [17]. P is the protecting group.

tium, the Cancer Genome Anatomy Project (CGAP) and the Institute of Genomic Research (TIGR) have each made major contributions to this sequencing project.

A program called UniGene has been used to identify clusters of overlapping EST contigs (continuous runs of sequence) that represent a unique gene set, and representatives of each cluster are commercially available as the UniGene set from selected companies including Genomic Solutions and Research Genetics. Genomic Solutions has also been able to extend its set via access to information from Incyte, a commercial organisation that has sequenced more than 3 million ESTs, producing a sequence-verified set of over 10,000 genes. The program Ensembl, which continuously scans the nearly completed human genome sequences obtained as part of the Human Genome Project and combines information from EST databases and prediction algorithms, has already identified more than 35,000 putative genes. The website addresses providing detailed information on EST sequences, the UniGene sets and Ensembl predictions are listed in Table 1.

Genetic gains and losses

Variation in gene dosage through either amplification or deletion of genomic regions is a frequent feature of human cancer. Amplification of genomic regions is believed to result in the overexpression of genes that drive tumour development and/or are involved in conferring drug resistance. In breast cancer, an amplification event at 17q results in overexpression of the *CERBB2* gene; amplification at 12q13–15 can cause overexpression of the *MDM2* and *CDK4* genes; and several different genes including *AIB1*, *ZNF217* and *BTAK* have been proposed to correspond to the gene driving an amplification event found at 20q13 [20–22]. Amplification events in breast cancer have attracted particular attention because they can often be used as clinical markers of tumour behaviour [23–25], as in studies on *ERBB2* amplification.

The technique of comparative genomic hybridisation (CGH) was developed to monitor genome-wide variations in DNA copy number. In this technique, differentially labelled test DNAs from a tumour and from normal tissue are co-hybridised to metaphase chromosomes [26]. The relative levels of hybridisation of test and control probes can indicate loss, gain or amplification of specific genomic regions. The resolution of this technique is poor, probably in the region of 10–20 megabases (Mb). The use of microarrays of mapped cDNAs or genomic clones (for example, bacterial artificial chromosomes [BACs]) instead of metaphase chromosomes as the probe for hybridisation offers the prospect of dramatically increasing the resolution of the CGH studies. In such investigations, the resolution would simply be determined by the genomic map distance between arrayed DNA segments.

The utility of this approach was first shown by Pinkel *et al* [27] who carried out CGH studies on arrayed BAC clones from chromosomes 20 and X, with the chromosome 20 clones mapping at an average interval of 3 Mb along the

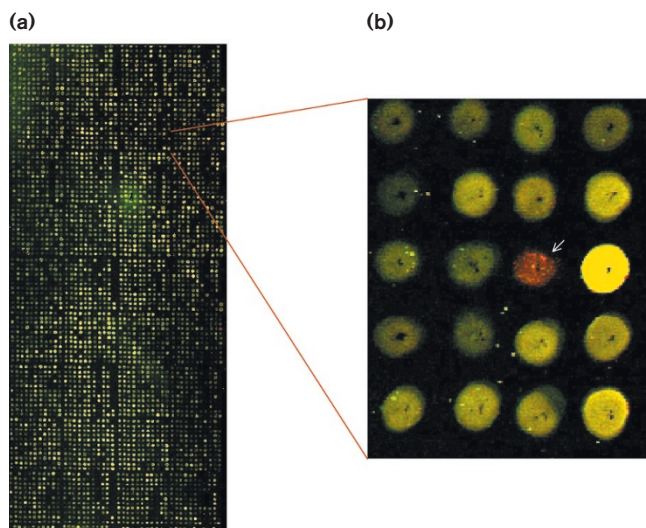
entire chromosome. Comparison of cells containing different copy numbers of DNA initially demonstrated that fluorescence ratios were proportional to copy number. Application of this technique to breast cancer yielded a high-resolution map of amplification at 20q13.2 in several cell lines, revealing the presence of three distinct regions of amplification. Previous work had discounted two of these regions as loci containing important cancer genes. However, the microarray studies revealed that both could be highly amplified and should therefore be reconsidered for their potential involvement in breast cancer development. In addition, the CGH analyses detected a short region of deletion. This deletion, which was in the same position as a recurrent deletion found in acute myeloid leukaemia, was confirmed by interphase fluorescence *in situ* hybridisation (FISH) studies. On the basis of this analysis, Pinkel *et al* concluded that, within the 20q region, multiple regions may be altered during tumour development and the complexity of amplification events in breast cancer may be significantly greater than previously recognised.

Pollack *et al* [28] used arrayed cDNAs in a genome-wide analysis of DNA copy number changes. The rationale of this approach is that if the set of arrayed cDNAs is sufficiently large it should contain representatives of all regions of the genome. The ability of this technique to detect variations in copy number was again initially confirmed in CGH studies using DNA from cell lines containing different numbers of X chromosomes. The procedure was then used to map chromosomal genes in the BT474 breast carcinoma cell line. The fluorescence ratios of hybridisation to BT474 genomic DNA and normal female genomic DNA was determined for 3,360 cDNAs whose chromosomal positions had been located onto radiation hybrid maps. An example of such a result is shown in Figure 3. These analyses not only confirmed the presence of known amplification events on chromosomes 17q and 20q, but also detected many previously uncharacterised over-representations on 1q, 8q, 11q and 15q, as well as deletions on chromosomes 3p, 6q, 9p, 10q and Xq. The usefulness of this technique to identify novel amplified genes was demonstrated when it was applied to the analysis of the NGP neuroblastoma cell line, leading to the discovery of the amplification of the zinc-finger gene *ZNF133* on chromosome arm 20p [29].

Tumour classification

Microarray technology provides a method for monitoring the RNA expression levels of many thousands of genes simultaneously in primary tumours and cell lines. In principle, data from such studies could revolutionise cancer diagnosis. The rationale behind this proposition is that the overall behaviour of a cancer must be determined by the expression of the genes within it. It should, therefore, be possible to identify sets of genes whose expression or lack of expression defines each individual property of a tumour,

Figure 3



Comparative genomic hybridisation (CGH) on human cDNA clones microarrayed onto a glass slide. The slide was hybridised simultaneously to normal DNA (green) and DNA from a breast cancer cell line (red). **(a)** Complete array of 6,000 cDNAs; **(b)** magnified region of the array showing the *CERBB2* gene (arrow). The red colour of this array point indicates that the *CERBB2* gene is amplified. Figure provided by Jeremy Clark.

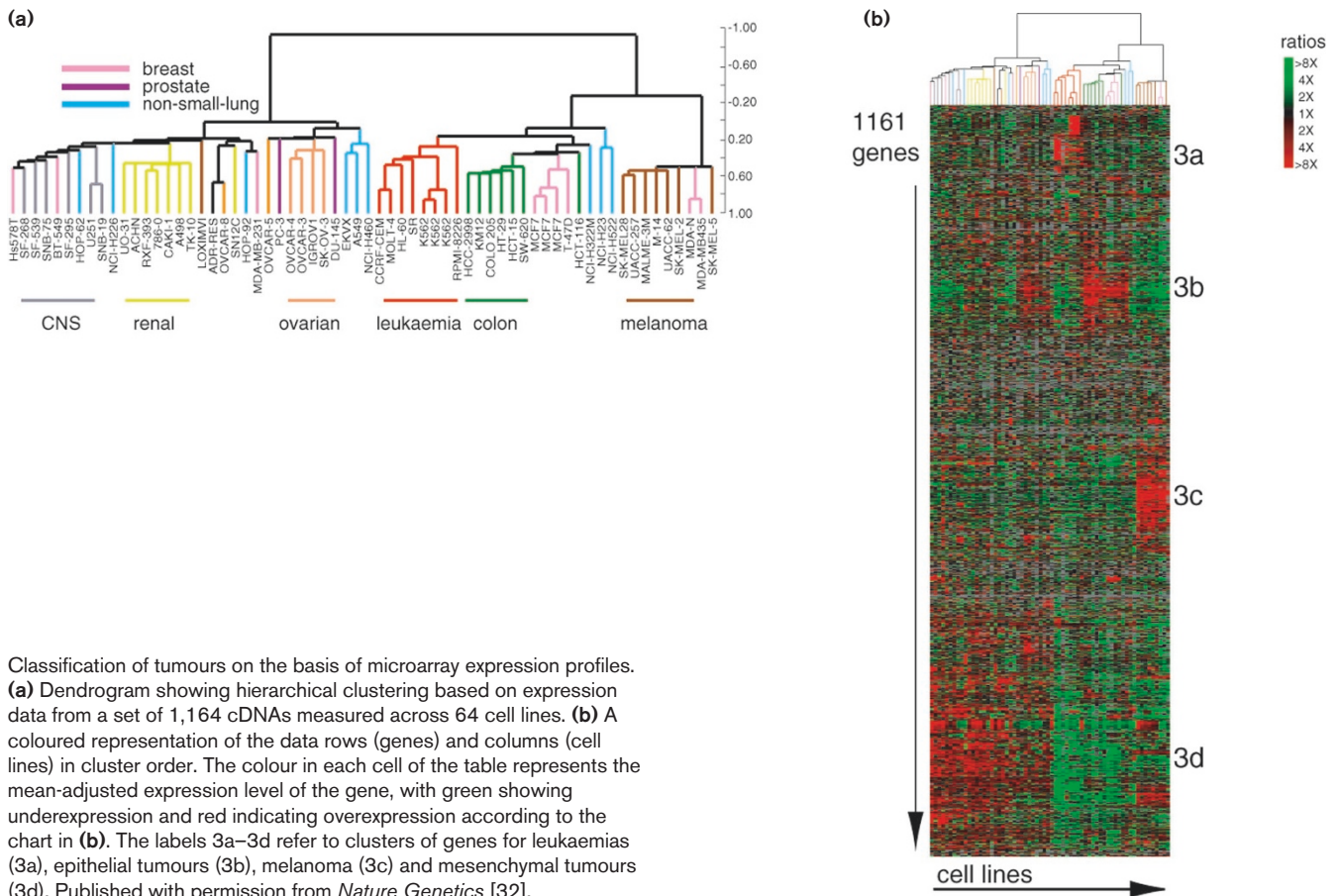
including its precise diagnosis and clinical behaviour. The potential of this approach was demonstrated by Golub *et al* [30] who determined the RNA expression profiles of a series of acute myeloid leukaemias (AML) and acute lymphoblastic leukaemias (ALL). A class discovery program automatically identified the distinction between these leukaemia groups without prior knowledge of the diagnosis. Using this data set, the program was then able to classify new leukaemia cases. Alizadeh *et al* [31] extended this approach to the analysis of diffuse large B-cell lymphoma (DLBCL), the most common subtype of Hodgkin's lymphoma. Analysis of the microarray expression profiles led to the definition of two molecularly distinct categories of DLBCL. One subtype, which had a statistically significant better overall survival, had a gene expression profile characteristic of germinal B cells. The second subtype, which had poor prognosis, expressed genes normally induced following *in vitro* activation of peripheral blood B cells. This study showed that microarray technology has the potential for identifying previously uncharacterised and clinically significant tumour subgroups. Interestingly, these analyses also highlighted the potential limitations of the microarray approach, as the two new DLBCL groups were not monomorphic. For example, within the group showing overall favourable prognosis, five patients in fact died within two years of diagnosis, whereas three patients from the poor prognosis group were alive after five years. The

authors proposed that more extensive microarray analyses might reveal additional markers that would improve the predictive value of microarray profiling.

Ross *et al* [32] used cDNA microarrays to determine the expression of 8,000 genes within the 60 cell lines used in the National Cancer Institute screen for anticancer drugs (the NCI60 cell lines). When hierarchical clustering analysis was performed, cells of the same tissue origin usually grouped together. Clustering was observed for groups of cell lines derived from leukaemia, melanoma, the central nervous system, colon, kidney and ovarian tissue (Figure 4). However, lines derived from breast tissue were located in multiple distinct branches, suggesting a heterogeneous pattern of gene expression. More specifically, the profile obtained for two related breast carcinoma cell lines, MDA-MB435 and MDA-N, that were derived independently from the same patient, was similar to that from melanoma cell lines (Figure 4). This suggested either that some breast cancers may have expression profiles exhibiting neuroendocrine features or that the cell lines are actually derived from a melanoma.

A potential problem with the application of microarray technology to primary human tumour specimens is that the specimens may represent mixtures of cell types. The presence of variable levels of normal cells, supporting stroma, blood vessels and lymphocytes in samples could mask expression patterns attributable to cancer cells. To investigate this issue, Ross *et al* [32] determined the microarray profiles of specimens of primary breast carcinoma. The samples expressed sets of genes in common with two breast-derived cell lines MCF-7 and T47D, stromal cells, and cells of haematopoietic lineage. This is consistent with the presence of stromal tissue and lymphocyte infiltration within the primary cancer specimens. Such a study indicates that, for optimal analysis of primary breast tumours, it may be necessary to microdissect tumour specimens to separate populations enriched in cancer cells and/or to electronically remove signals believed to result from contamination with normal cells. Despite these potential pitfalls, microarray profiling has been applied to the gross analysis of primary cancer specimens. For example, using an Affymetrix GeneChip containing 6,500 human genes, Alon *et al* [33] determined the expression profiles for a series of 40 colon adenocarcinomas and 22 normal colon tissue samples. Clustering analysis demonstrated that cancerous and non-cancerous specimens could be readily distinguished.

Sgroi *et al* [34] demonstrated that laser capture microdissection (LCM) can be used to obtain high-quality microarray profiles from primary breast carcinomas. LCM was used to isolate purified populations of normal breast epithelial cells, invasive cells and metastatic cells from a single patient. Labelled cDNA targets were then hybridised to an array of 8,084 cDNAs. These studies identified genes

Figure 4

Classification of tumours on the basis of microarray expression profiles. **(a)** Dendrogram showing hierarchical clustering based on expression data from a set of 1,164 cDNAs measured across 64 cell lines. **(b)** A coloured representation of the data rows (genes) and columns (cell lines) in cluster order. The colour in each cell of the table represents the mean-adjusted expression level of the gene, with green showing underexpression and red indicating overexpression according to the chart in **(b)**. The labels 3a–3d refer to clusters of genes for leukaemias (3a), epithelial tumours (3b), melanoma (3c) and mesenchymal tumours (3d). Published with permission from *Nature Genetics* [32].

that were differentially expressed in normal, invasive and metastatic cells, and the differences in expression were verified by real-time quantitative polymerase chain reaction (PCR) and by immunohistochemistry. Genes found overexpressed in invasive and metastatic disease compared to normal tissue included the breast cancer susceptibility gene *BRCA1* and genes for apolipoprotein D, annexin I and the chemokine RANTES.

Thirteen grade II–III grossly dissected infiltrating breast ductal carcinoma specimens were also examined as part of this study. Several clusters of genes showing altered expression were detected. A cluster of genes involved in cellular proliferation was highly expressed in a subset of tumours and a correlation was observed between the level of expression of these genes as determined in the microarray studies and the number of cells positive for the Ki-67 proliferation-associated antigen. The patterns of expression were also consistent with the presence of lymphocytes and stromal cells in the primary tumour specimens. The interferon-regulated gene cluster identified in studies of cultured mammary epithelial cells was highly expressed in some tumours, moderately in others, and was silent in others.

Perou *et al* [35] obtained microarray portraits of a set of 65 surgical specimens of human breast tumours from 42 individuals. There was considerable variation in the pattern of gene expression among the tumours. This variation could be partly due to changes in the levels of certain cell types within the tumours, such as endothelial cells, stromal cells, adipose-enriched normal breast cells, B and T lymphocytes and macrophages. Once genes characteristic of these cell types had been excluded, the authors selected a subset of 496 genes, called the 'intrinsic' gene set, that still showed considerable variation in expression levels between different tumours. When variations in level of expression within the genes were used to order the tissue samples, a striking division of the tumours into oestrogen receptor (ER)-positive and ER-negative categories occurred. Interestingly, the ER-positive group was characterised by the expression of many genes specific to breast luminal cells. The ER-negative tumours could be further divided into several subgroups. A subgroup of six tumours had an expression pattern characteristic of breast basal (myoepithelial) cells, whereas another subgroup was partially characterised by high expression levels of genes associated with overexpression of the *ERBB2* oncogene.

On the basis of these results the authors suggested that we are far from a complete understanding of the diversity of human breast tumours.

Drug discovery and development

Microarray technology can, in principle, provide many types of information to help drug discovery and development. In their simplest application, microarrays can be used to screen for changes in gene expression following exposure of tumour cells to drugs either in culture or in patients following treatment. Studies of this type may provide information on the precise mechanism of action of the drug or could lead to the identification of early markers of drug response. For predicting the longer-term clinical response to drug treatment, microarray information could also yield information about possible side effects, and identify markers that, in a clinical context, could be used to predict possible adverse events. This technology can also provide information for identifying and validating new therapeutic targets (reviewed in [36]).

Scherf *et al* [37] used microarrays to determine the expression profiles of 9,703 genes in the NCI60 cell lines. To dissect the mechanisms of drug action, they combined the database of gene expression data obtained in this study with molecular pharmacology data that had been obtained using the same cell lines. They constructed a dendrogram of relationships between a set of 188 drugs based only on the activity pattern of the drugs against the NCI60 cell lines. Five large drug clusters were obtained, corresponding to different mechanisms of drug action: DNA and DNA/RNA antimetabolites; tubulin inhibitors; DNA-damaging agents; topoisomerase I (Top1) inhibitors; and topoisomerase 2 (Top2) inhibitors. When data from gene expression and drug activity patterns were used together to construct the dendrogram, however, many of the clusters were altered. In some cases, the changes were not clearly related to known mechanistic or metabolic characteristics of the drug, suggesting the existence of hitherto unsuspected biological relationships between drugs that remain to be unmasked. In other cases, the changes could be interpreted on the basis of our current knowledge of the drug. For example, for the topoisomerase inhibitors, mechanistic distinctions between individual drugs were revealed: Top1 inhibitors that did not require activation clustered together, whereas prodrugs formed a distinct group. In addition, a subgroup of the Top2 inhibitors, including mitoxantrone and oxanthrazole, clustered close to porfiromycin and mitomycin, suggesting that the ability to induce double-stranded DNA breaks may be a common feature of these drugs.

A good example of how the NCI60 data set can be used to generate new clinical hypotheses is provided by the analyses of the effects of 5-fluorouracil (5-FU), which is used to treat both colorectal and breast cancer. The NCI60

microarray data unveiled a very strong negative correlation between the level of dihydropyrimidine dehydrogenase (DPYD) mRNA and the potency of 5-FU, with most of the lines deficient in DPYD showing high levels of sensitivity to 5-FU [37]. Indeed, DPYD catalyses the rate-limiting step in the catabolism of uracil, thymidine and 5-FU, so tumours with high levels of this enzyme are expected to show resistance to 5-FU. These observations suggested that DPYD should be investigated further as a possible marker of response of breast and other cancers to 5-FU.

Marton *et al* [38] used a yeast model system to validate drug targets and identify secondary drug targets. The method was applied to FK506 and cyclosporin A (CsA), drugs that inhibit calcineurin activity in both mammalian and yeast cells and are used clinically as immunosuppressants. Calcineurin is a highly conserved calcium- and calmodulin-activated serine/threonine protein phosphatase that is required in yeast for intracellular ion homeostasis, regulation of the onset of mitosis, and response to mating pheromone. Treatment of wild-type *S. cerevisiae* by FK506 or CsA resulted in a signature pattern in which the levels of expression of a small group of genes (36 for FK506) were altered more than twofold. A very similar signature pattern was found in an untreated yeast mutant that had deletions of the genes encoding calcineurin catalytic subunits, demonstrating the equivalence of removal of calcineurin function by either drug action or genetic deletion. To assist target validation, a second or 'decoder' step was used in which the yeast strain mutated in the proposed target gene is treated with the drug. If the mutated gene encodes a protein involved in the pathway targeted by the drug, the microarray signature pattern should not be altered. Application of this 'decoder' strategy to FK506 and CsA confirmed that their characteristic signature pattern was not observed in the strain with the mutated calcineurin genes when exposed to these drugs.

To investigate secondary drug effects, wild-type yeast strains were exposed to higher doses of FK506 and CsA, leading to much more complex alterations in microarray expression profiles. Significantly, many of the new alterations in expression were also observed when strains harboured mutations in calcineurin genes, indicating that they resulted from secondary drug effects in calcineurin-independent pathways. Further investigation revealed that FK506 may have several other targets, including the drug efflux pump PD45 and a pathway involving the transcriptional activator Gcn.

This approach has been extended by producing a compendium of profiles corresponding to 300 yeast mutations and chemical treatments. Comparisons with this compendium can then be used to investigate the mechanism of drug action [39]. For example, treatment of yeast with the anaesthetic drug dyclonine caused profiles that

resemble those resulting from perturbation of the ergosterol pathway. Biochemical analysis subsequently indicated that the sterol C-8 isomerase Erg2p within this pathway may represent the drug target in yeast. The human homologue of Erg2p is known as the sigma receptor, a neurosteroid-intracting protein that regulates potassium conductance and binds to known neuroactive drugs. It was therefore proposed that the anaesthetic properties of dyclonine in humans may be mediated by its binding to the sigma receptor.

A yeast model system has been used to investigate the mechanism of action of flunaripiridol and a purvalanol analogue called compound 52, which inhibit human and *S. cerevisiae* cyclin-dependent kinases (CDKs) [40]. Sixty-two transcripts were identified whose levels changed more than twofold in wild-type yeast in response to treatment with either drug. They included groups of genes involved in cell-cycle progression (*CLB1*, *CLB2*, *HTA2*, *HTB2* and *EGT2*) and phosphate metabolism (*PHO80*, *PHO81*, *PHO84*, *PHO5*, *CTT2*, *HSP12* and *UBI4*). These two groups of alterations were entirely consistent with the demonstrated ability of compound 52 to inhibit both the cell-cycle-regulating kinase Cdc28p and the Pho85p kinase, which is involved in phosphate metabolism.

Using a filter microarray of 4,132 genes and ³²P-labelled targets, Clarke *et al* [41] investigated alterations in gene expression pattern in human colon cancer cell lines following inhibition of signal transduction by 17-allylamino-17-demethoxygelanmycin, an inhibitor of the molecular chaperone, heat-shock protein 90 (HSP90). Biochemical studies demonstrated that treatment of each of four colon cancer cell lines resulted in depletion of RAF1 and AKT proteins and inhibited signal transduction. The array studies revealed that the genes for HSP70, HSP90B and caveolin were upregulated, whereas the genes for keratins 8 and 18 were consistently downregulated. Interestingly, expression of genes for the protein clients of HSP90 was not affected by drug treatment. The authors suggest that these genes could be used as possible molecular markers of drug action in clinical trials.

Mutation detection

As the Human Genome Project nears completion and alterations in more genes become implicated in human pathology, there will be a growing demand for techniques allowing high-throughput resequencing of genomic DNA. In the breast cancer field, there is already a requirement for large-scale population-based detection of inherited mutations within genes such as *BRCA1*, *BRCA2*, *P53* and *CHK2*, which predispose towards the development of this disease. Such studies could provide information on the prevalence of particular classes of mutations and, through the collection of epidemiological data, shed some light on the possible role of aetiological agents in cancer

development. Large-scale screening studies on new genes found to be somatically mutated in breast cancer might lead to the identification of molecular diagnostic markers and, through analysis of mutational spectrum, provide clues to the possible role of chemical exposure in breast cancer development.

Affymetrix arrays for comparative sequencing

Several microarray-based strategies have been developed to facilitate large-scale comparative sequencing. Hacia *et al* [42,43] have described a 'gain-of-hybridisation signal' approach to identification, in which the arrays contain large sets of oligonucleotides complementary to all possible sequence changes under investigation. Hybridisations are performed under conditions in which fluorescently tagged target DNA only binds to wild-type and mutant oligonucleotides that are exactly complementary to its sequence, leading to a gain-of-hybridisation signal at selected oligonucleotide positions. The Affymetrix array for identifying mutations in the *BRCA1* gene contains over 96,000 dimers corresponding to wild-type sequences and all possible single-base substitutes, single-base insertions and 1–5 base pair (bp) deletions. To detect substitution mutations, the array contains four oligonucleotides for each position in the *BRCA1* sequence. One oligonucleotide is precisely complementary to the wild-type sequence, whereas the remaining three are complementary to the three possible substitution mutations at that position. To maximise the discrimination of hybridisation of target sequences to the oligonucleotides, the base being interrogated is positioned in the centre of the oligonucleotide. Hybridisation to the array is then performed using a two-colour system to provide a direct comparison between wild-type sequence and the test sample potentially containing a mutant sequence. The strategy is shown in Figure 5a. Disappointingly, only four of the fourteen *BRCA1* mutations examined could be detected by this method. An example of the results obtained by Hacia *et al* [42] is shown in Figure 6.

Hacia *et al* [42] also utilised a 'loss-of-signal' analysis to glean additional information from the *BRCA1* Affymetrix array. In this approach, changes in the signal ratio between test and wild-type target samples are monitored (Figure 5b). Homozygous loss (complete loss of wild-type sequence) in the test sample should result in total removal of the hybridisation signal, whereas heterozygous mutations should cause a 50% reduction in signal intensity. Whereas this strategy does not, unfortunately, provide information on the nature of the mutations, the sensitivity of detection is improved, as 14 of the 15 *BRCA1* mutations screened were detected.

Affymetrix arrays have now been used to interrogate *BRCA1* and *BRCA2* and gene sequences from human mitochondria, *P53* and the human immunodeficiency

virus (HIV) [3,42–47]. For example, analysis of germline *P53* mutations in 42 breast cancer families using these arrays identified three families with a G to C base change at nucleotide 13,964 [45]. A significant challenge for this technology is to develop assay conditions where an even hybridisation of targets to attached oligonucleotides is achieved, irrespective of the base composition of the sequence (the GC:AT ratio). To address this issue, Hacia *et al* [19] incorporated modified bases into target sequences and found that targets containing 5-methyluridine gave a more even signal and retained hybridisation specificity.

Minisequencing assay

High-density oligonucleotide chips have some potential drawbacks, such as low sensitivity in the gain-of-hybridisation strategy and high background and problems in achieving even hybridisations across all sequences independently of the GC:AT composition. To overcome these problems, alternative microarray-based sequencing strategies have been developed. In the 'minisequencing' assay (reviewed in [48]), target hybridisation is combined with an enzymatic primer extension assay. Oligonucleotides are attached to the surface by their 5' ends, leaving free 3-OH groups. Following hybridisation to the test DNA, the attached oligonucleotide acts as a primer for nucleotide incorporation at the 3-OH, using the hybridised test DNA as a template (Figure 5c). The extension reaction contains a mixture of four dideoxynucleoside triphosphates, each tagged with a distinct fluorescent label. The presence of dideoxynucleotides ensures that only a single fluorescently tagged nucleotide is added to each 3'-OH group, so that the identity of the tagged nucleotide that becomes covalently attached to each oligonucleotide can be monitored by fluorescence microscopy. To scan both strands of a sequence of length N using this approach the array must contain $2N$ oligonucleotides, each with its 3'-OH immediately preceding the base to be interrogated. It is important to note that Affymetrix chips are not suitable for microsequencing because the oligonucleotides are attached to the surface through their 3'-OH ends.

Universal DNA microarrays

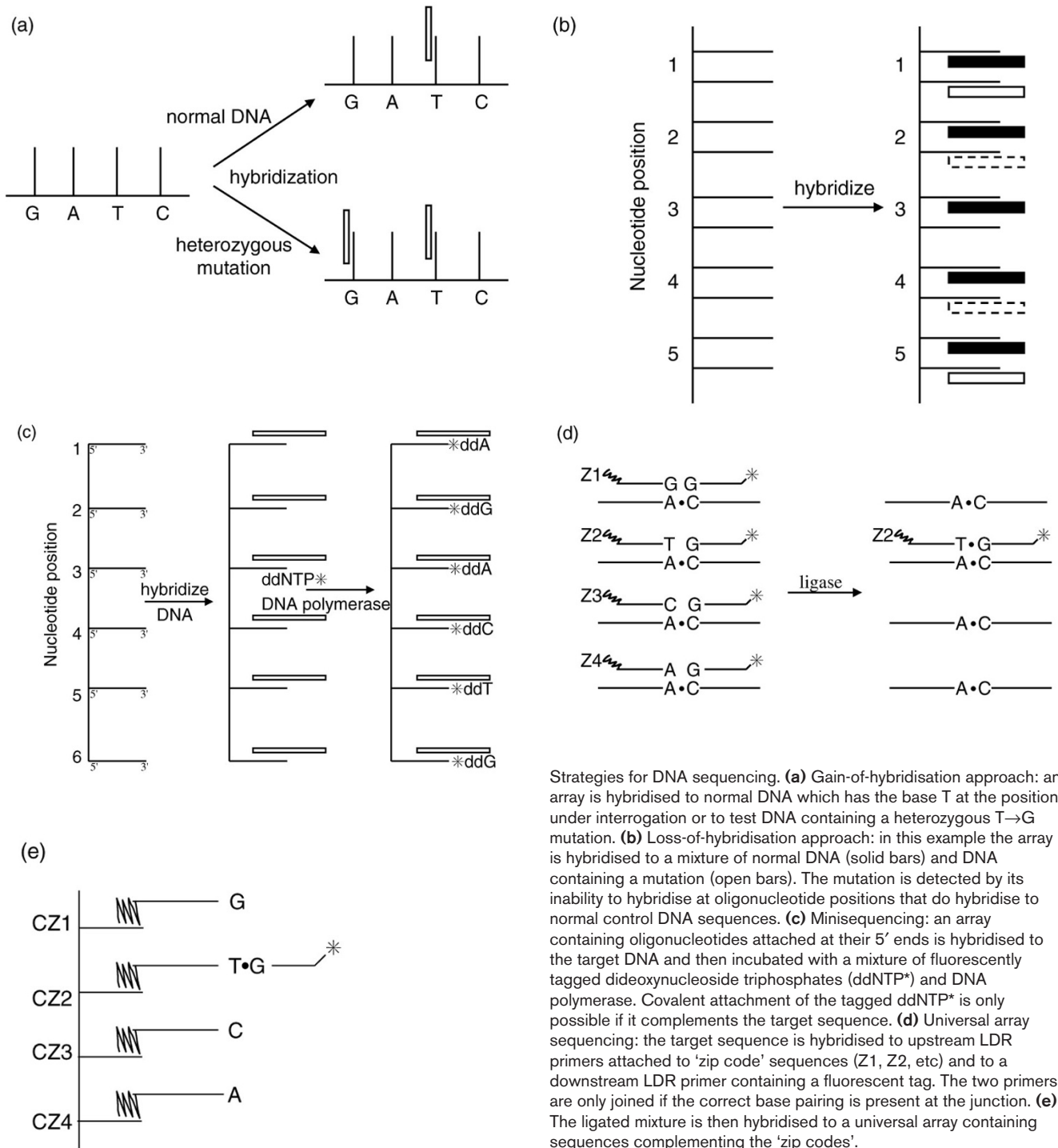
A universal DNA microarray method may be used for high-throughput detection of small groups of previously characterised mutations [49–51]. In this procedure, the PCR-amplified target gene sequences are annealed to two oligonucleotides (called the upstream and downstream LDR primers) that complement immediately adjacent regions in the genomic DNA flanking the nucleotide under investigation. The two annealed primers are then subject to a ligase detection reaction (LDR) that links the two oligonucleotides if, and only if, the correct base pairing is present at the junction (Figure 5d). The upstream allele-specific LDR primer contains a nucleotide complementing the mutant sequence being interrogated at its most 3' end

and a 'zip code' sequence composed of a six tetramer repeat, for example (CGTT)₆, at its 5' end. The downstream LDR primer contains a fluorescent tag that becomes covalently joined to the oligonucleotide containing the zip code sequence if ligation is successful. Four different upstream primers, each containing a unique zip code sequence and a different base at their 3' ends are used to screen for substitution mutations at each nucleotide position. After the LDR step, the unique zip code sequences are used to direct the LDR products containing the fluorescent tag to specific complementary zip code address sequences attached covalently in an array format to a glass microscope slide (Figure 5e). For example, the zip code address (AACG)₆ attached to the glass surface would be used to bind the (CGTT)₆ oligonucleotide zip tag mentioned above. The technique is referred to as 'universal' DNA microarray analysis because the arrayed zip code addresses remain constant and their complementary zip code tags can be attached to any set of LDR primers. This approach can detect mutation with extreme selectivity, even when the mutant sequence is only present at low abundance (down to 1:200). This technique has been successfully applied to the detection of point mutations in *KRAS* and *P53* in human tumours and to the detection of small insertions and deletions in *BRCA1* and *BRCA2* [49,50,52].

Determining the function of normal or mutated genes

Gene function may be monitored by examining the perturbations of gene expression after introduction of either normal or mutated genes. Studies involving, for example, transformation of NIH3T3 cells by the *PAX-FKHR* oncogenes revealed activation of the myogenic transcription programme involving upregulation of genes for the transcription factors MyoD, myogenin, Six and Slug, as well as many other genes involved in muscle function [53]. *BRCA1* encodes a protein that has been implicated in the cellular response to DNA damage. Affymetrix GeneChip arrays were used to monitor altered gene expression following induced expression of *BRCA1* in U2OS osteosarcoma cells and in MDA435 breast cancer cells [54]. *BCL1* was constitutively expressed in these cells to prevent apoptosis, which usually occurs after introduction of *BRCA1*. Twenty-three genes and ESTs had increased expression following *BRCA1* induction. These included the DNA-damage-inducible gene *GADD45* (35-fold) and the immediate early gene, early growth response 1 (*EGR1*) (10-fold). Repressed genes included *Ki67* (12-fold) and the gene for prothymosin- α (4-fold), which have both previously been implicated as possible prognostic markers in breast cancer. The induction of *GADD45* was associated with the p53-independent activation of the Jun N-terminal kinase (JNK)/stress-activated protein kinase (SAPK) pathway, which may be involved as a possible pathway for *BRCA1*-induced apoptosis.

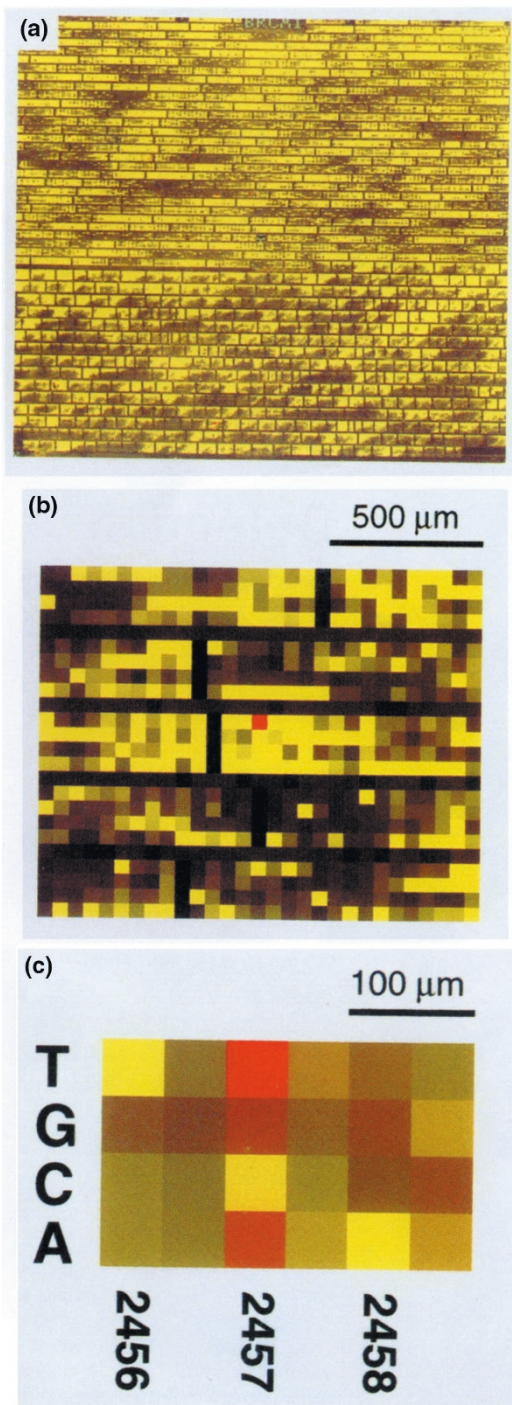
Figure 5



An array of 6,416 genes was used to investigate the effects of the overexpression of the proto-oncogene *CMYC* in primary human fibroblastomas [55]. Following retroviral infection with a construct expressing *CMYC*, 27 genes were consistently upregulated and 9 were consis-

tently downregulated [56]. The downregulation of the extracellular matrix proteins fibronectin and collagen and of the cytoskeletal protein tropomyosin indicated that *CMYC* may have a role in modulating cell adhesion and cell structure. Several cell-cycle genes were identified as

Figure 6



The use of an Affymetrix DNA microarray to sequence the *BRCA1* gene. The array is hybridised with a mixture of normal DNA (green) and test DNA from a carrier of the *BRCA1* mutation (red). Equal hybridisation to the two probes gives yellow. (a) Composite image of hybridisation to normal control and test DNA. (b) Magnification of the region surrounding the 2,457 C→T mutation. (c) Close-up of the probe sets surrounding the 2,457 C→T mutation. The bright red signal indicates the presence of the mutation. Published with permission from *Nature Genetics* [42].

targets, including those for cyclin D2 and the cyclin-dependent kinase-binding protein CKSHS2, which were induced, and the *P21^{Gp1}* gene, which was repressed. Identification of the gene encoding the tumour necrosis factor receptor-associated protein TRAP1 as a target suggested a potential link to an apoptosis-associated pathway. The results were compared to data obtained using the same microarray in experiments in which HL60 cells were induced to undergo differentiation by exposure to phorbol ester (TPA), a process that involves rapid downregulation of *MYC* expression. Notably, 17 of the 27 genes upregulated following *CMYC* expression in human fibroblasts were downregulated in this experiment, providing further evidence for the role of *CMYC* in their regulation.

Induction of p53 expression from a metallothionein promoter in the p53-deficient colon-derived EB1 cell line results in cell death by apoptosis within 1–4 hours. Microarrays were used to identify 161 genes whose expression was altered more than threefold following p53 induction [57,58]. These genes could be divided into eight clusters with distinct expression kinetics following p53 induction, and into several distinct functional groups, such as genes involved in cell regulation (*P21*, *GADD45* and *GOS8*), apoptosis (*FAS*, *KILLER*), oxidative stress (*PIG3*, genes for neutrophil NADPH oxidase and superoxide dismutase 3), cell structure (genes for collagen and NRP/B nuclear matrix protein), signal transduction (*ECK*, *P2XM*, *EPR1*, *ACK*, *HSR1*, *ARL2*, *C/EBP α* , *TGF- α*) and oncogenes (genes for endothelin 2 and thrombospondin).

Response to radiation

Amundson *et al* [59] identified 48 sequences whose expression was changed when the ML-1 human myeloid cell line, which contains wild-type p53, was treated with ionizing radiation. Many of these transcripts were not known to be induced by radiation exposure. Analysis of a subset of these genes in a series of 12 cell lines, including the MCF7 and T47D breast cancer cell lines, following exposure to ionizing radiation, UV radiation or methylmethanesulphonate (MMS) treatment revealed a heterogeneous response pattern with the exception that expression of the *ATF3* gene was consistently upregulated following UV or MMS treatment. ATF belongs to the ATF/CREB family, whose members can homodimerise to repress transcription from promoters containing ATF-binding sites. *ATF3* can be induced following stresses such as exposure to carbon tetrachloride (CCl_4), alcohol intoxication and wounding, and may have a key role in modulating cellular response to radiation and chemical exposure. The studies also provided evidence that a second gene, *FRA1*, was involved in the p53-associated response to radiation treatment. Following γ -irradiation, expression of this gene was upregulated in MCF7 breast cancer cells that contain wild-type p53, but no response was observed in MCF7/E6 cell lines, which lack wild-type p53 function.

In a more extensive investigation of the mechanism of radiation-induced apoptosis using a 11,000-gene microarray, Voehringer *et al* [60] compared expression profiles in apoptosis-sensitive and apoptosis-resistant mouse B-cell lymphomas, both before and after exposure to 5 Gy of γ -irradiation. In these studies, 184 genes were uniquely induced following irradiation in the apoptosis-resistant line, and 617 were uniquely induced in the apoptosis-sensitive line. One interesting cluster of genes induced in the apoptosis-sensitive cells disrupts normal mitochondrial function. These included *Vdac-1*, which has been recognised to be part of the permeability transition (PT) pore, which has a central role in controlling apoptosis, and *Ucp-2*, which is believed to be involved in uncoupling electron transfer from oxidative phosphorylation. As *Ucp-2* expression peaked before apoptosis-associated mitochondrial changes, it was proposed that *Ucp-2* may have a role in regulating apoptosis. These studies also identified a pathway involving the expression of a family of *Fabp* (fatty acid-binding protein) genes that may be important in preventing apoptosis in the resistant line. The upregulation of FABP proteins is significant, because they bind fatty acids such as retinoic acids, which can function as signals for differentiation as well as for apoptosis. The authors propose that FABPs may have a specific role in sequestering fatty acids that act as apoptotic signals. An alternative explanation is that they may act as scavengers that bind to the oxidised fatty acids generated during oxidative stress, thus terminating a cascade of lipid peroxidation which may represent an early step in commitment to apoptosis.

Subcellular fractionation

Subcellular fractionation may be combined with microarray technology to investigate gene function. This approach has been used to identify eukaryotic mRNAs that are translated in the absence of the cap-binding complex eIF4F [61]. Most eukaryotic mRNA needs a functional cap-binding complex for efficient translational initiation. However, a few cellular RNAs and transcripts produced from hepatitis C virus and picornaviruses can function even in the presence of low levels of eIF4F. Polyribosomes were first prepared from human cells depleted for eIF4F. Analysis of the polyribosome-associated mRNA on microarrays showed that approximately 200 of the 7,000 microarrayed genes remained associated with the polyribosome, including the *MYC* and *PIM1* proto-oncogenes and genes for immediate early transcription factors, kinases and phosphatases.

Subcellular fractionation has also been used by Diehn *et al* [62] to identify secreted and membrane-associated gene products. mRNA species bound to membrane-associated polysomes were first separated from other cytosolic mRNA by sedimentation. The different fractions were then used to prepare labelled cDNA probes that were hybridised to microarrays. Based on these analyses, 275

human gene and 285 yeast genes were identified that potentially encoded previously unrecognised secreted or membrane-associated proteins [63].

Gene deletion

Gene deletion or inactivation, for example by the production of knockout mice or mutations, may also be combined with microarrays to investigate gene function. An elegant demonstration of the power of this approach was provided by Hughes *et al* [39], who used a yeast microarray to compile a database of expression profiles for 300 mutations and chemical treatments. Analysis of the 300 profiles present in the compendium identified groups of co-regulated transcripts as well as groups of experiments with similar profiles, and it appeared that different mutations affecting the same cellular process in general displayed related profiles. To determine the function of novel yeast genes, the profile caused by deletion of the uncharacterised gene was then compared to the compendium. Using this approach, this group identified and experimentally verified the involvement of new genes in cell wall function, mitochondrial respiration and protein synthesis.

Treatment by agents that induce growth and differentiation

A very simple experimental design involves the analysis of alteration of gene expression profile following exposure of cells to growth factors or agents that induce differentiation or apoptosis. Perou *et al* [64] utilised a glass-based array system to analyse the gene expression patterns of mammary epithelial cells grown in culture and subjected to a variety of experimental perturbations. Epithelial cells were treated with transforming growth factor- β 1 (TGF- β 1), interferon- α (IFN- α) or IFN- γ , and were also subjected to withdrawal of epidermal growth factor (EGF). The effects of senescence and growth in Matrigel were also examined. Analysis of the data by hierarchical clustering revealed that reduction in cell proliferation rate, which occurred with several of the treatment protocols, was associated with alteration in expression levels of a specific set of genes involved in cell-cycle progression, including *MCM2*, *MCM3*, *MCM6* (*cyclin B*), and *Ki-67*. When cultures became confluent or underwent senescence, many interferon-regulated genes were consistently induced, for example those for (2'-5') oligoadenylate synthetase E, interferon-induced 17 kDa protein and Stat1. Induction of transcription from this gene set is modulated by the JAK/STAT signalling pathway, and Perou *et al* suggest that reaching confluence and undergoing senescence both result in activation of this pathway.

Particular attention has been directed to the analysis of leukaemias and T- and B-cell responses. For example, Rusiniak *et al* [65] examined the effects of retinoic acid (RA) on leukaemia cells engineered to contain a fusion of the retinoic acid receptor- α gene (*PML-RAR α* constructs),

the gene fusion that characterises acute promyelocytic leukaemia. They identified *B94*, originally isolated as a gene inducible by tumour necrosis factor- α (TNF- α) in endothelial cells, as a gene induced by RA exposure. Expression arrays have been used to investigate the mechanism of T-cell and B-cell stimulation [66–68]. Teague *et al* [67] showed that T-cell activation was associated with considerable changes in expression profile compared to resting T cells and, as expected, many genes associated with cell division were activated. Rogge *et al* [68] compared the gene expression profiles in T helper type1 (Th1) and T helper type 2 (Th2) cells in an attempt to unravel the genetic programme that controls the functional properties of these cells. This approach identified 15 differentially expressed genes encoding proteins involved in transcriptional regulation, apoptosis, proteolysis and cell adhesion and migration.

Iyer *et al* [69] examined the response of human fibroblasts to serum treatment using a 8,600 gene array. They found that the altered genes could be grouped on the basis of their temporary pattern of expression. For example, genes such as *P27*, *KIP1*, *P57*, *KIP2* and *P18* were expressed in quiescent fibroblasts but downregulated following fibroblast stimulation. One of the most striking features was the altered expression of many genes known to be involved in the physiology of wound healing, including genes involved in remodelling blood clots, promoting chemotaxis and activating neutrophils and T and B cells, promoting angiogenesis and promoting the migration and proliferation of fibroblasts and keratinocytes. Iyer *et al* proposed that the role of fibroblasts in the response to wounding is greater and more complex than had previously been appreciated.

Extracellular interaction of plasma clotting factor VIIa (FVIIa) with tissue factor (TF) on the cell surface results in intracellular signalling, but it is currently unclear which of these signals initiates blood coagulation. Using a microarray approach, Pendurthi *et al* [70] examined changes in the transcriptional programme in human fibroblasts in response to treatment with FVIIa and noted that the genes encoding the extracellular matrix signalling protein CYR61 and connective tissue growth factor (CTGF) were upregulated in a time and dose-dependent manner. Other studies have looked at the response of HT1080 fibrosarcoma cells to interferon treatment [71], of HL60 cells to stimulation of the cannabinoid receptor [72] and of prostate cancer cells to androgen treatment [73].

Arrays were used to investigate the effect of inhibiting DNA methyltransferase by 5-aza-2'-deoxycytidine (5AC) in HT29 colon adenocarcinoma cells [74]. The studies revealed that 10 of 19 genes induced by 5AC were previously identified interferon-response genes. Whereas the expression levels of the interferon genes themselves remained unaltered,

biochemical studies show that STAT transcription factors and interferon signalling were upregulated. As interferons are growth inhibitors, this observation may explain the growth inhibition observed following 5AC treatment.

Tumour growth and progression

Several distinct approaches have been used to examine tumour growth and progression. Hilsenbeck *et al* [75] used a xenograft model system to investigate changes in gene expression during the development of acquired tamoxifen resistance in the human MCF-7 breast carcinoma cell line. MCF-7 cells were injected into the mammary fat pads of athymic mice that had been supplemented with an oestrogen pellet to allow the tumour cells to grow. When the pellet was removed and the animals treated with tamoxifen, the tumours shrank and remained stable for several months before developing resistance to tamoxifen and resuming growth. Expression patterns were determined for the original oestrogen-stimulated tumours (OS) before tamoxifen treatment, for the tamoxifen-sensitive (TS) tumours during tamoxifen treatment but before acquired resistance, and for the tamoxifen-resistant (TR) tumours following growth resumption. Two of the genes, *ERK2* and *HSF1*, whose expression altered during the transition from OS to TR, were selected by western blot analyses. The western blot data agreed with the array data: HSF1 protein, which is involved in the cellular response to stress was upregulated in TS cells compared to OS cells and downregulated in TR cells; expression of the kinase gene *ERK2* increased in the TS tumours relative to OS tumours.

To study the effect of infection of keratinocytes by human papilloma virus type 31, Chang and Laimins [76] used an array containing 7,075 genes and ESTs. They identified 178 upregulated genes and 150 downregulated genes. Although no specific pattern of alteration was identified, the authors highlighted the fact that Stat1, a transcription activator with a role in mediating the response to interferon, was repressed. Bubendorf *et al* [77] used microarrays to identify differentially expressed genes in hormone-refractory human prostate cancer. Differential expression between hormone-refractory CWR22R prostate cancer xenografts and xenografts of the parental hormone-sensitive CWR22 strain was examined using a 588 cDNA Clontech filter microarray. These analyses identified 10 overexpressed genes. They included the genes for insulin-like growth factor binding protein 2 (IGFBP2), the insulin receptor, insulin-like growth factor 3 (IGF-3) and HSP27, as well as 14 underexpressed genes. Tissue arrays were then used to analyse the expression of *IGFBP2* and *HSP27* in 238 primary human prostate cancers. A strong association between increased *IGFBP2* and *HSP27* expression and progression to hormone-refractory disease was observed. For example, *IGFBP2* was expressed in 100% of human refractory clinical tumours, in 36% of primary tumours and in no benign tumours.

The same Clontech microarray was used to identify genes that had altered expression in prostate cancer compared to normal prostate tissue [78]. The filter was independently hybridised to ³²P-labelled targets prepared from three separate prostate tumours and from normal tissue. Sixteen genes were found to be altered in at least two of the three tumours. With the exception of the gene for glutathione-S-transferase 1, however, reverse transcription-polymerase chain reaction (RT-PCR) studies could not confirm differential expression. Expression profiles were also collected for LNCaP cells grown in the presence and absence of the androgen analogue R1881. Androgen treatment appeared to cause the upregulation of several genes including *HSP27*, *DBI* (diazepam-binding inhibitor), *DAD1* (defender against cell death) and *NME-2* (non-metastatic cell 2 antigen) as well as the transcription factor genes *EGR-1*, *GATA2* and *CJUN*.

Alternatively, it is possible to construct custom-made microarrays tailored to suit specific investigations. To investigate gene expression in prostate cancers, Carlisle *et al* [79] constructed a microarray comprising 5,184 different cDNAs selected from the 35,000 prostate cDNA library-derived ESTs present in the database at the National Center for Biotechnology Information (Table 1). cDNAs for microarrays can also be preselected by cDNA subtraction. This approach was used by Villaret *et al* [80] to identify new tumour markers and vaccine candidates for head and neck squamous cell carcinomas (HNSCCs). A subtracted library enriched for expression in HNSCCs was prepared and arrayed on glass slides. When the slides were probed simultaneously with fluorescently labelled probes prepared from primary HNSCC and from control tissues, the differentially overexpressed genes identified included those for keratins 6 and 16, laminin-5, plakophilin-1, matrix metalloproteinase-2, vascular endothelial growth factor, connexin 26, 14-3-3 sigma, CaN19, and four previously unidentified genes. A similar approach has been used to identify genes that are differentially expressed in human prostate cancer [81]. Yang *et al* [82] combined suppression subtractive hybridisation (SSH) with microarray technology to identify differentially expressed genes in ER-positive (MCF-7 and T47D) and ER-negative (MDA-MB 23 and HBL100) breast cancer cell lines. SSH is based on the technique of representational difference analysis (RDA) but modified to analyse mRNA abundance. SSH was first performed using ER-positive MCF-7 mRNA as a 'tester' and ER-negative MDA-MB-231 cDNA as a 'driver'. A set of 332 cDNA clones which should be enriched for genes overexpressed in MCF-7 cells compared to MDA-MB-231 cells was identified and arrayed. When microarrays were hybridised to probes prepared from ER-positive and ER-negative breast cell lines, 10 clones were found to be overexpressed at least fivefold in ER-positive cells. The sequences included those for cytokeratin 19, GATA3, CD24 and glutathione-S-transferase γ -3, as well as several EST sequences and novel genes.

Similar approaches usually comparing tumour and normal tissue and sometimes incorporating cDNA subtraction have been used to examine progression in lung cancer [83], rhabdomyosarcoma [84,85], ovarian cancer [86], kidney cancer [87], melanoma [88], prostate cancer [78], Ewing's sarcoma [89] and colon cancer [33].

Microarrays and developmental biology

Microarrays are powerful tools for dissecting programmes of organogenesis. Li *et al* [90] have investigated the role of the mouse homeobox gene *GSH1*, which is expressed in discrete domains in the ganglionic eminences, diencephalon and hindbrain during brain development. Transgenic mouse technology was first used to construct immortal *GSH1*^{-/-} null cell lines from developing brain cells that normally express *GSH1*. The *GSH1* gene was then reintroduced into the cells, and Affymetrix GeneChips were used to monitor alterations in gene expression. When 15 apparently differentially expressed genes were examined in northern blot analyses, around half appeared to represent display artefacts. Genes whose altered expression was confirmed included the pro- α 2 (I) collagen gene, which was downregulated, and the *PBX1* homeobox gene, *GAS1* (growth arrest specific 1) and ceruloplasmin genes, which were upregulated.

Lee *et al* [91] used microarrays to investigate the mechanism of action of the *WT1* Wilms' tumour gene during kidney development. When introduced into U2OS osteosarcoma cells, the WT1(+KTS) isoform induced apoptosis after 48 h, an effect that was not observed for the WT1(-KTS) isoform. Further analysis of alteration of gene expression induced by the WT1(+KTS) isoform using a 6,800 gene microarray identified 12 genes and ESTs that were upregulated, four of which were confirmed by northern analysis. The most striking alteration was a 74-fold induction of the amphiregulin gene which was accompanied by lower low levels of induction were observed for *HSP70*, *P21CIP1* and the gene for acidic fibroblast growth factor. Subsequent analysis showed that the *in vivo* expression profile of amphiregulin mirrors the pattern of WT1 expression, that the WT1(+KTS) isoform can bind directly to the amphiregulin promoter, and that, in primary cultures of embryonic mouse kidney, amphiregulin can stimulate epithelial branching. These studies strongly indicate that a major role of WT1 is to act as a transcriptional activator of amphiregulin.

Work carried out by Phillips *et al* [92] demonstrated the way in which microarrays can be used to identify genes specifically expressed in stem-cell populations. A cDNA library from which housekeeping genes had been subtracted was first prepared from mouse fetal liver, the first tissue in development to contain significant numbers of haematopoietic stem cells. The library of 18,000 clones was then arrayed onto nylon membranes and genes that

were differentially expressed either in fetal haematopoietic stem cells or adult bone marrow stem cells were identified by a variety of screening strategies. Four genes, including *CD27* and three novel sequences, were overexpressed in both fetal and adult stem cells. Sets of genes that were predominant in either fetal or adult hematopoietic cells were also identified. The cytosine methyltransferase gene *Dnmt-3b* and the variant histone gene *macroH2A1.2* were, for example, highly overexpressed in fetal stem cells.

The use of microarrays in gene cloning

Microarray technology may be used to assist in positional cloning projects as illustrated by the recent identification of the gene responsible for insulin resistance in the spontaneously hypertensive rat strain SHR [93]. To identify genes differentially expressed between SHR and insulin-sensitive controls, microarrays of rat cDNA clones were hybridised to targets from adipose tissue from the SHR strain, a congenic SHR.4 strain and the parent BN strain. These experiments pinpointed clones encoding rat *CD36* that showed substantially reduced hybridisation signals in the SHR strain. *CD36* mapped to the region of rat chromosome 4 associated with insulin resistance and encoded a fatty acid translocase, and its encoded product was completely missing from the SHR adipocyte plasma membrane. It was concluded from these studies that *CD36* was the gene whose alteration was responsible for the insulin resistance.

The use of microarrays in toxicology

Microarray technology can, in principle, be used to study the toxicology of anticancer drugs and of environmental and dietary agents potentially involved in cancer development [97,98]. To facilitate these analyses, a so-called 'ToxChip' has been developed that contains most of the human genes known or proposed to be involved in toxicological responses. These include DNA replication and repair genes, apoptosis genes and genes involved in cellular responses to polycyclic aromatic hydrocarbons (PAHs), dioxins, peroxisome proliferators, oestrogenic compounds and oxidants. The goal of these studies is to identify the patterns of alteration of gene expression characteristic of exposure to each class of toxicant in cultured human cells. Once signatures are identified, the patterns of altered gene expression induced by unknown agents might identify their likely mechanism of action. This approach could also be applied, with the equivalent rat or mouse gene arrays, to the investigation of responses to toxicants in rodent models. The aim would be to identify signatures for various types of tissue-specific toxicants, providing a more rapid test for the possible toxicological effect of drugs and less need to use animals.

It has been proposed that microarray profiling could be used to monitor environmental exposure to chemicals in humans. The rationale is that, as gene expression is a sen-

sitive end-point, alterations in microarray expression profiles may act as useful biomarkers to define more precisely the nature and level of exposure to hazardous chemicals. Gene expression profiles in an exposed individual would be compared to control samples taken before exposure, for example, in an occupational health setting. Studies are currently underway to apply this approach to monitoring gene expression in peripheral blood in potential cases of extreme exposure to chemical toxicants, such as Polish coke oven workers.

Amplification of mRNAs for microarray analysis

A problem with mRNA profiling by microarray is that up to 200 µg of total RNA or 5 µg of poly(A)⁺ RNA may be required to determine an expression profile, making analysis of small tumour lesions extremely difficult. In some cases, many smaller lesions can be pooled to make enough RNA. Amplification of poly(A)⁺ RNA or cDNA can in principle increase detection by orders of magnitude [4,94–96]. For example, Wang *et al* [96] have developed a procedure to optimise amplification of small RNA samples. First, a 5' reverse transcriptase primer containing the T7 promoter sequence fused upstream of an oligodT sequence together with template switching is used to generate full-length cDNA molecules from the template RNA. Next, many hundreds of antisense RNA molecules are generated from each cDNA molecule using T7 polymerase. Finally, the antisense RNA is reverse transcribed to produce fluorescently labelled cDNA that is hybridised to the microarray. One round of this amplification yielded a 10³-fold amplification, and two rounds yielded 10⁵-fold amplification. The microarray expression profiles obtained with amplified RNA were comparable to those obtained with the original RNA.

Conclusions

Microarray technology is a versatile technique that can be used in a rich diversity of approaches to help understand cancer development, to improve patient treatment and management, and to identify those predisposed to develop cancer. Although 50,000 genes may be present in the human genome, the function of only around 10,000 has currently been established. A top priority must therefore be to construct microarrays that include all human genes. The power of microarray technology is that it allows global analysis of patterns of simultaneous gene expression. This can identify novel gene–gene interactions or enable entire control pathways to be followed, for example. It is particularly powerful when the database of expression patterns obtained using one microarray is linked to other databases. Microarray expression patterns could be integrated on the one hand with clinical data to identify new markers to predict biological behaviour of tumours, and on the other hand with databases of drug sensitivity to unravel the molecular basis of drug action.

Microarray data may also be used in conjunction with the new technique of tissue array to enable the expression of individual genes in hundreds of histopathological cancer specimens to be examined [99]. With the vast amount of work still to be done, microarray technology will have an increasingly important role in the post-genomic era and will most certainly be an essential player in the post-genomic era.

Acknowledgements

I thank the Cancer Research Campaign for funding, Christine Bell for typing this manuscript, Jeremy Clark and Paul Clarke for providing figures and Karine Maillard for helpful comments.

References

- Bassett DE, Eisen MB, Boguski MS: **Gene expression informatics – its all in your mine.** *Nat Genet* 1999, **21** (suppl):51–55.
- Ramsay G: **DNA chips: state-of-the-art.** *Nat Biotechnol* 1998, **16**:40–44.
- Chee M, Yang R, Hubbel E, Berno A, Huang XC, Stern D, Winkler J, Lockhart DJ, Morris MS, Fodor SP: **Accessing genetic information with high-density DNA arrays.** *Science* 1996, **274**: 610–614.
- Lockhart DJ, Dong H, Byrne MC, Follettie MT, Gallo MV, Chee MS, Mittman M, Wang C, Kobayashi M, Horton H, Brown EL: **Expression monitoring by hybridisation to high-density oligonucleotide arrays.** *Nat Biotechnol* 1996, **14**:1675–1680.
- Lipshutz RJ, Fodor SPA, Gingeras TR, Lockhart DJ: **High density synthetic oligonucleotide arrays.** *Nat Genet* 1999, **21** (suppl): 20–24.
- Schena M, Shalon D, Heller R, Chai A, Brown PO, Davis RW: **Parallel human genome analysis: Microarray-based expression monitoring of 1000 genes.** *Proc Natl Acad Sci USA* 1996, **93**:10614–10619.
- DeRisi J, Penland L, Brown PO, Bittner ML, Meltzer PS, Ray M, Chen Y, Su YA, Trent JM: **Use of a cDNA microarray to analyse gene expression patterns in human cancer.** *Nat Genet* 1996, **14**:457–460.
- Okamoto T, Suzuki T, Yamamoto N: **Microarray fabrication with covalent attachment of DNA using bubble jet technology.** *Nat Biotechnol* 2000, **18**:438–441.
- Radtkey R, Feng L, Muralhidar M, Duhon M, Canter D, DiPierro D, Fallon S, Tu E, McElfresh K, Nerenberg M, Sosnowski R: **Rapid, high fidelity analysis of simple sequence repeats on an electronically active DNA microchip.** *Nucleic Acids Res* 2000, **28**: E17–E17.
- Drmanac S, Drmanac R: **Processing of cDNA and genomic kilobase-size clones for massive screening, mapping and sequencing by hybridisation.** *Biotechniques* 1994, **17**:328–336.
- Drmanac S, Stavropoulos NA, Labat I, Vonau J, Hauser B, Soares MD, Drmanac R: **Gene-representing cDNA clusters defined by hybridisation of 57,419 clones from infant brain libraries with short oligonucleotide probes.** *Genomics* 1996, **37**:29–40.
- Milosavljevic A, Savkovic S, Crkvenjakov R, Salbego D, Serrato H, Kreuzer H, Gemmell A, Batus S, Grujic D, Carnahan S, Paunesku T, Tepavcevic J: **DNA sequence recognition by hybridisations to short oligomers: experimental verification of the method on the *E. coli* genome.** *Genomics* 1996, **37**:77–86.
- Yershov G, Barsky V, Belgovskiy A, Kirillov E, Kreindlin E, Ivanov I, Parinov S, Guschin D, Drobishev A, Dubiley S, Mirzabekov A: **DNA analysis and diagnostics on oligonucleotide microchips.** *Proc Natl Acad Sci USA* 1996, **93**:4913–4918.
- Southern E, Mir K, Shchepinov M: **Molecular interactions on microarrays.** *Nat Genet* 1999, **21** (suppl):5–9.
- Cheung VG, Morley M, Aguilar F, Massimi A, Kucherlapati R, Childs G: **Making and reading microarrays.** *Nat Genet* 1999, **21**:15–19.
- Fodor SP, Read JL, Pirrung MC, Stryer L, Lu AT, Solas D: **Light-directed, spatially addressable parallel chemical synthesis.** *Science* 1991, **251**:767–773.
- Pease AC, Solas D, Sullivan EJ, Cronin MT, Holmes CP, Fodor SP: **Light-generated oligonucleotide arrays for rapid DNA sequence analysis.** *Proc Natl Acad Sci USA* 1994, **91**: 5022–5026.
- McGall G, Labadie J, Brock P, Wallraff G, Nguyen T, Hinsberg W: **Light-directed synthesis of high density oligonucleotide arrays using semiconductor photoresists.** *Proc Natl Acad Sci USA* 1996, **93**:13555–13560.
- Hacia JG, Woski SA, Fidanza J, Edgemon K, Hunt N, McGall G, Fodor SP, Collins FS: **Enhanced high density oligonucleotide array-based sequence analysis using modified nucleoside triphosphates.** *Nucleic Acids Res* 1998, **26**:4975–4982.
- Brinkmann U, Gallo M, Polymeropoulos MH, Pastan I: **The human CAS (cellular apoptosis susceptibility) gene mapping on chromosome 20q13 is amplified in BT474 breast cancer cells and part of aberrant chromosomes in breast and colon cancer cell lines.** *Genome Res* 1996, **6**:187–194.
- Anzick SL, Kononen J, Walker RL, Azorsa DO, Tanner MM, Guan XY, Sauter G, Kallioniemi OP, Trent JM, Meltzer PS: **AIB1, a steroid receptor coactivator amplified in breast and ovarian cancer.** *Science* 1997, **277**:965–968.
- Sen S, Zhou H, White RA: **A putative serine/threonine kinase encoding gene BTAK on chromosome 20q13 is amplified and overexpressed in human breast cancer cell lines.** *Oncogene* 1997, **14**:2195–2200.
- Slamon DJ, Clark GM, Wong SG, Levin WJ, Ullrich A, McGuire WL: **Human breast cancer: correlation of relapse and survival with amplification of the HER-2/neu oncogene.** *Science*, 1987, **235**:177–182.
- Gusterson BA, Gelber RD, Goldhirsch A, Price KN, Save-Soderborgh J, Anbazhagan R, Styles J, Rudenstam CM, Golouh R, Reed R: **Prognostic importance of c-erbB-2 expression in breast cancer.** *International (Ludwig) Breast Cancer Study Group. J Clin Oncol* 1992, **10**:1049–1056.
- Tanner MM, Tirkkonen M, Kallioniemi A, Holli K, Collins C, Kowbel D, Gray JW, Kallioniemi O-P, Isola J: **Amplification of chromosomal region 20q13 in invasive breast cancer: prognostic implications.** *Clin Cancer Res* 1995, **1**:1455–1461.
- Forozan F, Karhu R, Kononen J, Kallioniemi A, Kallioniemi O-P: **Genome screening by comparative genomic hybridisation.** *Trends Genet* 1997, **13**:405–409.
- Pinkel D, Segreaves R, Sudar D, Clark S, Poole I, Kowbel D, Collins C, Kuo W-L, Chen C, Zhai Y, Dairkee SH, Ljung BM, Gray JW, Albertson DG: **High resolution analysis of DNA copy number variation using comparative genomic hybridisation to microarrays.** *Nat Genet* 1998, **20**:207–211.
- Pollack J R, Perou CM, Alizadeh AA, Eisen MB, Pergamenschikov A, Williams CF, Jeffrey SS, Botstein D, Brown PO: **Genome-wide analysis of DNA copy-number changes using cDNA microarrays.** *Nat Genet* 1999, **23**:41–46.
- Heiskanen MA, Bittner M, Chen Y, Khan J, Adler KE, Trent JM, Meltzer PS: **Detection of gene amplification by genomic hybridisation to cDNA microarrays.** *Cancer Res* 2000, **60**:799–802.
- Golub TR, Slonim DK, Tamayo P, Huard C, Gaasenbeek M, Mesirov JP, Coller H, Loh ML, Downing JR, Caligiuri MA, Bloomfield CD, Lander ES: **Molecular classification of cancer: class discovery and class prediction by gene expression monitoring.** *Science* 1999, **286**:531–537.
- Alizadeh AA, Eisen MB, Davis RE, Ma C, Lossos IS, Rosenwald A, Boldrick JC, Sabet H, Tran T, Yu X, Powell JI, Yang L, Marti GE, Moore T, Hudson J, Lu L, Lewis DB, Tibshirani R, Sherlock G, Chan WC, Greiner TC, Weisenburger DD, Armitage JO, Warnke R, Staudt LM: **Distinct types of diffuse large B-cell lymphoma identified by gene expression profiling.** *Nature* 2000, **403**:503–511.
- Ross DT, Scherf U, Eisen MB, Perou CM, Rees C, Spellman P, Iyer V, Jeffrey SS, Van de Rijn M, Waltham M, Pergamenschikov A, Lee JC, Lashkari D, Shalon D, Myers TG, Weinstein JN, Botstein D, Brown PO: **Systematic variation in gene expression patterns in human cancer cell lines.** *Nat Genet* 2000, **24**:227–235.
- Alon U, Barkai N, Notterman DA, Gish K, Mack YD, Levine AJ: **Broad patterns of gene expression revealed by clustering analysis of tumor and normal colon tissues probed by oligonucleotide arrays.** *Proc Natl Acad Sci USA* 1999, **96**:6745–6750.
- Sgroi DC, Teng S, Robinson G, LeVangie R, Hudson JR Jr, Elkahloun AG: **In vivo gene expression profile analysis of human breast cancer progression.** *Cancer Res* 1999, **59**:5656–5661.
- Perou CM, Sorlie T, Eisen MB, van de Rijn M, Jeffrey SS, Rees CA, Pollack JR, Ross DT, Johnsen H, Akslen LA, Fluge O, Pergamenschikov A, Williams C, Zhu SX, Lonning PE, Borresen-Dale AL, Brown PO, Botstein D: **Molecular portraits of human breast tumours.** *Nature* 2000, **406**:747–752.

36. Debouck C, Goodfellow PN: **DNA microarrays in drug discovery and development.** *Nat Genet* 21: 48–50.
37. Scherf U, Ross DT, Waltham M, Smith LH, Lee JK, Tanabe L, Kohn KW, Reinhold WC, Myers TG, Andrews DT, Scudiero DA, Eisen MB, Sausville EA, Pommier Y, Botstein D, Brown PO, Weinstein JN: **A gene expression database for the molecular pharmacology of cancer.** *Nat Genet* 2000, 24:236–244.
38. Marton MJ, DeRisi JL, Bennett HA, Iyer VR, Meyer MR, Roberts CJ, Stoughton R, Burchard J, Slade D, Dai H, Bassett DE, Hartwell LH, Brown PO, Friend SH: **Drug target validation and identification of secondary drug target effects using DNA microarrays.** *Nat Med* 1998, 4:1293–1301.
39. Hughes TR, Marton MJ, Jones AR, Roberts CJ, Stoughton R, Armour CD, Bennett HA, Coffey E, Dai H, He YD, Kidd MJ, King AM, Meyer MR, Slade D, Lum PY, Stepaniants SB, Shoemaker DD, Gachotte D, Chakraburty K, Simon J, Bard M, Friend SH: **Functional discovery via a compendium of expression profiles.** *Cell* 2000, 102:109–126.
40. Gray NS, Wodicka L, Thunnissen AM, Norman TC, Kwon S, Espinoza FH, Morgan DO, Barnes G, LeClerc S, Meijer L, Kim SH, Lockhart DJ, Schultz PG: **Exploiting chemical libraries, structure, and genomics in the search for kinase inhibitors.** *Science* 1998, 281:533–538.
41. Clarke PA, Hostein I, Banerji U, Stefano FD, Maloney A, Walton M, Judson I, Workman P: **Gene expression profiling of human colon cancer cells following inhibition of signal transduction by 17-allylamino-17-demethoxygeldanamycin, an inhibitor of the hsp90 molecular chaperone.** *Oncogene* 2000, 19:4125–4133.
42. Hacia JG, Brody LC, Chee MS, Fodor SPA, Collins FS: **Detection of heterozygous mutations in BRCA1 using high density oligonucleotide arrays and two-colour fluorescence analysis.** *Nat Genet* 1996, 14:441–447.
43. Hacia JG: **Resequencing and mutational analysis using oligonucleotide microarrays.** *Nat Genet* 1999, 21 (suppl):42–47.
44. Ahrendt SA, Halachmi S, Chow JT, Wu L, Halachmi N, Yang SC, Wehage S, Jen J, Sidransky D: **Rapid p53 sequence analysis in primary lung cancer using an oligonucleotide probe array.** *Proc Natl Acad Sci USA* 1999, 96:7382–7387.
45. Lehman TA, Haffty BG, Carbone CJ, Bishop LR, Gumbs AA, Krishnan S, Shields PG, Modali R, Turner BC: **Elevated frequency and functional activity of a specific germ-line p53 intron mutation in familial breast cancer.** *Cancer Res* 2000, 60:1062–1069.
46. Wen W-H, Bernstein L, Lescallett J, Beazer-Barclay Y, Sullivan-Halley J, White M, Press MF: **Comparison of TP53 mutations identified by oligonucleotide microarray and conventional DNA sequence analysis.** *Cancer Res* 2000, 60:2716–2722.
47. Wilson JW, Bean P, Robins T, Graziano F, Persing DH: **Comparative evaluation of three human immunodeficiency virus genotyping systems: the HIV-Genotype R method, the HIV PRT GeneChip assay and the HIV RT line probe assay.** *J Clin Microbiol* 2000, 38:3022–3028.
48. Syvanen AC: **From gels to chips: 'Minisequencing' primer extension for analysis of point mutations and single nucleotide polymorphisms.** *Hum Mut* 1999, 13:1–10.
49. Favis R, Day JP, Gerry NP, Phelan C, Narod S, Barany F: **Universal DNA array detection of small insertions and deletions in BRCA1 and BRCA2.** *Nat Biotechnol* 2000, 18:561–564.
50. Gerry NP, Witowski NE, Day J, Hammer RP, Barany G, Barany F: **Universal DNA microarray method for multiplex detection of low abundance point mutations.** *J Mol Biol* 1999, 292:251–262.
51. Gerry NP, Witowski NE, Day J, Hammer RP, Barany G, Barany F: **Universal DNA microarray method for multiplex detection of low abundance point mutations.** *J Mol Biol* 1999, 292:251–262.
52. Favis R, Barany F: **Mutation detection in K-ras, BRCA1, BRCA2, and p53 using PCR/LDR and a universal DNA microarray.** *Annl NY Acad Sci* 2000, 906:39–43.
53. Khan J, Bittner M, Saal LH, Teichmann U, Azorsa DO, Gooden GC, Pavan WJ, Trent JM, Meltzer PS: **cDNA microarrays detect activation of a myogenic transcription program by the PAX3-FKHR fusion oncogene.** *Proc Natl Acad Sci USA* 1999, 96:13264–13269.
54. Harkin DP, Bean JM, Miklos D, Song YH, Truong VB, Englert C, Christians FC, Ellisen LW, Maheswaran S, Oliver JD, Haber DA: **Induction of GADD45 and JNK/SAPK-Dependent apoptosis following inducible expression of BRCA1.** *Cell* 1999, 97:575–586.
55. Coller HA, Grandori C, Tamayo P, Colbert T, Lander ES, Eisenman RN, Golub TD: **Expression analysis with oligonucleotide microarrays reveals that MYC regulates genes involved in growth cell cycle signaling and adhesion.** *Proc Natl Acad Sci USA* 2000, 97:3260–3265.
56. **Molecular Pattern Recognition: Whitehead/MIT Center for Genome Research** [http://www.genome.wi.mit.edu/MPR]
57. Zhao R, Gish K, Murphy M, Yuxin Y, Nottermann D, Hoffman WH, Tom E, Mack DH, Levine AJ: **Analysis of p53-regulated gene expression patterns using oligonucleotide arrays.** *Genes Dev* 2000, 14:981–993.
58. <http://www.rockefeller.edu/labheads/levine/levine.html>
59. Amundson SA, Bittner M, Chen Y, Trent J, Meltzer P, Forance AJ Jr: **Fluorescent cDNA microarray hybridisation reveals complexity and heterogeneity of cellular genotoxic stress responses.** *Oncogene* 1999, 18:3666–3672.
60. Voehringer DW, Hirschberg DL, Xiao J, Lu Q, Roederer M, Lock CB, Herzenberg LA, Steinman L, Herzenberg LA: **Gene microarray identification of redox and mitochondrial elements that control resistance or sensitivity to apoptosis.** *Proc Natl Acad Sci USA* 2000, 97:2680–2685.
61. Johannes G, Carter MS, Eisen MB, Brown PO, Sarnow P: **Identification of eukaryotic mRNAs that are translated at reduced cap binding complex eIF4F concentrations using a cDNA microarray.** *Proc Natl Acad Sci USA* 1999, 96:13118–13123.
62. Diehn M, Eisen MB, Botstein D, Brown PO: **Large-scale identification of secreted and membrane-associated gene products using DNA microarrays.** *Nat Genet* 25:58–62.
63. **Stanford Membrane-bound Polysome Microarray Project** [http://genome-www.stanford.edu/mpbp]
64. Perou CM, Jeffrey SS, van de Rijn M, Rees CA, Eisen MB, Ross DT, Pergamenschikov A, Williams CF, Zhu SX, Lee JC, Lashkari D, Shalon D, Brown PO, Botstein D: **Distinctive gene expression patterns in human mammary epithelial cells and breast cancers.** *Proc Natl Acad Sci USA* 1999, 96:9212–9217.
65. Rusiniak ME, Yu M, Ross DT, Tolhurst EC, Slack JL: **Identification of B94 (TNFAIP2) as a potential retinoic acid target gene in acute promyelocytic leukemia.** *Cancer Res* 2000, 60:1824–1829.
66. Ollila J, Vihinen M: **Stimulation of B and T cells activates expression of transcription and differentiation factors.** *Biochem Biophys Res Commun* 1998, 249:475–480.
67. Teague TK, Hildeman D, Kedl RM, Mitchell T, Rees W, Schaefer BC, Bender J, Kappler J, Marrack P: **Activation changes the spectrum but not the diversity of genes expressed by T cells.** *Proc Natl Acad Sci USA* 1999, 96:12691–12696.
68. Rogge L, Bianchi E, Biffi M, Bono E, Chang SY, Alexander H, Santini C, Ferrari G, Sinigaglia L, Seiler M, Neeb M, Mous J, Sinigaglia F, Certa U: **Transcript imaging of the development of human T helper cells using oligonucleotide arrays.** *Nat Genet* 2000, 25:96–101.
69. Iyer VR, Eisen MB, Ross DT, Schuler G, Moore T, Lee JC, Trent JM, Staudt LM, Hudson J, Boguski MS, Lashkari D, Shalon D, Botstein D, Brown PO: **The transcriptional program in the response of human fibroblasts to serum.** *Science* 1999, 283:83–87.
70. Pendurthi UR, Allen KE, Ezban M, Rao LV: **Factor VIIa and thrombin induce the expression of Cyr61 and connective tissue growth factor, extracellular matrix signaling proteins that could act as possible downstream mediators in factor VIIa tissue factor-induced signal transduction.** *J Biol Chem* 2000, 275:14632–14641.
71. Der SD, Zhou A, Williams BRG, Silverman RH: **Identification of genes differentially regulated by interferon α , β , or γ using oligonucleotide arrays.** *Proc Natl Acad Sci USA* 1998, 26:15623–15628.
72. Jbilo O, Derocq JM, Segui M, Le Fur G, Casellas P: **Stimulation of peripheral cannabinoid receptor CB2 induces MCP-1 and IL-8 gene expression in human promyelocytic cell line HL60.** *FEBS Lett* 1999, 448:273–277.
73. Lin B, Ferfuson C, White JT, Wang S, Vessella R, True LD, Hood L: **Prostate-localised and androgen-regulated expression of the membrane-bound serine protease TMPRSS2.** *Cancer Res* 1999, 59:4180–4184.
74. Karpf AR, Peterson PW, Rawlins JT, Dalley BK, Yang Q, Albertsen H, Jones DA: **Inhibition of DNA methyltransferase stimulates the expression of signal transducer and activator of transcription 1, 2 and 3 genes in colon tumor cells.** *Proc Natl Acad Sci USA* 1999, 96:14007–14012.

75. Hilsenbeck SG, Friedrichs WE, Schiff R, O'Connell P, Hansen RK, Osborne CK, Fuqua SA: **Statistical analysis of array expression data as applied to the problem of tamoxifen resistance.** *J Natl Cancer Inst* 1999, **91**:453-459.
76. Chang YE, Laimins LA: **Microarray analysis identifies interferon-inducible genes and Stat-1 as major transcriptional targets of human papillomavirus type 31.** *J Virol* 2000, **74**:4174-4182.
77. Bubendorf L, Kolmer M, Kononen J, Koivisto P, Mousset S, Chen Y, Mahlamaki E, Schraml P, Moch H, Willi N, Elkahoun AG, Pretlow TG, Gasser TC, Mihatsch MJ, Sauter G, Kallioniemi OP: **Hormone therapy failure in human prostate cancer: analysis by complementary DNA and tissue microarrays.** *J Natl Cancer Inst* 1999, **91**:1758-1764.
78. Elek J, Park KH, Narayanan R: **Microarray-based expression profiling in prostate tumors.** *In Vivo* 2000, **14**:173-182.
79. Carlisle AJ, Prabhu VV, Eikehloun A, Hudson J, Trent JM, Linehan WM, Williams ED, Emmert-Buck MR, Liotta LA, Munson PJ, Krizman DB: **Development of a prostate cDNA microarray and statistical gene expression analysis package.** *Mol Carcinog* 2000, **28**:12-22.
80. Villaret DB, Wang T, Dillon D, Xu J, Sivam D, Cheever MA, Reed SG: **Identification of genes overexpressed in head and neck squamous cell carcinoma using a combination of complementary DNA subtraction and microarray analysis.** *Laryngoscope* 2000, **110**:374-381.
81. Xu J, Stolk JA, Zhang X, Silva SJ, Houghton RL, Matsumara M, Vedvick TS, Leslie KB, Badaro R, Reed SG: **Identification of differentially expressed genes in human prostate cancer using subtraction and microarray.** *Cancer Res* 2000, **60**:1677-1682.
82. Yang GP, Ross DT, Kuang WW, Brown PO, Weigel RJ: **Combining SSH and cDNA microarrays for rapid identification of differentially expressed genes.** *Nucleic Acids Res* 1999, **27**:1517-1523.
83. Wang T, Hopkins D, Schmidt C, Silva S, Houghton R, Takita H, Repasky E, Reed SG: **Identification of genes differentially over-expressed in lung squamous cell carcinoma using combination of cDNA subtraction and microarray analysis.** *Oncogene* 2000, **19**:1519-1528.
84. Khan J, Simon R, Bittner M, Chen Y, Leighton SB, Pohida T, Smith PD, Jiang Y, Gooden GC, Trent JM, Meltzer PS: **Gene expression profiling of alveolar rhabdomyosarcoma with cDNA microarrays.** *Cancer Res* 1998, **58**:5009-5013.
85. Scholl FA, Betts DR, Niggli FK, Schafer BW: **Molecular features of a human rhabdomyosarcoma cell line with spontaneous metastatic progression.** *Br J Cancer* 2000, **82**:1239-1245.
86. Wang K, Gan L, Jeffery E, Gayle M, Bown AM, Skelly M, Nelson PS, Ng WV, Schummer M, Hood L, Mulligan J: **Monitoring gene expression profile changes in ovarian carcinomas using cDNA microarray.** *Gene* 1999, **299**:101-108.
87. Moch H, Schraml P, Bubendorf L, Mirlacher M, Kononen J, Gasser T, Mihatsch MJ, Kallioniemi O, Sauter G: **High-throughput tissue microarray analysis to evaluate genes uncovered by cDNA microarray screening in renal cell carcinoma.** *Am J Pathol* 1999, **154**:981-986.
88. Maniotis AJ, Folberg R, Hess A, Seftor EA, Gardner LMG, Pe'er J, Trent JM, Meltzer PS, Hendrix MJ: **Vascular channel formation by human melanoma cells in vivo and in vitro: vasculogenic mimicry.** *Am J Pathol* 1999, **155**:739-752.
89. Welford SM, Gregg J, Chen E, Garrison D, Sorensen PH, Denny CT, Nelson SF: **Detection of differentially expressed genes in primary tumor tissues using representational differences analysis coupled to microarray hybridisation.** *Nucleic Acids Res* 1998, **26**:3059-3065.
90. Li H, Schrick JJ, Fewell GD, MacFarland KL, Witte DP, Bodenmiller DM, Hsieh-Li HM, Su C-Y, Potter SS: **Novel strategy yields candidate Gsh-1 homeobox gene targets using hypothalamus progenitor cell lines.** *Dev Biol* 1999, **211**:64-76.
91. Lee SB, Huang K, Palmer R, Truong VB, Herzlinger D, Kolquist KA, Wong J, Paulding C, Yoon SK, Gerald W, Oliner JD, Haber DA: **The Wilms tumor suppressor WT1 encodes a transcriptional activator of amphiregulin.** *Cell* 1999, **98**:663-673.
92. Phillips RL, Ernst RE, Brunk B, Ivanova N, Mahan MA, Deanehan JK, Moore KA, Overton GC, Lemischka IR: **The genetic program of hematopoietic stem cells.** *Science* 2000, **288**:1635-1640.
93. Aitman TJ, Glazier AM, Wallace CA, Cooper LD, Norsworthy PJ, Wahid FN, Al-Majali KM, Trembling PM, Mann CJ, Shoulders CC, Graf D, St Lezin E, Kurtz TW, Kren V, Pravenec M, Ibrahimi A, Abumrad NA, Stanton LW, Scott J: **Identification of Cd36 (fat) as an insulin-resistance gene causing defective fatty acid and glucose metabolism in hypertensive rats.** *Nat Genet* 1999, **21**:76-83.
94. Phillips J, Eberwine JH: **Antisense RNA amplification: a linear amplification method for analysing the mRNA population from single living cells.** *Methods* 1996, **10**:283-288.
95. Trenkle T, Welsh J, Jung B, Mathieu-Daude F, McClelland M: **Non-stoichiometric reduced complexity probes for cDNA arrays.** *Nucleic Acids Res* 1998, **26**:3883-3891.
96. Wang E, Miller LD, Ohnmacht GA, Liu ET, Marincola FM: **High-fidelity mRNA amplification for gene profiling.** *Nat Biotechnol* 2000, **18**:457-459.
97. Afshari CA, Nuwaysir EF, Barrett JC: **Application of complementary DNA microarray technology to carcinogen identification, toxicology, and drug safety evaluation.** *Cancer Res* 1999, **59**:4759-4760.
98. Nuwaysir EF, Bittner M, Trent J, Barrett JC, Afshari CA: **Microarrays and toxicology: The advent of toxicogenomics.** *Mol Carcinog* 1999, **24**:153-159.
99. Kononen J, Bubendorf L, Kallioniemi A, Barlund M, Schraml P, Leighton S, Torhorst J, Mihatsch MJ, Sauter G, Kallioniemi OP: **Tissue microarrays for high-throughput molecular profiling of tumor specimens.** *Nat Med* 1998, **4**:844-847.