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TITLE: Magnetic Resonance Spectroscopy: An Objective Modality to Identify the Pathology of Breast Neoplasms

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<p>13. ABSTRACT (Maximum 200 words)</p> <p>Fine Needle Aspirates have been obtained from over 300 patients with breast cancer and analysed by proton MR spectroscopy at 8.5 Tesla and the results compared with histopathological and clinical data. The results of the blinded study were compared with currently employed diagnostic approaches used in the assessment of breast lesions. Discrimination between invasive cancer and normal or benign or carcinoma <i>in situ</i> gave a sensitivity and specificity of 95 and 96% respectively.</p> <p>All carcinoma <i>in situ</i> samples with comedo necrosis or a microinvasive component were ranked by MRS with the invasive specimens. Those with <i>in situ</i> disease alone ranked with benign unless there was a malignant tumour elsewhere in the same breast. In order to identify the chemical species which differ in these CIS specimens two dimensional spectroscopy has commenced.</p> <p>Mathematical multivariate analysis procedures have been employed but the large water contribution to the spectrum has interfered with the outcome. Methods to overcome this problem are underway.</p> <p>Specimens have been assessed for their stability in storage and it was found that specimens could not be stored for longer than six months at -70C.</p> <p>The technology has now been extended and developed for MR spectroscopy assessment of fine needle aspirates from the lymph nodes of breast cancer patients.</p>			
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APPENDIX II. .... Attached  
    MANUSCRIPT PUBLISHED IN *RADIOLOGY*

APPENDIX III. .... Attached  
    FIGURES 1-6

APPENDIX IV. .... Attached  
    TABLE 1

APPENDIX V. .... Attached  
    MANUSCRIPT PUBLISHED IN *LIFE SCIENCES*

## INTRODUCTION

Recent improvement in breast cancer patient outcome is due to early diagnosis and effective management. The triage of mammography, clinical examination and fine needle aspiration biopsy is currently used to identify early breast cancers. Magnetic resonance imaging (MRI) has now been added to select women with breast abnormalities requiring biopsy. However, mammography and MRI are unable to distinguish cellular changes which correlate with the development of cancer and are unable to predict patient outcome. Fine needle aspiration cytology following mammography has reduced the incidence of unnecessary surgery but cannot predict at-risk status or tumour progression.

A new technology which could report on alterations to cellular chemistry and provide an adjunct to cytology would offer both independent and objective assessment of breast tissue. The potential then exists to identify an immediate or more distant predisposition towards breast cancer and thus screen, monitor and offer management protocols aimed at reducing tumour risk. Magnetic resonance spectroscopy offers this diagnostic modality and has been successfully developed to monitor tumour development and progression in other organs.

In the clinical situation where an established diagnosis of breast cancer has already been made, current predictors of patient outcome are of limited value. Despite methods of evaluation such as tumour typing and grading, surgico-histopathological staging, hormone and growth factor receptor status, genetic markers and ploidy, the reason for the variable clinical outcome in patients with established widespread metastatic disease remains unknown. The identification of biochemical markers both within primary and metastatic tumour deposits may be of great value in identifying patients who are likely to respond to specific therapeutic regimes.

**This proposal is aimed at developing magnetic resonance spectroscopy to be used as an adjunct to diagnostic histopathology. The MRS method offers the possibility of earlier diagnosis of cellular abnormalities in predisposed women, a precise documentation of the biological abnormalities of the cells, conclusive predictive value, clear distinction between cellular atypia, progressive and non-progressive carcinoma *in situ* and invasive cancer and the potential to determine patient outcome. These advantages over current technology warrant the thorough investigation of the application of magnetic resonance spectroscopy to breast pathology.**

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**SUMMARY OF PROGRESS to April 28, 1997**

To the end of 1997 218 FNA have been obtained from patients undergoing breast surgery and analysed by proton MR spectroscopy at 360 MHz (8.5 Tesla) and results compared with histopathological analysis. The results of blinded MR analysis were compared with currently employed diagnostic approaches used in assessment of breast lesions. Invasive carcinoma was identified spectroscopically by an increased signal at 3.25 parts per million (ppm) attributable to choline-containing metabolites. Discrimination between invasive carcinoma (n=82) and normal or benign (n=106) or carcinoma *in situ* (n=17) was made based on the intensity of the 3.25 ppm resonance standardised to the resonance intensity at 3.05 ppm ( $p < 0.0001$ , Mann-Whitney U test). An MRS ratio of  $< 1.7$  was recorded for 102 out of 106 normal or benign lesions. All carcinoma-*in-situ* samples with comedonecrosis or a microinvasive component (n=6) were ranked by MRS with invasive carcinoma while those with *in-situ* disease alone ranked with benign (n=11). The sensitivity and specificity of MRS on FNB for benign versus invasive breast cancer was 95% and 96% respectively

**SUMMARY OF PROGRESS from April 29, 1997 to April 28, 1998**

**Publications:**

1. Mackinnon WB, Barry PA, Malycha PL, Gillett DJ, Russell P, Lean, CL, Doran, ST, Barraclough BH, Bilous M, Mountford CE, Fine-needle biopsy specimens of benign breast lesions distinguished from invasive cancer *ex vivo* with proton MR spectroscopy, *Radiology*, 204: 66, 1997.
2. Lo W, Lean CL, Dowd S, Malycha PL, Russell P and Mountford CE, Fine-needle biopsy of human lymph nodes. *Proc. Int. Soc. Mag. Res. Med.*, 1: 327, 1998.
3. Mountford CE, Breast Cancer and Magnetic Resonance Spectroscopy, *Life Sciences*, Vol 10 (5) p 22, 1998.
4. Malycha PL and Mountford CE, *Australian Journal of Surgery*, In Press, 1998.

**Experimental Progress:**

**Increase in Number of Breast FNA Biopsies**

A further 68 FNA biopsies have been examined by 1 Dimensional MRS to determine the effect of A) storage time and B) method of collection (*ex vivo* or *in vivo*) on the MRS correlation with pathology.

***A) Effect of Time Stored at -70°C***

Experiments are underway to determine if time in storage at -70°C affects the MRS fingerprint in such a way as to invalidate the MRS correlation with pathology. Both benign and malignant specimens degrade in long term storage and this may result in the chemical markers becoming unreliable. Data shown in Figure 1 indicate that only specimens under six months are amenable to analysis.

***B) Effect of Collection Method***

Comparison of MR spectra of FNA biopsies obtained *in vivo* (prior to surgical excision) and *ex vivo* (following excision of the lesion) are underway (Figure 2). Preliminary data indicate that FNA obtained *in vivo* generate MR spectra equal in signal to noise and spectral resolution to *ex vivo* FNA spectra and thus amenable to visual and multivariate analysis. It has yet to be determined if the resonance ratio discriminating the two categories remains the same.



#### **Multivariate Analysis of One Dimensional MR Data**

Robust multivariate analysis has commenced in collaboration with the National Research Council of Canada. Initial classification of 55 benign and 69 malignant samples gave an accuracy of 90%. This will be improved by increasing the numbers in each pathology to at least 100 per class.

#### **Two Dimensional (2D) MR Assessment of Breast Tissue and FNA Biopsies**

Two dimensional (2D) Correlated Spectroscopy (COSY) has been successfully undertaken on intact breast tissues and FNA. Representative COSY spectra of lesions of malignant, ductal carcinoma *in situ* and benign pathologies are shown in Figure 3A, 3B and 3C, respectively. The COSY spectrum of an FNA from a malignant lesion is shown in Figure 4. The majority of crosspeaks assigned in adenocarcinoma from other organs have been identified in the spectra of adenocarcinoma of the breast (Table 1) including those from lipid, cellular metabolites and cell surface fucose (Figure 5). Data collection has now commenced.

#### **FNA of lymph nodes from breast cancer patients and control subjects**

The FNA technique has been extended to include biopsies from the axillary lymph nodes of breast cancer patients. Representative 1D MR spectra of tissue and FNA specimens of axillary nodes are shown in Figure 6. The signal to noise and spectral resolution of the FNA spectrum is adequate to allow visual and multivariate analysis of the data. Data collection has now commenced.

#### **New Collaborations on MRS /FNA breast study**

A collaborative program has been established between the Karolinska Institute in Sweden and the IMRR. The Karolinska Institute will carry out an independent study.

#### **Surgical students now being trained on this program**

The IMRR is now training surgeons on this project under the Australian NH&MRC Clinical Centres of Excellence award.

**BODY OF PROPOSAL (Results, progress and new directions during the last year are in bold)**

**PURPOSE**

1. To assess the sensitivity and specificity of  $^1\text{H}$  MRS (*ex vivo*) in the detection of neoplasia in breast, based on altered cellular chemistry.  
**Initial objective completed. Study extended to determine if length of storage and/or method of collection of FNA biopsies affects the MRS correlation with pathology.**
2. Correlate alterations to MRS detectable cellular chemistry associated with breast tumour development and progression with established clinicopathological criteria.  
**Study extended to include MR assessment of FNA biopsies of axillary lymph nodes from breast cancer patients.**
3. Ascertain MRS markers which correlate with known clinical, epidemiological and genetic risk factors to be used to identify women at-risk of developing breast cancer.  
**Study now extended to include 2D spectroscopy of breast tissues.**

**HYPOTHESES**

Proton magnetic resonance spectroscopy can:-

1. Identify altered cellular chemistry in breast tissue independent of method of biopsy eg. open biopsy or fine needle biopsy.
2. Distinguish invasive cancer from normal breast tissue.
3. Distinguish between breast cancers of different type (e.g. lobular or ductal) and grade.
4. Distinguish between progressive and non progressive 'carcinoma *in situ*'.
5. Distinguish between 'normal' breast tissue and 'normal' breast tissue from women with differing risk factors for breast cancer (including age, pre- and post menopausal status, cyclic hormonal effects, genetic predisposition and family history).
6. Identify MRS markers of potential for malignancy in morphologically normal tissue from high risk patients.
7. Independent of histopathology, predict tumour behaviour and clinical outcome (e.g. response to therapy, patterns of metastases) and thereby be a significant predictor of patient survival.

**EXPECTED RESULTS**

- Expertise in optimal handling and methodological protocols for assessment of breast tissue.
- An MRS data bank on a full spectrum of breast tissue from normal (ie. benign) to high grade malignancy. This will allow discrimination of new subsets of cancer-bearing patients for streaming into different management regimes with attendant improved psychosocial, cost

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efficiency and clinical outcomes.

- Identification of new cellular chemistry parameters of tumour development in the breast.
- Definition of MRS markers which correlate with a predisposition for breast cancer development.
- Statistical verification of MR diagnostic criteria.

## RESEARCH PLAN AND PROGRESS TO-DATE

*(Results and progress during the last year are in bold)*

### A. SAMPLE PREPARATION

#### Objective 1.

Optimise specimen handling and MR data acquisition protocols.

*Rationale:* Breast tissue contains substantial levels of fat which mask the diagnostic markers of tumour development and progression. Removal of as much of this fat component as possible from the biopsy prior to MRS analysis is both achievable and necessary.

*Results:* MRS handling criteria are established and global specimen handling protocols determined to ensure adequate histological correlation of MRS data on the test samples (see appendix II).

***Effect of Time Stored at -70°C on FNA MRS Correlation with Pathology:*** To date 13 FNA were stored at -70°C for greater than six months but less than 22 months and then assessed by MRS according to the standard protocol outlined in Appendix II. The 3.25/3.05 ppm MR intensity ratio was correlated with the pathology of the lesions (Figure 1B) and the results compared with those obtained for 15 FNA assessed after storage for greater than 6 weeks but less than six months (Figure 1A). The MRS correlation with pathology was maintained for FNA under six months old. Samples stored for greater than six months were found to be not suitable for MRS assessment due to a higher than expected number of false negatives. This albeit small study indicates that both benign and malignant specimens biodegrade during longer storage and the resonance intensities of the diagnostic marks are no longer reliable. This assessment continues.

#### Objective 2.

Ascertain if the same MR criteria can be obtained on fine needle biopsy or aspirate.

*Rationale:* If the same MR information can be obtained from a fine needle aspirate or needle core biopsy, open surgery may not be a prerequisite for determining the diagnostic parameters.

#### **Results:**

##### *Breast*

A previous study of MRS analysis on FNB of thyroid had established that as few as  $10^6$  cells were required to obtain one-dimensional MR spectroscopic data with adequate signal-to-noise in less than 15 minutes (256 accumulations) (39). To achieve an adequate breast sample, FNB was performed using multiple (typically 6) aspirated passes (23 gauge needle) either through the resected lesion *ex vivo* (n=129) or *in vivo* (n=89) after lesion identification during open biopsy. These techniques could be guaranteed to provide sufficient cells from the lesion and in addition, allowed the aspiration site to be identified at excision. Tissue from the aspiration site ( $3\text{mm}^3$ ) was collected for correlative histopathology. Prior to the  $^1\text{H}$  MRS experiment, each FNB specimen was thawed and transferred directly to a 5 mm MRS tube. The volume was adjusted to 300 $\mu\text{l}$  with PBS/D<sub>2</sub>O where necessary. The sample tube was fitted with a capillary insert containing 60  $\mu\text{l}$  para-aminobenzoic acid (10 mM in PBS/D<sub>2</sub>O) as an external standard.

***Effect of FNA Collection Method (in vivo versus ex vivo):*** Specimen collection protocols have been established for obtaining FNA biopsies *in vivo* (prior to surgical excision of the lesion). This is an important step towards clinical trial of the MRS technology. A representative proton 1D MR

spectrum of an FNA biopsy collected from a breast lesion *in vivo* is shown in Figure 2. The signal to noise and resolution of the *in vivo* spectra is of sufficient quality to allow correlation with histopathology on the basis of criteria generated from both visual inspection and multivariate analysis. This method of specimen collection is now used in the 1998-1999 year where clinically appropriate.

### *Lymph Nodes*

Attempts to detect malignant cells in lymph nodes using 1D MRS have been limited by the high fat content of the tissue and the low spectral resolution. Using 2D COSY spectroscopy lymph nodes containing cancer cells were detected based on changes in the intensities of crosspeak resonances from lactate, choline, fucose and amino acids and these MR result were confirmed by xenographing the nodes into nude mice (41). COSY experiments are, however, time consuming (4-5 hours). Alternatively, the contribution from fat to the 1D MR spectrum can be reduced, as for breast tissues (Objective 1), by assessment of fine needle aspiration (FNA) biopsies of the lymph node tissue.

The proton MR spectrum obtained from solid lymph node tissue (Fig 6A) is of poor spectral resolution with predominant resonances from lipid at 0.89, 1.3, 1.7, 2.0, 2.2 and 5.37 ppm. These peaks represent  $-\text{CH}_3$ ,  $(-\text{CH}_2)_n$ ,  $-\text{CH}_2-\text{CH}_2-(\text{CH}_2)_n$ ,  $(-\text{CH}_2)_n-\text{CH}_2-\text{CH}=\text{}$ ,  $-\text{COO}-\text{CH}_2-$  and  $-\text{CH}=\text{CH}-$ , respectively. Figure 6B shows the  $^1\text{H}$  MR spectrum of the FNA biopsy. A marked improvement in the spectral resolution of the lipid resonances at 0.89, 1.3, 1.7, 2.0, 2.2 and 5.37 ppm is achieved which allows a number of other resonances of potential diagnostic importance to be observed. In particular the resonance that represent  $-\text{CH}_2-\text{CH}_2-(\text{CH}_2)_n$  at 1.7 ppm is a distinct peak which was only observed as a shoulder in fig. 6A. The increase in spectral resolution is further evident in the choline peak at 3.2 ppm. In fig. 6A this peak is buried in noise while in fig. 6B the same resonance is resolved into its component (see insert fig. 6B). The component peaks at 3.20, 3.21 and 3.27 ppm, representing choline, phosphocholine and inositol respectively, can all be distinguished.

## B. CORRELATION WITH HISTOLOGICAL CRITERIA

### **Objective 3.**

Identify MRS criteria to facilitate distinction between resected carcinoma and normal tissue.

*Rationale:* The primary data base will be obtained from this section of the study. The 1D and 2D MR data are likely to contain the majority of resonances that need to be assigned to chemical species, biological criteria and clinicopathological criteria.

*Results:* All pathological and MRS analyses were undertaken in a blinded study. Correlation of MRS data with clinicopathological criteria were made after all reports were filed. 218 FNB and tissue specimens for MRS analysis and correlative histopathology respectively were obtained from 191 consecutive patients undergoing diagnostic biopsy or definitive treatment (lumpectomy, quadrantectomy or mastectomy) for histologically proven invasive breast cancer. Indications for surgery included mammographically detected impalpable lesions as well as palpable mass lesions which were suspicious by mammography, FNA cytology and/or clinical examination. The age range of patients was 20 to 81 years (mean  $\pm$  SD, 52  $\pm$  14). Where mastectomy for invasive carcinoma was performed, control specimens of macroscopically uninvolved breast tissue (which was later confirmed histologically) were obtained in the same patient (n=27). The MR experimental methods, data processing and analysis, peak assignment procedures and histopathological assessment protocols are described in detail in Appendix II.

Invasive carcinoma was identified by resonances at 3.25 ppm attributable to choline-containing

metabolites (Appendix II, Figure 2). A discrimination between invasive carcinoma (n=82) and normal or benign tissue (n=106) was made based on the intensity of the 3.25 ppm resonance standardised to the resonance intensity at 3.05 ppm containing contributions from creatine, phosphocreatine and lysine ( $p < 0.0001$ , Mann-Whitney U test)(Appendix II, Figure 3). A receiver operating characteristic (ROC) curve using this intensity ratio is shown in Appendix I, Figure 4.

Of 106 benign samples, 102 gave a 3.25/3.05 ppm intensity ratio of less than 1.7. Four false positive results were obtained from 3 palpable fibroadenomas, none of which had FNA cytology performed, and 1 lesion comprising moderate ductal hyperplasia. The diagnoses were based on correlative histopathology. FNB from 4 of 82 carcinoma had a ratio of  $< 1.7$ . Correlative histopathology from the aspiration site showed that one sample had only benign fibrocystic changes in this region. The other three samples were confirmed as invasive carcinoma but with a marked inflammatory cell infiltrate.

**Clinical Correlations:** All cases presenting as mammographically suspicious (n=56), mammographically negative (n=23), or non-diagnostic (n=14) or atypical/suspicious (n=25) FNA cytology, were accurately categorised by MRS (as benign or malignant) as confirmed by histopathology on tissue excised from the aspiration site. MRS on F.B. correlated 96% with the final histological diagnosis of benign lesions (Appendix II, Table 2) and yet, biopsy was performed because of clinical (34%) and/or mammographic features (45%) and/or FNA cytology (31%). MRS on F.B. correlated with a malignant histological diagnosis in 95% of cases (Appendix II, Table 2). While combined triple assessment indicated biopsy for all the malignant cases studied, no single pre-operative modality was an improvement on MRS in identifying malignancy (physical examination 84%, mammography 82%, FNA cytology 92%).

#### **Objective 4.**

Establish whether MRS can identify differences between variants of breast cancer (e.g. lobular and ductal carcinoma) which reflect altered biological behaviour (e.g. likelihood of response to treatment or location of secondary tumours).

*Rationale:* Lobular and ductal carcinoma have quite different patient outcome. Ductal carcinoma will usually metastasise to the liver, brain, bone, lungs etc.. whereas lobular carcinoma frequently metastasises to unusual sites. If spectral differences exist between these two types of breast carcinoma and can be assigned to specific biological criteria eg. altered cell surface glycosylation which could reflect altered immunosuppression (50), ability to lodge at different sites (51-53), or adhesion properties (54), the patient outcome could be rationalised at an early stage in the diagnosis and treatment altered accordingly. The reasons for variable survival of women with established metastatic disease may be manifest in the cellular chemistry of the carcinoma cells.

**Experimental:** Underway. This aspect of the project has been delayed due to a shortage of lobular specimens.

#### **Objective 5.**

Correlate MRS properties with the established pathological characteristics of breast epithelial hyperplasia and neoplasia.

*Rationale:* It is important to identify which MRS characteristics are consistent with established pathological criteria. MRS will be used, as an adjunct to current histopathology, with each method contributing to a more thorough and refined diagnosis and patient management.

*Experimental: Underway*

### C. CAN MRS REDEFINE THE PRECURSOR STATES OF BREAST NEOPLASIA?

#### **Objective 6.**

Compare simple hyperplasias, atypical hyperplasias and malignant tumours. Does MRS identify sub groups or categorise these histological states differently?

*Rationale:* The strength of the MR method as demonstrated in its application to other organs, was the identification of alterations to cellular chemistry which were not morphologically manifest, or which discriminated between subsets with overlapping or identical histological appearances (e.g. follicular adenoma and carcinoma of thyroid).

*Experimental: Underway*

#### **Objective 7.**

Assess resected tissue containing morphological carcinoma *in situ* to determine if the MR method can separate those, if any, which contain cells committed to invasion from those that cannot progress at that time.

*Rationale:* Diagnosis of carcinoma *in situ* (CIS) of the human cervix relies on the pathologist confirming that the cells (which are morphologically indistinguishable from invasive cancer) have not invaded. MRS has clearly shown that CIS of the cervix does not have the same cellular chemistry as those cell which are invasive. Does CIS of the breast have a different cellular chemistry from invasive cells? Can the distinction be made between a CIS which has cellular capability to invade from those which have yet to develop fully invasive properties?

*Results:* Specimens reported as ductal carcinoma-*in-situ* (DCIS) by routine hospital histopathology were obtained and assessed by MRS. Samples containing only DCIS (10 high grade, 1 low grade) all gave MR ratios  $\leq 1.7$  indicative of a low choline to creatine/lysine ratio similar to that obtained for benign lesions. Ductal cells had breached the basement membrane ( $< 1\text{mm}$ ) in one or more focus of the entire DCIS specimen in the 4 samples denoted 'microinvasion'. This group as well as 2 samples of high grade DCIS with extensive comedonecrosis gave ratios  $> 1.7$  similar to that obtained for malignant lesions.

**A further DCIS specimen was collected. By MRS criteria this specimen had a ratio greater than 1.7 making it malignant by MR criteria. Interestingly, the pathology indicated that the patient had invasive cancer elsewhere in the breast. This observation is consistent with data obtained on the prostate program where when cancer was present elsewhere in the organ a histologically benign specimen gave a MRS ratio consistent with malignant.**

**To further examine the extent to which MRS can record an adenoma-carcinoma sequence in breast neoplasia based on changes to cellular chemistry two dimensional (2D) correlated spectroscopy (COSY) techniques have been optimised for the assessment of intact breast tissue biopsies. Representative COSY spectra of lesions of malignant, ductal carcinoma *in situ* and benign pathologies are shown in Figures 3A, B and C, respectively.**

There are in excess of 50 chemical species (crosspeaks) identifiable in the 2D COSY MR spectra of some invasive tumour biopsies and malignant cell lines (2). Many of these crosspeaks have been assigned (8). Those used in other organs as diagnostic markers include lipid, cell surface fucosylation and cellular metabolites.

Resonances from cell surface fucose are of particular interest in the characterisation of the malignant potential of preinvasive lesions. 2D COSY spectroscopy of adenomatous colorectal polyps displayed a progressive increase in the complexity in the spectral pattern from fucosylated species that correlated with the malignant potential of the adenoma, specifically with the histological degree of dysplasia.

Crosspeaks identified and assigned in the spectra of breast lesions including those from lipid, cellular metabolites and cell surface fucose (Figure 5) are summarised in Table 1. Data collection is proceeding.

#### **D. CAN MRS IDENTIFY CHEMICAL PROFILES ASSOCIATED WITH A PREDISPOSITION TO BREAST CANCER?**

##### **Objective 8.**

Study morphologically normal tissue from women with differing risk factors for development of breast cancer.

*Rationale:* It is most likely that alterations to cellular chemistry are able to be documented in the above categories. Are there specific changes which can be identified in at-risk patients?

The effect of :-

- age,
- pre vs post menopausal status,
- cyclic hormonal effects,
- genetic predisposition,
- family history,

on the spectral profile will be considered in a retrospective study in association with the breast data bank registries.

*Experimental:* Underway.

#### **E. LONGITUDINAL STUDY**

##### **Objective 9.**

Statistical and mathematical multivariate analysis to correlate MRS data with clinicopathological, epidemiological and genetic data.

*Rationale:* By examining tissue specimens by MRS, it may be possible to predict the precise progression of breast cancer in individual patients more accurately than histopathology.

*Experimental:* Underway

##### **Results**

MR spectra comprise a large number of variates, the intensities of absorption as a function of



frequency. As many as 4000 variates may be available for each spectrum to be classified.

Extensive experience with classifying MR spectra indicated that better and more reliable classification is obtained if we only deal with the magnitude spectra. (The subjective spectral phasing step is completely eliminated.) Thus all analyses were conducted on the magnitude spectra.

Efficient application of multivariate analysis involves identification of the minimum number of variates required to classify the spectra accurately. We have developed a powerful and versatile preprocessing method (ORS\_GA) that is Genetic Algorithm-driven and selects from the spectra those subregions that are optimally discriminatory (62). Reduction of the number of features to 1/5 – 1/10 of the number of samples per class is an essential requirement for creating reliable classifiers.

We used simple Linear Discriminant Analysis (LDA) with the selected optimal features (each such feature is the average intensity value of its spectral subregion). Classification robustness and reliability is achieved by our resampling procedure. This involves the random selection (with replacement) of ~half the samples from each class to use as the training set for the LDA, with the remainder serving as a test set. This is repeated N times (N is typically 500-1000), and the N sets of LDA coefficients averaged to produce a single, optimal set. (This combination of optimal region selection and resampled and averaged LDA has been successful for the accurate classification of MR and IR spectra of tissues and biofluids for a variety of diseases and disease stages.)

We applied the above classification strategy to the breast tissue spectra (water-suppressed, with 1250 data points per sample in the 0.5-4.0 ppm spectral range). There were 55 benign and 69 malignant samples. Three independent sets of 9 variates each gave very similar results: ~70% classification accuracy for the entire 124 spectra. However, when only the crisply (i.e., with probabilities to belong to a given class > 75%) classified spectra were considered, their classification accuracy reached ~90%. Unfortunately, the crisply classified spectra comprise only ~25% of the total number of spectra. Our consensus classifier, which uses the outputs of the three individual classifiers as inputs to another LDA classifier, increased the number of crisply classified spectra to 53%, but the overall accuracy of these remained at ~90%.

Further improvement requires:

- Increase in spectral data base to at least 100 per class.
- Removal of minor contaminants present in the storage D<sub>2</sub>O solution present in some data files.
- Since the misclassified and fuzzily classified spectra are evenly distributed between the two classes, this suggests that better quality spectra would yield better classification results.
- Lipid suppression will also be tested.

## **METHODS** (*Methods additional to original submission are in bold*)

### **THE SELECTION OF PATIENTS**

Biopsy specimens are to be obtained at the time of surgery on 500 patients undergoing surgery to excise benign and malignant lesions by participating surgeons. The indications for surgery include:

1. Mammographically detected impalpable lesions where malignancy cannot be excluded. Stereotactic fine needle aspiration biopsy will be the indicator for surgery.

In this subgroup approximately 50% will have small invasive cancers, 30% of patients can be expected to have benign lesions such as sclerosing adenosis whilst the remainder will have premalignant conditions like atypical hyperplasia through to carcinoma *in situ*.

2. Excisions of mass lesions which have been proven by mammography, fine needle biopsy, cytology and clinical examination to be malignant where breast conservation can be performed. This is generally for patients with smaller tumours but is dependent upon other factors such as breast size.

The attending surgeon would undertake to provide this follow-up through out this period with regular reports to a central registry office. Initially, patients will be recruited to the study consecutively. However, it is anticipated that, as the study progresses, selection criteria may be introduced to enhance the data base of specific subgroups of patients.

**Lymph node biopsy specimens will be obtained at the time of surgery from the following patients undergoing surgery to excise benign and malignant lesions:**

1. **All patients undergoing mastectomy or segmentectomy with axillary sampling or clearance.**
2. **Patients undergoing sentinel node sampling.**

### **THE PARTICIPATING SURGEONS**

#### **THE ROYAL ADELAIDE HOSPITAL**

South Australian clinical material in the first instance will be obtained from the patients treated by one surgeon (PLM) from the Breast Endocrine and Surgical Oncology Unit at the Royal Adelaide Hospital. This unit treats 200 primary or new breast cancers per year and provides a dedicated service to a 900 bed teaching hospital on the campus of the University of Adelaide. All patients are treated according to protocol and management is reviewed by a multidisciplinary team prior to treatment. Patients are regularly entered into Australian, New Zealand and international trials where appropriate. The routine pathology service is provided by pathologists from the Institute of Medical and Veterinary Science who also provide a dedicated service and attend the multidisciplinary meetings.

The unit is undertaking research in the following fields:

1. Endocrine responses to oestrogen and progesterone in breast cancer with particular reference to insulin-like growth factor binding proteins.
2. The immunological response associated with human breast cancer with reference to tumour infiltrating lymphocytes (TILs) boosted by lymphocyte growth factors.
3. The evaluation of magnetic resonance imaging of the breast in two subgroups of patients:
  - a) young women with dense parenchymal breast tissue
  - b) for the evaluation and accurate assessment of women with T3 breast cancers.

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4. Dynamic doppler studies to evaluate vascular function in breast reconstruction using autologous tissues.
5. Angiogenesis in breast tumours determined by dynamic doppler.
6. A comparative study of carbon track localisation hook wire for mammographically detected impalpable breast lesions.
7. On-going evaluation of the following tumour markers: **a)** vimentin, **b)** cERB2, **c)** ER, **d)** PR, **e)** CA125, 153.
8. Open label study of high dose chemotherapy in patients with breast cancer using autologous peripheral blood, stem cells and G-CSF support.

All patients treated by the unit are reviewed at regular intervals according to protocols and information provided to the Cancer Registry.

The unit works in close association with the South Australian Breast X-ray Service which screens 30,000 women per year between the ages of 40 - 69 years. From 1994 the number of women screened will increase to 45,000 per annum. This service provides a constant supply of small tumours as 70% of lesions detected by the clinic are less than 2 cm in size. This service is closely audited and offers the service to the point of diagnosis with particular emphasis upon stereotactic fine needle aspiration biopsy and ultrasound guided needle biopsy. The program is independently audited.

This service can provide biological material ranging through benign, premalignant, ductal carcinoma *in situ* and carcinoma.

#### **WESTMEAD HOSPITAL**

The Breast Surgery Unit at Westmead Hospital is multidisciplinary involving all aspects of breast cancer patient care, with a major commitment to the management of patients with breast cancer irrespective of the stage of the disease at presentation. Approximately 150 patients with breast cancer are treated each year within the unit, with approximately 10% having advanced breast cancer and with an increasing number having *in situ* disease as the number of patients accessed through the Screening Unit increases.

The Unit is undertaking research in the following fields:

1. Since 1979 patients with operable breast cancer have had the option of a breast conservation approach involving 'lumpectomy', or 'quadrantectomy' with clear surgical margins, axillary clearance, and radiotherapy to the breast. A particular form of axillary clearance has been developed with improvements in the way the procedure can be taught to trainees and a video tape is in production and will be shown next year at surgical meetings of the Royal Australasian College of Surgeons.
2. Approximately 50 - 55% of the patients with operable breast cancer currently achieve breast conservation. An initial cohort of approximately 130 patients undergoing a breast preservation procedure have been followed and the results have been reported at 5 and 10 years. Patients needing mastectomy have been treated with total mastectomy and axillary clearance again using the axillary clearance technique developed by the unit.
3. A study has recently been completed to determine the value of the cERB2 antigen in predicting recurrence in node negative breast cancer patients followed for more than 5 years.
4. Apart from its own trials, the unit takes part in a number of international studies including the Zoladex trial for node positive breast cancer.
5. Ongoing evaluation of the following markers is being undertaken: **a)** ER, **b)** PR, **c)** ploidy, **d)** epidermal growth factor receptors.

The surgical team works closely with Radiation and Medical Oncologists, with the Breast

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Screening Unit and with the Cytology and Pathology Departments. Combined clinics are held and a major Breast Cancer Data Base has been established within the Radiation Oncology Department. Reports have been published on the efficacy of cytology prior to breast surgery, on the problems encountered with the procedures involved in breast conservation, and also the results from our 'Advanced Protocol Treatment' of advanced breast cancer at presentation. The senior surgeon is also the senior surgeon of the Screening Unit which now has considerable expertise in all aspects of Screening, and is recognised as a training unit for medical and paramedical professionals involved with Breast Screening. Surgical and radiotherapy trainees take part in the clinical program and for the past 12 months a 'Breast Fellow' has been appointed and this is a recognised post for the Royal Australasian College of Surgeons for postgraduate training breast surgery for young surgeons who have achieved Fellowship of the Royal Australasian College of Surgeons.

This service can provide biological material ranging through benign, premalignant, ductal carcinoma *in situ* and carcinoma.

### **CONCORD HOSPITAL**

The Breast Endocrine Unit at Concord Hospital was established in 1986. It is composed of four dedicated surgeons working from a forty bed unit. It is closely associated with the University of Sydney and is involved in student teaching, registrar training and research.

Approximately 100 cases are seen per annum. The data collection is made on a standard protocol and processed using computer programs.

The unit is associated with the breast screening clinics of Central and Western Sydney. The principals attend these clinics and patients are then referred for treatment at Concord Hospital.

Multi-disciplinary meetings involving pathologists, radiologists and surgeons are held on a regular basis and a routine monthly review of all cases is undertaken. Standard protocols for breast treatment have been instituted and are followed by the treating surgeons.

Papers have been published on the accuracy of fine needle aspiration cytology in breast cancer patients, the incidence of mammography negative breast cancers seen through the clinic and the incidence of multi focal breast cancer.

This service can provide fewer specimens than the larger two centres but a strong collaboration between the MR Unit and surgeons at Concord Hospital is well established.

### ***MAGNETIC RESONANCE SPECTROSCOPY***

***Sample Handling*** Tissues (tissue or FNA) obtained at surgery will be placed into a sterile tube containing pre-cooled (4 C) phosphate buffered saline in D<sub>2</sub>O (PBS/D<sub>2</sub>O) immediately after excision. Alternatively, biopsies will be snap frozen in liquid nitrogen, transported to the laboratory and stored at -70 C until ready for examination. Samples to be examined by MRS will be gently thawed, washed in PBS/D<sub>2</sub>O (5 x 1 ml) and placed in a 5 mm MR tube containing sufficient PBS/D<sub>2</sub>O to cover the biopsy. Placement within the transmitter/receiver coil will be ensured by either resting the biopsy on top of a plug of glass wool (5), or by suspending the biopsy inside an inner capillary tube of 2.5 mm diameter (10,34). In the case of the capillary method, the external volume will be filled with 350 µl of 1 mM p-aminobenzoic acid (PABA) in PBS/D<sub>2</sub>O which serves as a chemical shift and concentration reference (34). **A third method is being included for the study of FNA from axillary lymph nodes. Samples suspended in PBS/D<sub>2</sub>O (final volume 450 µl) will be placed in specialised susceptibility matched 5 mm MR tubes containing a raised platform (Shigemi Co. NMR division).** As in the case of colorectal biopsies (21), prior to the MRS experiment the specimens will have excess adipose tissue and vasculature excised. Alternative methods such as passing the tissue through a metal sieve to trap the fat (see Page 17) will be explored.

**F.B.:** will be performed using 5 aspirated passes through the specimen with a 21 gauge needle (39). Previous studies (55) have shown that this combination gives the greatest number of cells, both single and in clumps, although it is not the preferred technique if clear cellular detail is required for accurate cytological examination. F.B. are washed with 2 x 1 ml PBS/D<sub>2</sub>O. Between washes the samples are centrifuged (1000g for 5 min) and the supernatant discarded. The F.B. are suspended in PBS/D<sub>2</sub>O (final volume 125  $\mu$ l) and then placed on top of a glass wool plug in a 5 mm MRS tube.

**Data Collection** Data will be collected on a Bruker AM360 wide-bore MR spectrometer equipped with an Aspect 3000 computer and a dedicated 5 mm or 8 mm <sup>1</sup>H probe. Temperature is maintained at 37 C using a Bruker VT1000 temperature regulation unit.

**Pulse Sequences** All pulse sequences to be used are functional in this laboratory at the time of application. Typical experiments are as follows:-

**1D <sup>1</sup>H spectroscopy:** 1D spectra (at 360 MHz) are obtained using a spectral width of 3600 Hz (10 ppm) and 8K data points. A relaxation delay of 2 sec is used during which gated decoupling (15 dB below 0.2 W) is applied for the final 1 sec to reduce the residual water signal (56). 128 transients are averaged.

**CPMG:** One-dimensional T<sub>2</sub>- filtered experiments are performed using the Carr-Purcell-Meiboom-Gill pulse sequence (90<sub>x</sub>-( -180<sub>y</sub>- )<sub>n</sub>-acquire) with an interpulse delay of  $\tau = 1$  msec and a 2 sec relaxation delay between acquisitions (48). Gated presaturation is used in the final 1 sec before data acquisition. 128 transients are collected using a spectral width of 10 ppm. T<sub>2</sub>- filtered 1D experiments on biopsy specimens is performed using selected values of n. Typical values of n<sub>2</sub> = 16, 480, 720, 960 ms.

**2D <sup>1</sup>H-<sup>1</sup>H COSY spectroscopy:** Magnitude-mode COSY spectra are performed using a standard two pulse sequence with the two pulses separated by an incremented delay (57). The sweep width in the t<sub>2</sub> domain is 3000 Hz, and the size in the t<sub>2</sub> domain is 2K data points. The initial delay between the 2 pulses is 1 msec with an increment time of 334  $\mu$ sec. There is a relaxation delay of 1 sec before each accumulation during which the water resonance is presaturated using a CW irradiation power of 30 dB below 0.2 W. The number of time domain points collected in t<sub>1</sub> (free induction decays, FIDs) is subject to the viability limits of the sample. Tissue experiments consist of 180-220 FIDs, each of 32-48 transients (plus 2 dummy scans) over a total experiment time of three to five hours.

**T<sub>2</sub>-filtered Correlation Spectroscopy:** T<sub>2</sub>-filtered correlation spectra are obtained by replacing the first pulse of a standard COSY pulse sequence with a CPMG sequence (48). Typical parameters are described above with n<sub>2</sub> equal to 500 - 750 msec. The sequence removes crosspeaks arising from short T<sub>2</sub> species, like lipid, leaving only resonances from more mobile metabolites. The pulse sequence is useful in resonance assignment in specimens, like breast, which contain large quantities of lipid that can be reduced or removed using this technique.

**Processing of MRS Data** Data will be processed on a Bruker X32 (UNIX) Data Station or a Silicon Graphics Indigo 2 work station equipped with Bruker XWINNMR data processing software. The complexities of processing FIDs from biological material containing a wide range of T<sub>2</sub> relaxation values (0.3 - 1.5 s) has been addressed in this laboratory (17). The processing parameters vary according to the MR visible chemicals of each tissue type.

**1D spectroscopy:** One dimensional spectra (1D and CPMG) are routinely processed using a line broadening of 3 Hz applied before Fourier transformation. Data are phase corrected using zero and first order phase correction and baselines are corrected using a fourth order polynomial baseline correction routine. Linewidths or ratios of peak heights are measured in 1D spectra.

**2D spectroscopy:** COSY data matrices undergo zero filling to 1K in t<sub>1</sub>, Fourier transformation and magnitude calculation ( (Real<sup>2</sup> + Imaginary<sup>2</sup>) ) to give 1024 x 1024 real data points for each COSY spectrum. Sine-bell window functions are uniformly applied in the t<sub>1</sub> domain and Lorentzian-Gaussian

window functions of varying width and maximum positions are applied in the  $t_2$  domain prior to Fourier transformation as previously described (17). Crosspeak volumes and subsequent ratios to external or internal reference peaks will be measured as previously described (2,7,8,58).

Referencing peak height integrals, or peak heights, to those of an external standard with a constant concentration and  $T_2$  relaxation value allows a semi quantitative concentration measurement. However, differences in crosspeak volumes can arise from either concentration changes or from changes in  $T_2$  relaxation of the species. These two effects cannot be separated, but an increase in crosspeak volume will reflect either a chemical change or a reorganisation of the compound within the cell, and may still have diagnostic relevance.

### ***MATHEMATICAL ANALYSIS OF MR DATA FROM THE UNIX***

Unprocessed MRS data will be transferred electronically via internet to the Silicon Graphics server at the Institute for Biodiagnostics, Winnipeg, Canada for a thorough mathematical analysis. The MR spectra will be prepared for analysis by means of the proprietary software ALLFIT (National Research Council of Canada), which provides appropriate baselines and integrals for each distinguishable peak. The spectra will then be preprocessed by formation of a correlation matrix to avoid problems due to widely disparate variate ranges. Principal component analysis will then be applied to the spectral regions of interest, in order to reduce the number of variable in the computation. One half the available data will be used as a training set, and the remaining half will be classified blindly. To make all analyses robust, the training set data will be analysed by the leave-one-out method *i.e.* train on  $k-1$  of the  $k$  samples, classify the sample that was excluded from the training set, and repeat this  $k$  times, once for each sample.

Classification will be performed by a variety of methods, alone and in combination. The principal methods are linear and quadratic discriminant analysis (45), neural nets of various types (44), and genetic programming (46). Consensus analysis will be performed within each method using different regions of the spectrum and with combinations of methods, to increase accuracy of classification. Fuzzy logic methods will be applied where appropriate.

### ***HISTOPATHOLOGY***

Every MR sample will be assessed by one of two pathologists.

***Expertise of the Pathologists*** The two pathologists participating in this study are Senior Hospital Consultants, each with over 25 years experience. Professor P. Russell is an acknowledged authority (59) and Dr J. Phillips is well recognised internationally in the field of aspiration cytology. Each pathologist has indicated that he/she is willing and able to make the necessary contribution in time to ensure the success of this project.

#### ***Rationale for the Extent of Histological Assessment***

1. Primary correlation is obtained by comparing the MRS result with standard hospital histopathological diagnosis. This involves no additional time spent by the pathologist. Long-term storage of fixed tissue for later re-examination will be required.
2. The MRS sample is always examined **initially** by six "step-sections"  $7\mu\text{m}$  sections (taken at  $350\mu\text{m}$  intervals) at  $\times 40$  magnification. The intervening sections are mounted, stained and stored for future assessment if required. Tissue preservation, cellular content and presence of potentially confounding factors such as fat and inflammatory cells are reported in addition to the diagnosis. This involves an additional 5-6 minutes of pathologist time per specimen and is undertaken without reference to clinical or MRS data (in both MRS specimens and remainder of surgical specimen).
3. Where disagreement exists between MRS diagnosis and histological diagnosis, the MRS sample

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will be step-serially sectioned every 7  $\mu\text{m}$  (refer to 2) and examined by the pathologist in a blind study. To avoid bias other specimens will be included at the same time.

***Tissue Preparation***

**Routine:** Tissue is fixed in 10% buffered formalin or FAA (formalin:acetic acid:alcohol), paraffin embedded and sectioned, stained with haematoxylin and eosin according to standard protocols.

**Serial sectioning:** Routine sectioning of paraffin blocks will be at 7  $\mu\text{m}$ . Step serial sectioning of paraffin blocks will be undertaken on selected specimens.

***Criteria for establishing firm histological diagnosis of cancer and its precursors in the tissues to be included in this study, will follow established guidelines.*** In general terms, the various pathological subtypes of cancer will be classified according to the relevant WHO International Histological Tumour Classification and, where difficult diagnostic problems are encountered (particularly for borderline malignancies), the guidelines in the following reference text will be used viz Page D.L. & Anderson T.J. (1990) Diagnostic Histopathology of the Breast. Churchill Livingstone, United Kingdom.

***Quantification of Cell Types*** This will be performed usually on 'step' or 'full' serial sections and is only intended to provide an approximate guide to relative proportions of study tissues to background stroma and reactive inflammatory infiltrates etc.

***STATISTICAL ANALYSIS***

The epidemiologist (O.D.) in Canberra will examine associations statistically between MRS assessment and pathology and clinical variables using comparisons between means, contingency tables and logistic regression. Associations between MRS spectra and patient survival will be assessed by Kaplan - Meier Survival analysis (60) and proportional hazards regression models (61).

**CONCLUSIONS**

- **This project is proceeding as outlined in the original document and as described above.**
- **Of the three “purposes” listed on page 6 all three are underway.**
- **Hypotheses 1 and 2 (page 6) have been shown to be correct. Data collected so far indicate that hypothesis 4 is also correct.**
- **No unforeseen difficulties have been encountered and the program is proceeding to schedule.**



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APPENDIX I

ACRONYM /SYMBOL DEFINITION

1D	-	one dimensional
2D	-	two dimensional
$^1\text{H}$	-	proton
12p	-	chromosome 12 p (short) arm
18q	-	chromosome 18 q (long) arm
CA125	-	tumour marker
CA153	-	tumour marker
cERB2	-	tumour marker
CH/CH <sub>2</sub>	-	methine to methylene ratio
CH <sub>2</sub> /CH <sub>3</sub>	-	methylene to methyl ratio
CIN	-	cervical intraepithelial neoplasia
CINI	-	cervical intraepithelial neoplasia - stage I
CINII	-	cervical intraepithelial neoplasia - stage II
CINIII	-	cervical intraepithelial neoplasia - stage III
CIS	-	carcinoma <i>in situ</i>
CPMG	-	Carr-Purcell-Meiboom-Gill
COSY	-	COrelated SpectroscopY
CW	-	continuous wave
dB	-	decibel
D <sub>2</sub> O	-	deuterium oxide
ER	-	oestrogen receptor
f <sub>1</sub> and f <sub>2</sub>	-	frequency in the first and second dimensions of a 2D MR experiment
FAA	-	formalin:acetic acid:alcohol
FID	-	free induction decay
FNB	-	fine needle biopsy
Fuc	-	fucose
GB	-	Gaussian broadening
G-CSF	-	granulocyte colony stimulating factor
H <sub>5</sub> -H <sub>6</sub>	-	coupling between protons attached to the C <sub>5</sub> and C <sub>6</sub> of

		carbohydrate moieties
<b>Hz</b>	-	Hertz
<b>K-ras</b>	-	oncogene
<b>LB</b>	-	Lorentzian broadening
<b>Le<sup>y</sup></b>	-	Lewis <sup>y</sup> (antigen)
<b>MHz</b>	-	mega Hertz
<b>MRI</b>	-	magnetic resonance imaging
<b>MRS</b>	-	magnetic resonance spectroscopy
<b>MR</b>	-	magnetic resonance
<b>NRC</b>	-	National Research Council of Canada
<b>p53</b>	-	tumour supressor gene
<b>PABA</b>	-	p-aminobenzoic acid
<b>PBS</b>	-	phosphate buffered saline
<b>PCA</b>	-	principal component analysis
<b>ppm</b>	-	parts per million (units of chemical shift)
<b>PR</b>	-	progesterone receptor
<b>SFNAB</b>	-	stereotactic fine needle aspiration biopsy
<b>t<sub>1</sub> and t<sub>2</sub></b>	-	first and second time domains in a 2D MR experiment
<b>T1</b>	-	tumour size less than 2 cm
<b>T2</b>	-	tumour size 2 - 5 cm
<b>T3</b>	-	tumour size greater than 5 cm
<b>T<sub>2</sub></b>	-	spin-spin (transverse) relaxation
<b>Thr/Fuc</b>	-	threonine/fucose
<b>TIL</b>	-	tumour infiltrating lymphocytes

## FNA stored at -70°C less than 6 months

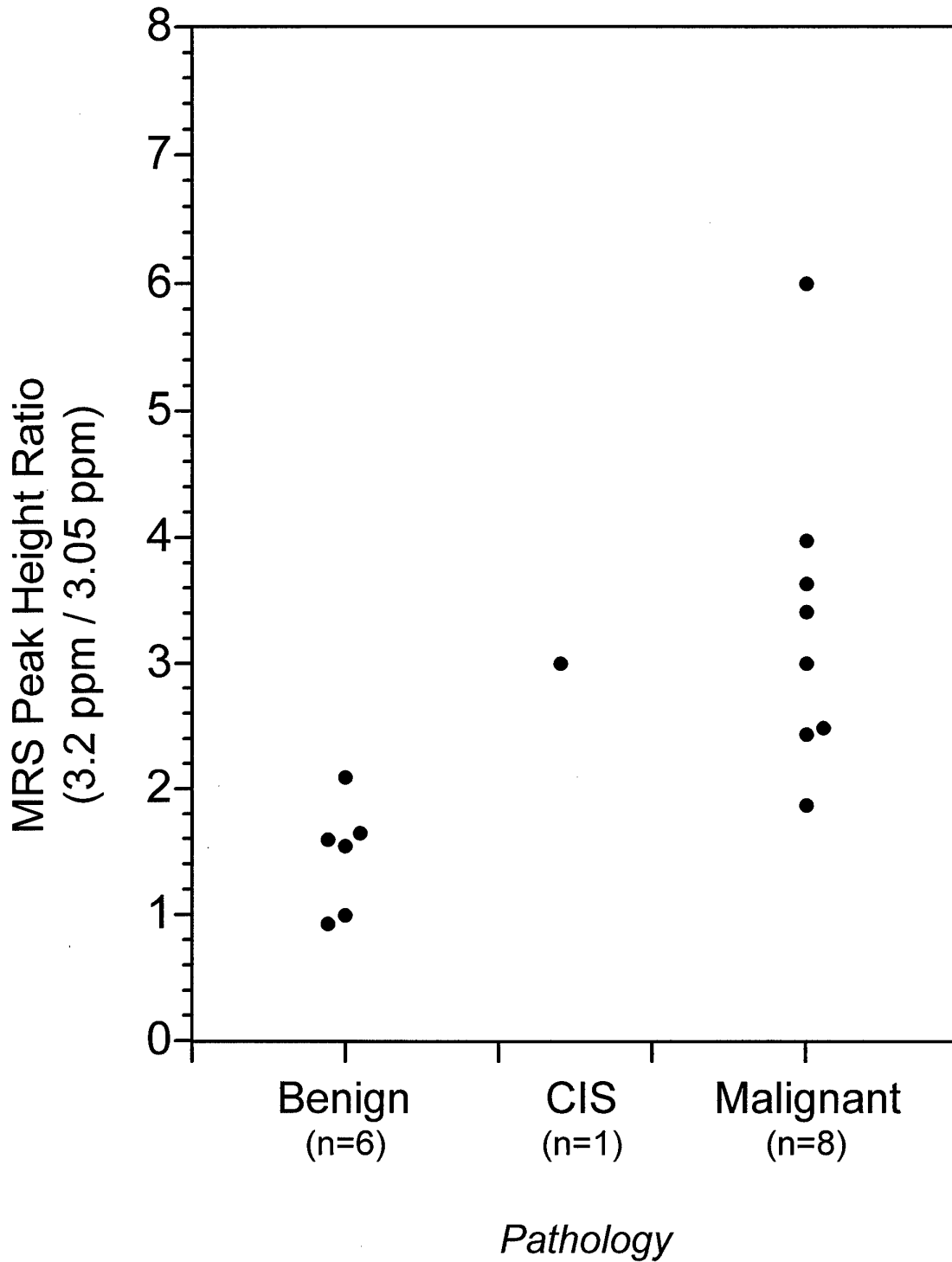


Figure 1A: Breast FNA specimens: MR ratios of benign, carcinoma and carcinoma *in situ* specimens stored less than 6 months at -70°C.

### FNA stored at -70°C for 6-22 months

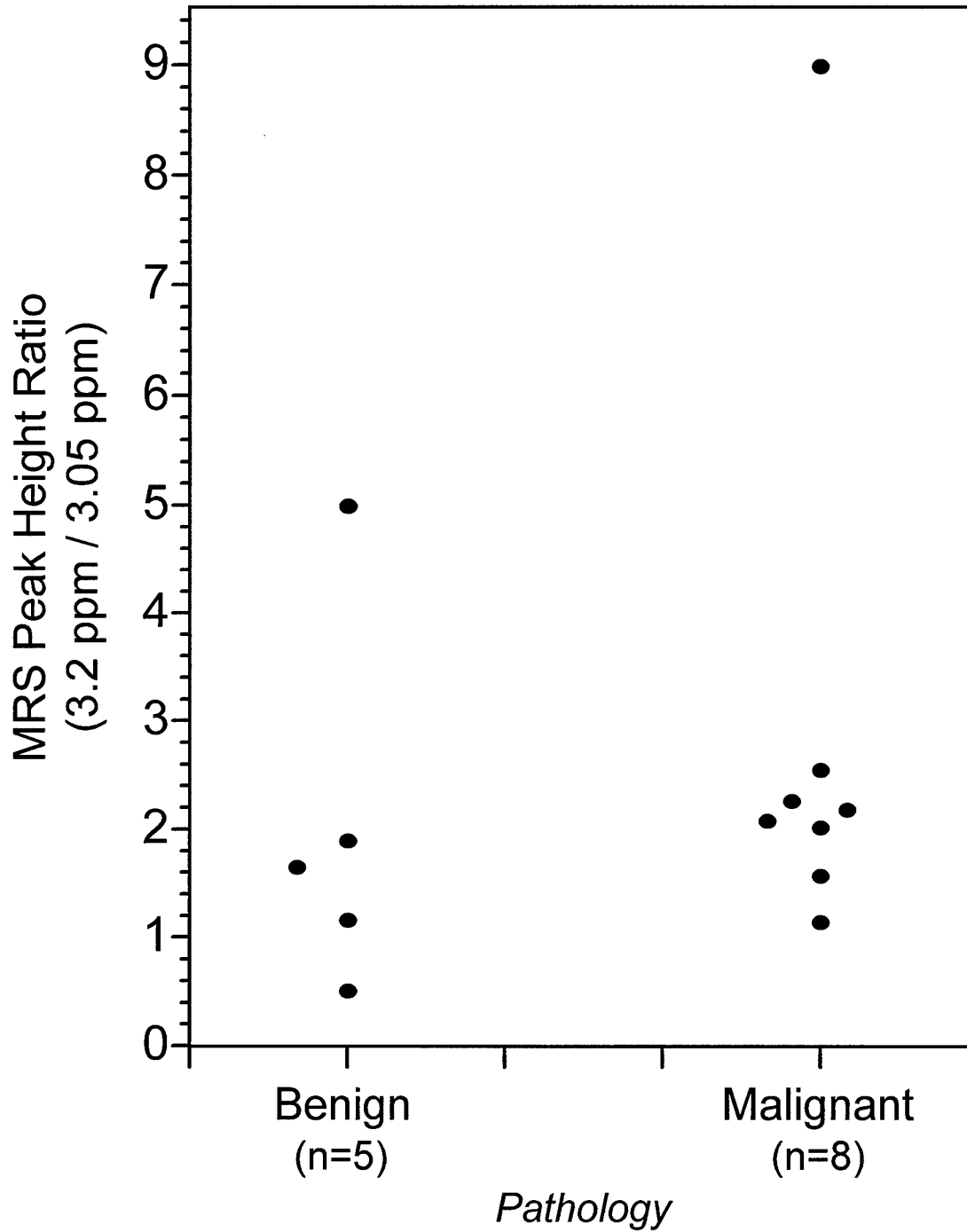
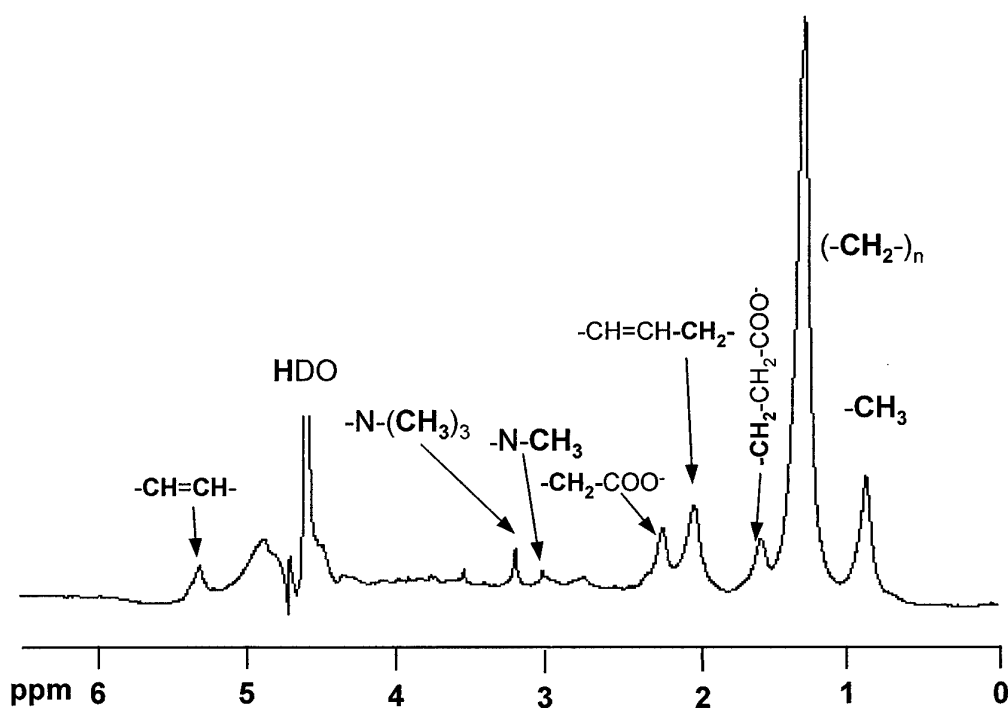


Figure 1B: Breast FNA: MR ratios of benign and carcinoma specimens stored longer than 6 months and less than 22 months at -70°C.

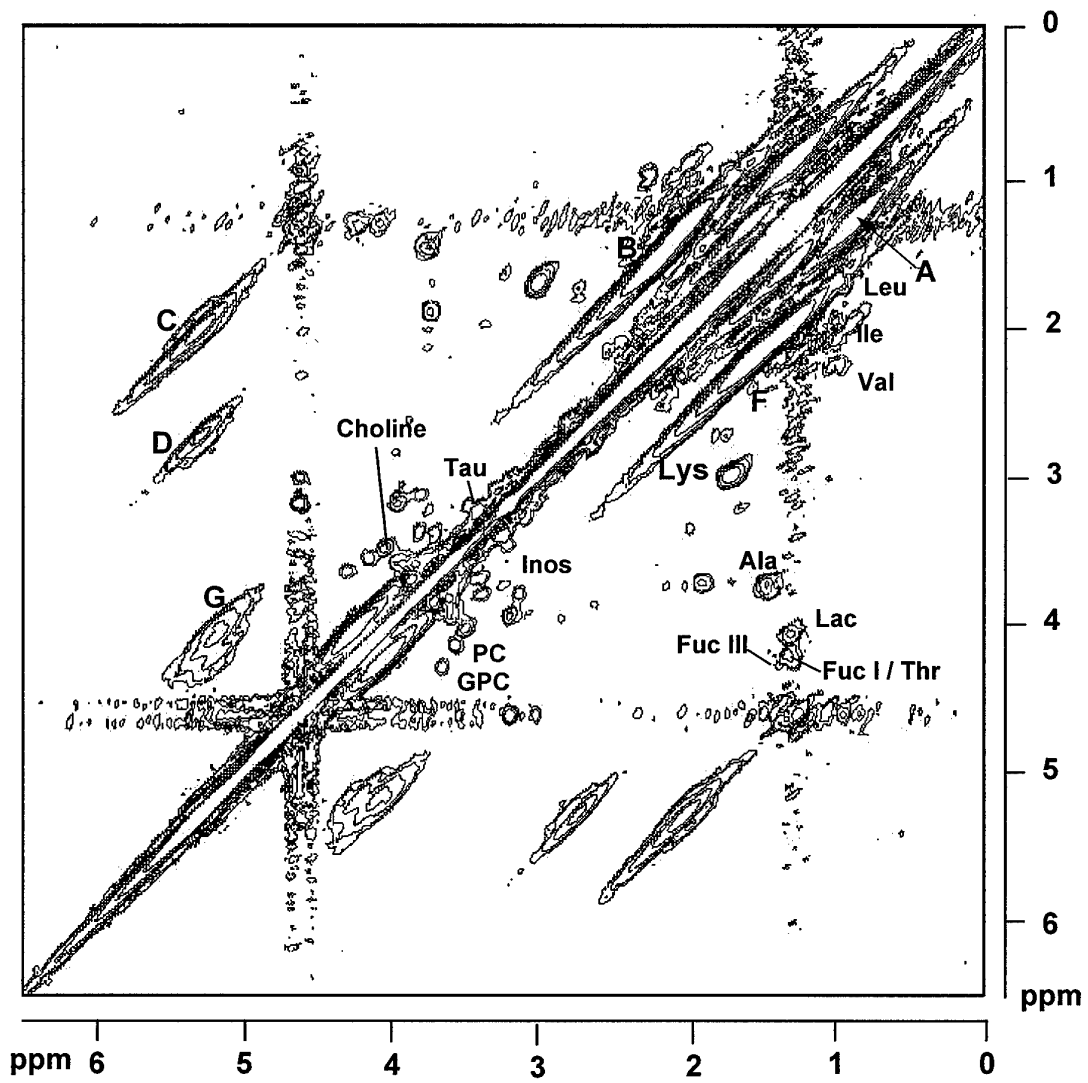


**FNA specimen collected from breast  
lesion *in vivo***

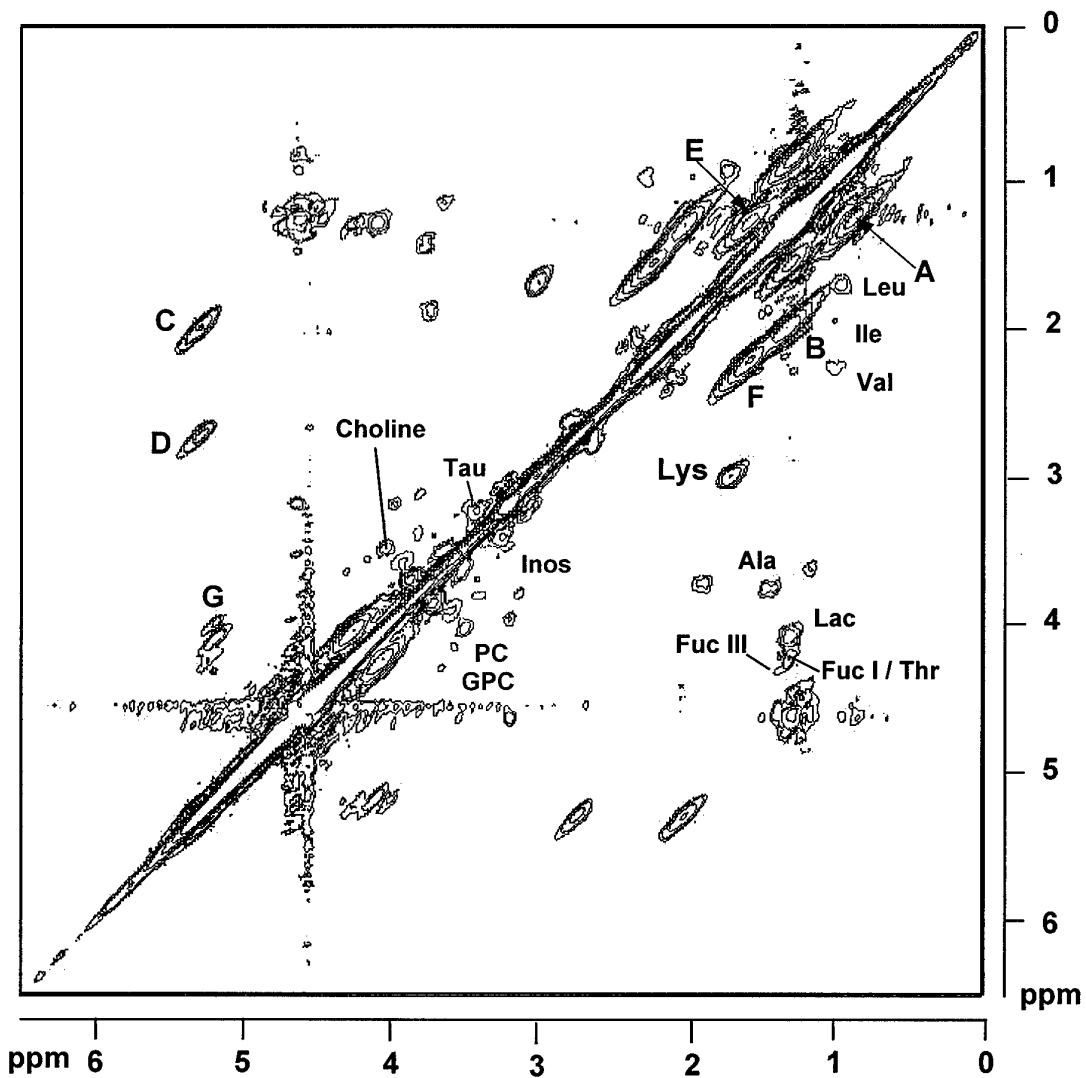


**Figure 2:**  $^1\text{H}$  MR 1D spectrum (360 MHz) of malignant breast FNA collected *in vivo*. Both specimens have malignant histology. Spectra (256 scans, sweep width 3597 Hz) were collected at 37°C with the sample spinning at 20 Hz on a Bruker AM360 MR spectrometer. Residual water was suppressed by selective gated irradiation. A line broadening of 3 Hz was applied before Fourier transformation.

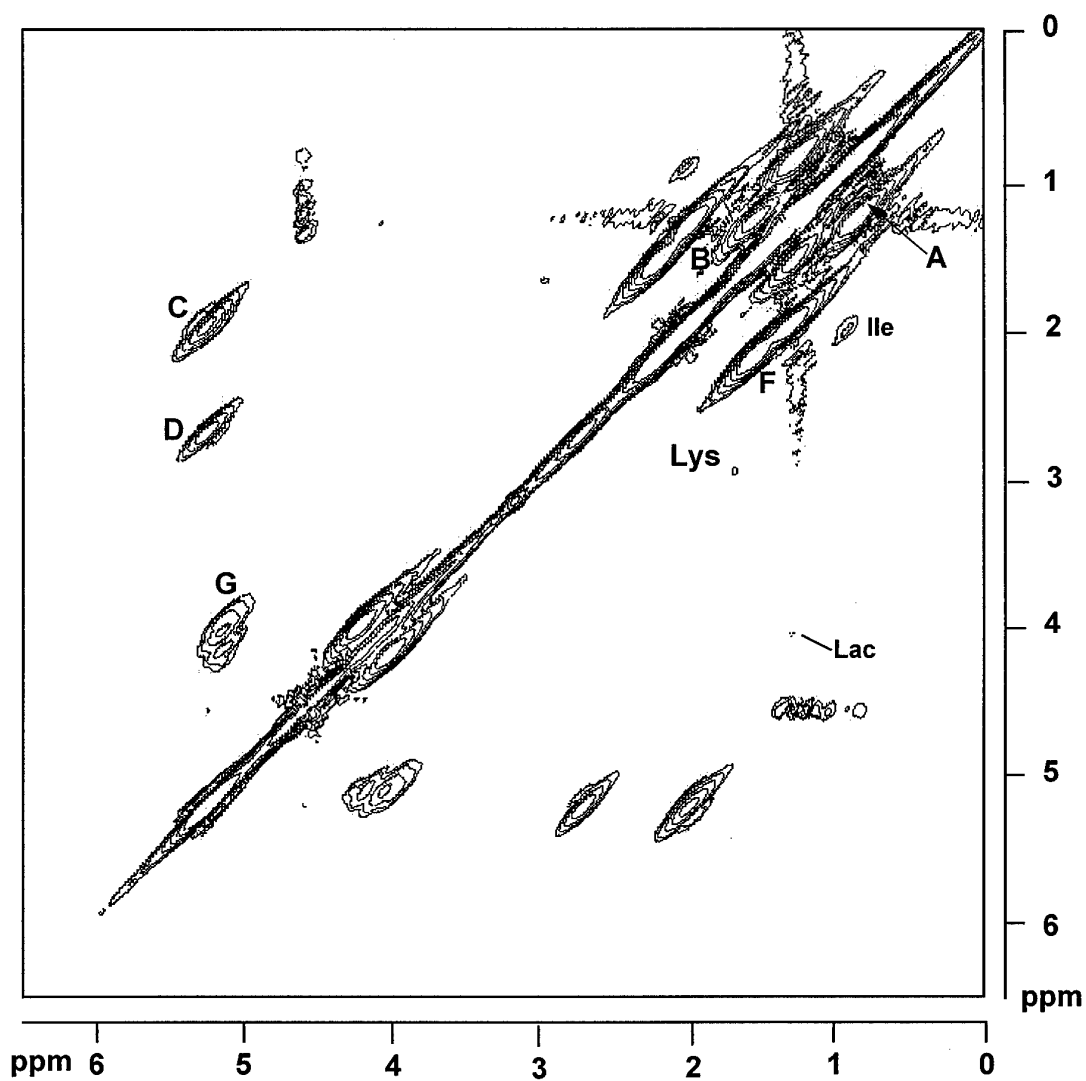
### 3A: Malignant (tissue specimen)



3B: *Carcinoma in situ* (tissue specimen)



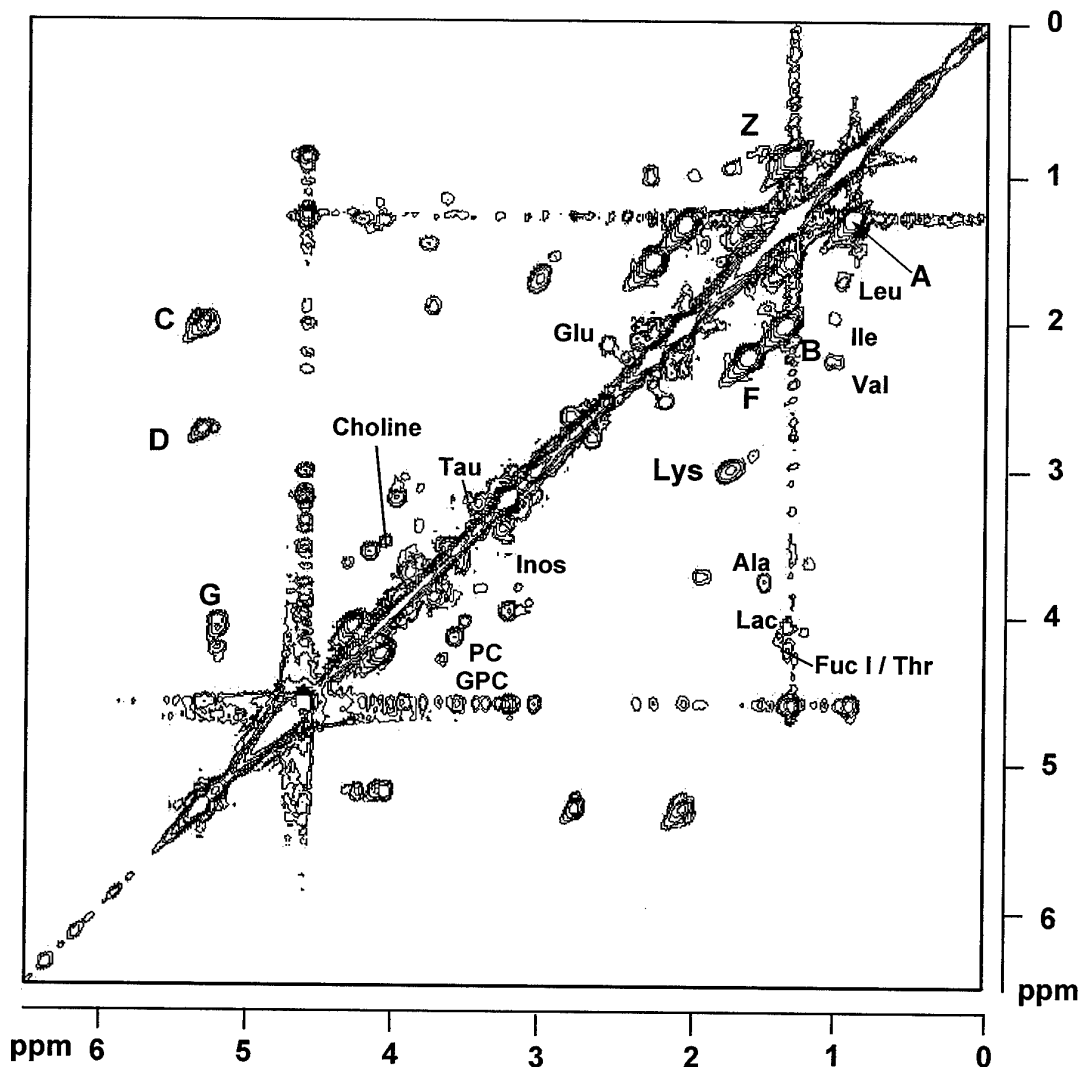
### 3C: Benign (tissue specimen)



**Figure 3:** 360 MHz <sup>1</sup>H MR symmetrized COSY spectra of breast tissue specimens in PBS/D<sub>2</sub>O, (NS=32, NE=200). A) Malignant; B) *Carcinoma in situ*; C) Benign tissue. Data were collected at 37°C with sweep width 3597 Hz. A sinebell window function in t<sub>1</sub> domain, and a Lorentzian-Gaussian window function (LB = -40, GB = 0.15) in the t<sub>2</sub> domain were applied before Fourier transformation.

## Malignant breast FNA.

Specimen collected intraoperatively



**Figure 4:** 360 MHz <sup>1</sup>H MR symmetrized COSY spectra of malignant breast FNA specimen, (NS=32, NE=200). Data were collected at 37°C with sweep width 3597 Hz. A sinebell window function in t<sub>1</sub> domain, and a Lorentzian-Gaussian window function (LB = -40, GB = 0.15) in the t<sub>2</sub> domain were applied before Fourier transformation.

## Methyl-methine coupling region from COSY

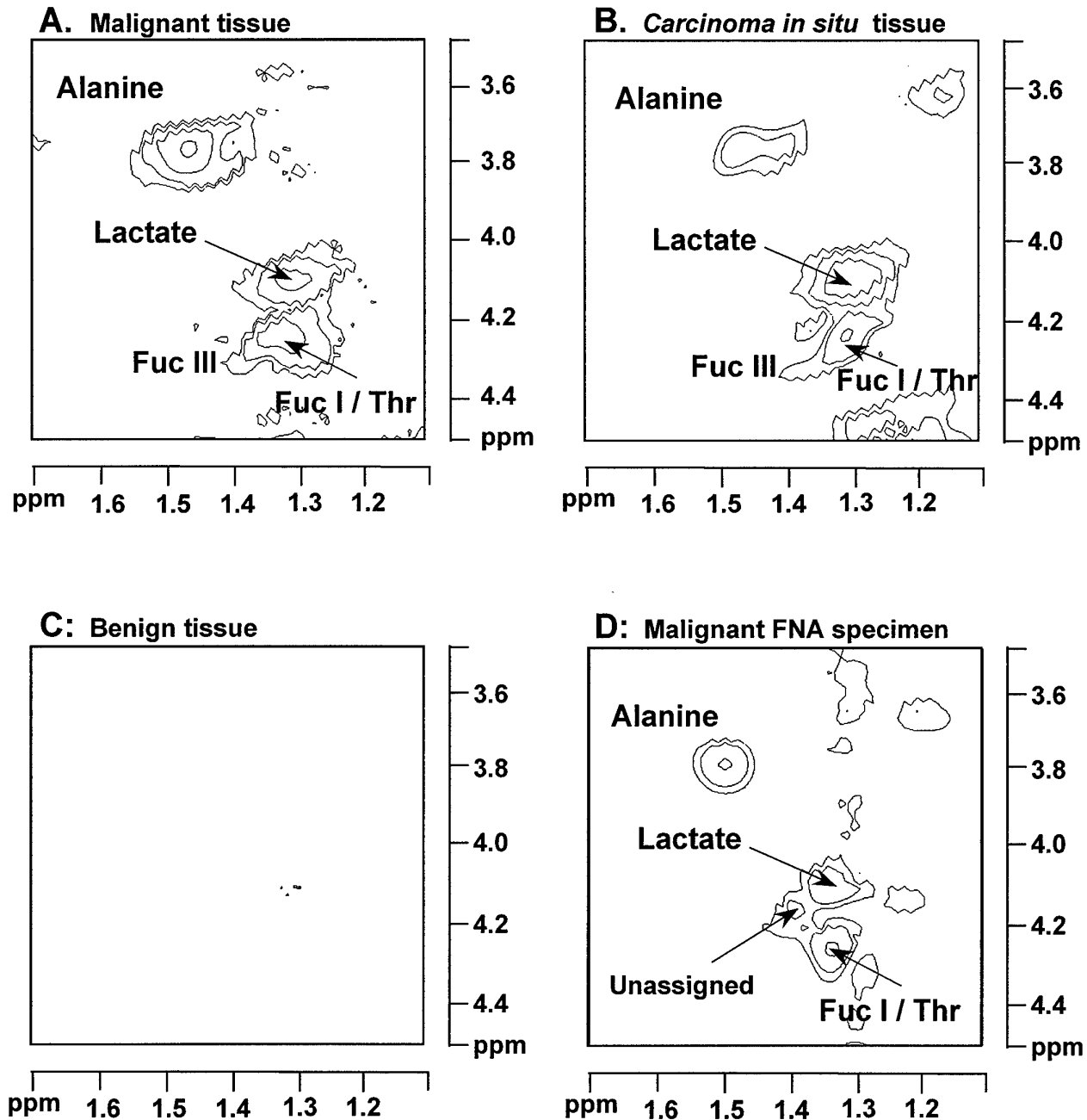
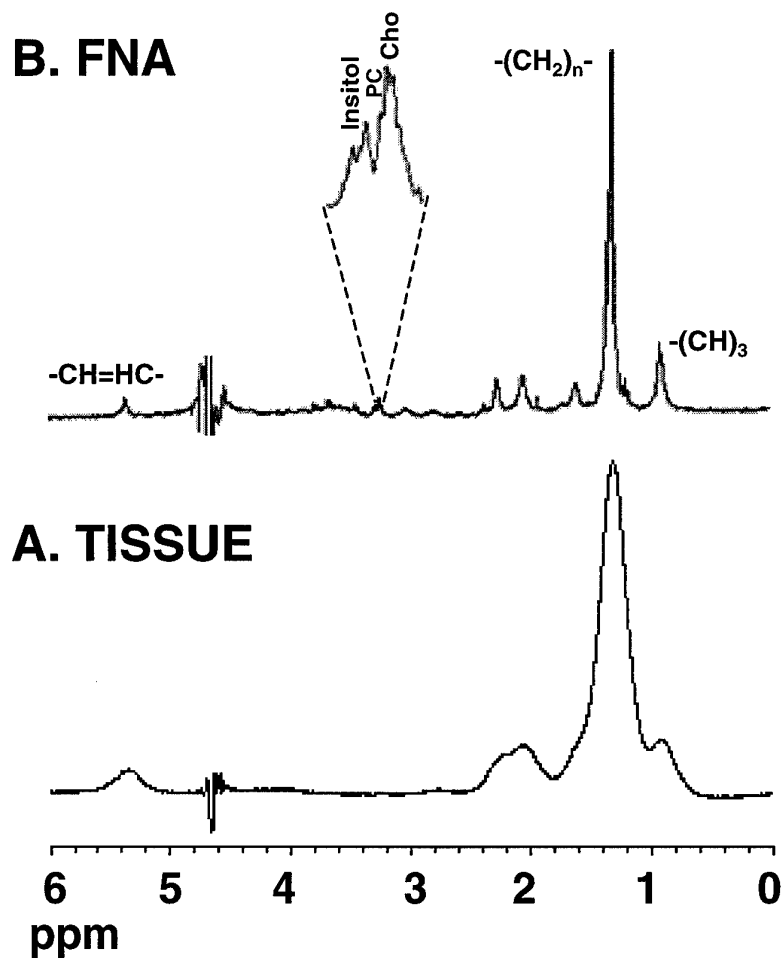


Figure 5: methyl - methine coupling region ( $F_1 = 3.5 - 4.5$  ppm,  $F_2 = 1.1 - 1.7$  ppm) from 360 MHz  $^1\text{H}$  MR symmetrized COSY spectra of breast specimens (NS=32, NE=200). A) malignant tissue; B) *Carcinoma in situ* tissue; C) benign tissue; D) malignant FNA. Data were collected and processed as described in Figure legends 3+4.

## Human Lymph Node Tissue Assessed by MRS



**Figure 6:** <sup>1</sup>H MR spectra (360MHz) of human lymph nodes. A. Tissue B. FNA biopsy. Spectra (128 scans, sweep width 3597 Hz) were collected at 37°C with the sample spinning at 20 Hz on a Bruker AM360 MR spectrometer. Residual water was suppressed by selective gated irradiation. A line broadening of 1Hz was applied before Fourier transformation.

**Table 1. Chemical species identified in 2D <sup>1</sup>H MR spectra of human breast specimens.**

Molecules	Abbreviation	Coupling Partners (bold face)	Cross-peak Coordinates (ppm)
<b>LIPIDS</b>			<b>f 2 , f 1</b>
Cholesterol	Z	CH <sub>3</sub> -CH-ring $\alpha$	0.85, 1.52
Choline	Chol	(CH <sub>3</sub> ) <sub>3</sub> N <sup>+</sup> -CH <sub>2</sub> -CH <sub>2</sub> -OH	3.50, 4.07
Glycero-PC	GPC	(CH <sub>3</sub> ) <sub>3</sub> N <sup>+</sup> -CH <sub>2</sub> -CH <sub>2</sub> -OP(O)-O-CH <sub>2</sub> -	3.69, 4.38
Phosphoethanolamine	PE	(CH <sub>3</sub> ) <sub>3</sub> N <sup>+</sup> -CH <sub>2</sub> -CH <sub>2</sub> -OPO <sub>3</sub> <sup>=</sup>	3.30, 4.14
Phosphocholine	PC	(CH <sub>3</sub> ) <sub>3</sub> N <sup>+</sup> -CH <sub>2</sub> -CH <sub>2</sub> -OPO <sub>3</sub> <sup>=</sup>	3.61, 4.25
Triacylglycerol	A	-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>3</sub>	1.33, 0.90
	B	=CH-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	2.01, 1.33
	C	-CH <sub>2</sub> -CH <sub>2</sub> -CH=CH-	2.02, 5.38
	D	-CH=CH-CH <sub>2</sub> -CH=CH-	5.38, 2.84
	E	-O-C(O)-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	1.62, 1.33
	F	-O-C(O)-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	2.30, 1.60
	G (vicinal)	RO-CH <sub>2</sub> -CH (OR)-CH <sub>2</sub> -OR	4.12, 5.26
	G' (geminal)	RO-CHH'-CH-OR	4.09, 4.29
<b>AMINO ACIDS</b>			
Alanine	Ala	-CH-CH <sub>3</sub>	3.79, 1.49
Glutamate	Glu	-CH-CH <sub>2</sub> -CH <sub>2</sub> -COO <sup>-</sup>	2.21, 2.62
Isoleucine	Ile	-CH <sub>2</sub> -CH <sub>3</sub>	2.12, 0.97
Leucine	Leu	-CH-(CH <sub>3</sub> ) <sub>2</sub>	1.78, 0.97
Lysine/polyamines	Lys	-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -N <sup>+</sup> H <sub>3</sub>	1.72, 3.05
Threonine	Thr	-CH-CH (OH)-CH <sub>3</sub>	4.27, 1.33
Valine	Val	-CH-(CH <sub>3</sub> ) <sub>2</sub>	2.34, 1.03
<b>CARBOHYDRATE MOIETIES</b>			
Fucose	Fuc I	-CH-CH <sub>3</sub>	4.27, 1.33
	Fuc II	-CH-CH <sub>3</sub>	4.28, 1.25
	Fuc III	-CH-CH <sub>3</sub>	4.30, 1.41
<b>OTHER METABOLITES</b>			
Inositol	Inos	-CH (OH)-CH (OH)	3.28, 3.64
Lactate	Lac	-CH (OH)-CH <sub>3</sub>	4.12, 1.33
Taurine	Tau	H <sub>3</sub> N <sup>+</sup> -CH <sub>2</sub> -CH <sub>2</sub> -OSO <sub>3</sub> <sup>=</sup>	3.28, 3.50
Unassigned			3.96, 3.11
			3.76, 1.92
			4.22, 1.35
			3.63, 1.15



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## Fine-Needle Biopsy Specimens of Benign Breast Lesions Distinguished from Invasive Cancer *ex Vivo* with Proton MR Spectroscopy<sup>1</sup>

**PURPOSE:** To determine whether invasive breast cancer can be distinguished from benign lesions with proton magnetic resonance (MR) spectroscopy *ex vivo* on the basis of altered cellular chemistry.

**MATERIALS AND METHODS:** Two hundred eighteen fine-needle biopsy specimens were obtained in 191 patients undergoing surgery and were analyzed with proton MR spectroscopy. MR spectroscopic and histopathologic findings were compared.

**RESULTS:** Invasive carcinoma produced increased signal at 3.25 ppm, attributable to choline-containing metabolites. Discrimination between invasive carcinoma ( $n = 82$ ), benign lesions ( $n = 106$ ), or carcinoma *in situ* ( $n = 17$ ) was based on the resonance intensity at 3.25 ppm standardized to the resonance at 3.05 ppm ( $P < .001$ ). The ratio of peak height intensities of resonances at 3.25 to those at 3.05 ppm was less than 1.7 in 102 of the 106 normal or benign lesions. All carcinoma *in situ* specimens with comedonecrosis or a microinvasive component ( $n = 6$ ) were categorized at MR spectroscopy with invasive carcinoma, while others with *in situ* disease alone were categorized with benign lesions ( $n = 11$ ). The sensitivity and specificity of MR spectroscopy in fine-needle biopsy specimens in distinguishing benign lesions from invasive cancer were 95% and 96%, respectively.

**CONCLUSION:** Proton MR spectroscopy of fine-needle biopsy specimens provides objective diagnostic information that complements findings of conventional preoperative investigations of breast lesions.

**I**N Australia, breast cancer is the leading cause of cancer-related death in women (1). The incidence of breast cancer outranks all other cancers in women older than 35 years. In the past decade, the incidence has risen by 25%, and the lifetime risk (from birth to the age of 74 years) of breast cancer in white women is comparable to Western world figures at one in 13 (1).

Recent improvement in breast cancer patient outcome is due to earlier diagnosis and more effective management (2,3). The combination of physical examination, mammography, and fine-needle aspiration cytologic analysis (triple assessment) is to date the most sensitive method for the preoperative diagnosis of clinically and radiographically detected breast lesions. While triple assessment has a high probability of detection of all malignant lesions, the suboptimal specificity results in diagnostic uncertainty; thus, open biopsy is needed to exclude malignancy in many women.

Physical examination has limitations due to individual variation in breast consistency, the site and size of the lesion (lesions smaller than 1 cm are usually impalpable), and the presence of a diffuse versus discrete tumor. Screening mammography guidelines ensure that biopsy is performed in approximately one benign lesion

for every malignant lesion detected (4). Even so, 10%–40% of palpable breast cancers are missed at mammography alone, especially in women younger than 50 years in whom radiographically opaque breast tissue may obscure changes associated with malignancy (5–8). Fine-needle aspiration cytologic analysis has a sampling error rate in the range of 1%–15% (9), which partly explains the varied sensitivity. While the complete sensitivity of fine-needle aspiration biopsy is 81%–97% (10), this includes the 50%–80% of cases with atypical and suspicious diagnoses in which cancer is typically confirmed histologically with open biopsy (11).

A technology that monitors cellular chemistry, which correlates with different cell behaviors, could offer both independent and objective assessment of breast tissue. The potential then would exist to identify a predisposition toward or early features of breast cancer and offer interventions aimed at reducing tumor development. Proton magnetic resonance (MR) spectroscopy is one diagnostic modality that has been successfully applied to monitor tumor development and progression in other organs (12–18). Preinvasive cancer of the uterine cervix can be distinguished from invasive cancer by means of proton MR spectroscopy, with a sensitivity and speci-

**Index terms:** Breast, biopsy, 00.1261, 00.1262 • Breast neoplasms, diagnosis, 00.30 • Breast neoplasms, MR, 00.12145, 00.30 • Magnetic resonance (MR), spectroscopy, 00.12145

**Abbreviation:** DCIS = ductal carcinoma *in situ*.

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ficity of 98% and 94%, respectively (13). The technique also distinguishes between genuinely benign and malignant follicular lesions in the human thyroid (18) and helps discriminate between degrees of loss of cellular differentiation in ovarian tumors (16).

Preliminary unlocalized one- and two-dimensional proton MR spectroscopic examinations of excised breast tissue showed increased levels of glycerophosphocholine and phosphocholine in invasive breast carcinoma compared with levels in benign fibroadenomas (19). Specimens of benign fibrocystic disease were characterized by an absence of resonances from choline, amino acids, and other metabolites. However, the high adipose content in excised breast tissue resulted in major difficulty in attaining adequate spectral resolution. The intense broad MR resonances from this fat often masked other diagnostic resonances in the one-dimensional spectrum. This problem is largely overcome by applying a T2 filter (Bruker, Karlsruhe, Germany; Carr-Purcell-Meiboom-Gill sequence) during data collection (20), postacquisitional data processing, or both (21). A simpler remedy was to optimize specimen collection. Collection procedures substantially affected the amount of exogenous fat sampled. Fine-needle aspiration biopsy methods developed for thyroid sampling (17) provided cellular material adequate for assessment with MR spectroscopy with fat levels lower than those in excised tissue.

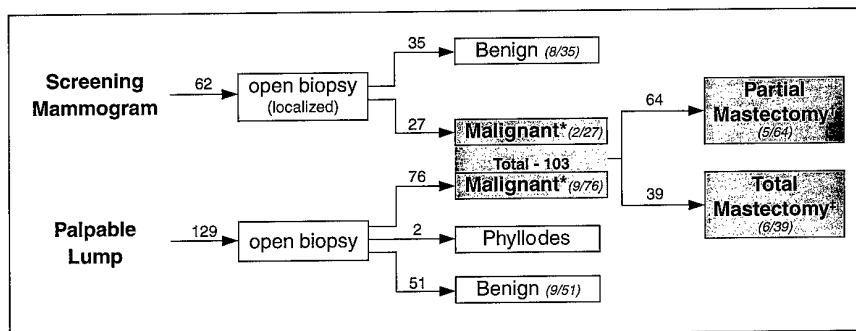
Our objectives for this study were (a) to assess the sensitivity and specificity of proton MR spectroscopy in fine-needle biopsy specimens for delineating invasive breast cancer *ex vivo*, (b) to determine whether carcinoma *in situ* can be distinguished from invasive carcinoma, and (c) to compare diagnosis with MR spectroscopy in fine-needle biopsy specimens with diagnosis with traditional preoperative investigations such as physical examination, mammography, and fine-needle aspiration cytologic analysis.

## MATERIALS AND METHODS

All histopathologic and MR spectroscopic analyses were blind. MR spectroscopic data were correlated with clinicopathologic criteria after all reports were filed.

### Patients

Two hundred eighteen fine-needle biopsy or tissue specimens for MR spectroscopic analysis or correlative histopatho-



**Figure 1.** Flow chart for management and final histopathologic diagnosis. The numbers in parentheses indicate the numbers of patients who had an uncertain cytologic diagnosis during the diagnostic work-up. The numbers alongside the arrows indicate the total numbers of patients. Specimens obtained in 11 patients were rejected. \* = invasive and *in situ* carcinoma, † = lumpectomy and quadrantectomy (nine of these patients underwent complete mastectomy [not shown]), ‡ = 12 for *in situ* carcinoma and 27 for invasive carcinoma.

logic analysis, respectively, were obtained in 191 consecutive patients undergoing diagnostic biopsy or definitive treatment (lumpectomy, quadrantectomy, or mastectomy) for histologically proved invasive breast cancer. Indications for surgery included mammographically detected impalpable lesions, as well as palpable mass lesions, which had suspicious mammographic, fine-needle aspiration cytologic analysis, or clinical examination findings (Fig 1). The age range of patients was 20–81 years (mean age  $\pm$  standard deviation, 52 years  $\pm$  14). When mastectomy for invasive carcinoma was performed, control specimens of macroscopically uninvolved breast tissue (which was later confirmed histologically) were obtained in the same patient ( $n = 27$ ).

### Specimen Collection

Previous findings of MR spectroscopic analysis in fine-needle biopsy thyroid specimens had established that as few as  $10^6$  cells are required to obtain one-dimensional MR spectroscopic data with an adequate signal-to-noise ratio in less than 15 minutes (256 accumulations) (17). To acquire an adequate breast specimen, fine-needle biopsy was performed with multiple (typically six) passes with a 23-gauge needle either through the resected lesion *ex vivo* ( $n = 129$ ) or *in vivo* after lesion identification during open biopsy ( $n = 89$ ). These techniques could be guaranteed to provide cells from the lesion and, in addition, allowed the aspiration site to be identified at excision. Tissue from the aspiration site (3 mm<sup>3</sup>) was collected for correlative histopathologic analysis.

### Specimen Handling

Cells or tissue specimens were placed in polypropylene vials that contained 300  $\mu$ L of phosphate-buffered saline in deuterium oxide. All specimens were immediately immersed in liquid nitrogen and stored at  $-70^\circ\text{C}$  for up to 6 weeks until MR spectroscopic analysis.

### Preparation of Specimens for Proton MR Spectroscopy

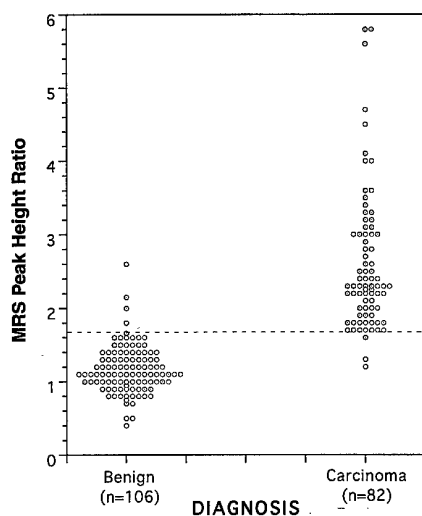
Before proton MR spectroscopy, each fine-needle biopsy specimen was thawed and transferred directly to a 5-mm MR spectroscopic tube. The volume was adjusted to 300  $\mu$ L with phosphate-buffered saline in deuterium oxide when necessary. The sample tube was fitted with a capillary insert that contained 60  $\mu$ L of paraaminobenzoic acid (10 mmol/L in the phosphate-buffered saline–deuterium oxide solution) as an external standard.

### Proton MR Spectroscopy

Proton MR spectroscopic assessment of all specimens was performed without knowledge of the final histologic diagnosis.

**Data acquisition.**—MR spectroscopic experiments were performed at 360 MHz or 8.5 T with a wide-bore spectrometer (model AM-360; Bruker) that was equipped with a computer (model 3000; Aspect, Karlsruhe, Germany) and a standard 5-mm dedicated proton probe head (Bruker). The sample was spun at 20 Hz, and the temperature was maintained at 37°C. Residual water signal was suppressed with selective gated irradiation by using low power (15 dB below 0.2 W). The chemical shifts of resonances were referenced to aqueous sodium 3-(trimethylsilyl)propanesulphonate at 0.00 ppm. One-dimensional spectra were acquired as previously described (19) over a sweep width of 3,597 Hz (10.0 ppm) by using a 90° pulse, 8,192 data points, 256 free induction decays, an acquisition time of 1.14 seconds, and a relaxation delay of 2.00 seconds, which resulted in a pulse repetition time of 3.14 seconds.

**Data processing.**—Data processing for each specimen was performed independently by two operators (P.A.B., S.T.D.) without access to the histopathology reports; one used the spectrometer's computer (model 3000; Aspect), and the other used a Unix workstation (model X32; Bruker). A line broadening of 3.0 Hz was applied to the data before Fourier transfor-



**Figure 2.** Breast fine-needle biopsy MR spectroscopic (MRS) findings of unequivocally benign versus infiltrating carcinoma. MR spectroscopic ratios determined as shown in Figure 3. Data are grouped on the basis of the final histopathologic findings in tissue specimens from the aspiration site.

**Table 1**  
**Summary of Histologic Subtypes of Fine-Needle Biopsy Specimens**

Histopathologic Subtype	No. of Lesions
<b>Benign (n = 106)</b>	
Fibrocystic changes	68
Fibroadenoma	15
Ductal hyperplasia (mild to florid)	9
Fat necrosis	4
Sclerosing adenosis	2
Radial scar	2
Atypical ductal hyperplasia	2
Ductal ectasia	2
Miscellaneous	2
Phyllodes tumor	2
<b>DCIS* (n = 17)*</b>	
High grade	10
Low grade	1
Comedonecrosis	2
With microinvasion	4
<b>Invasive carcinoma (n = 82)</b>	
Ductal carcinoma of no special type	66
Ductal carcinoma of no special type with an extensive intraductal component	7
Lobular carcinoma	5
Tubular carcinoma	4

Note.—Histopathologic findings are the dominant findings in correlative histopathologic samples.

\* DCIS = ductal carcinoma in situ.

mation. Zero- and first-order phase corrections were used in the data. Baselines were corrected by using a fourth-order polynomial baseline-correction routine.

**Data analysis.**—The ratio of the peak height intensities of spectral resonances at 3.25 ppm to those at 3.05 ppm (the MR spectroscopic ratio) was calculated by each operator, and the two results for each speci-

men were averaged. This ratio was used to generate Figure 2. Data were rejected because of an inadequate signal-to-noise ratio (in 11 specimens) if the peak intensity of the  $\text{CH}_2$  resonance at 1.3 ppm in the fine-needle biopsy specimen spectrum was less than 40% of the intensities of those spectra generated by the external standard or if the calculated signal-to-noise ratio was less than 25.

### Histopathologic Analysis

Diagnostic correlation was attained by comparing the diagnosis made with the MR spectroscopic ratio with the postoperative hospital histopathologic report in each patient. The final histologic diagnoses in the study group are shown in Table 1.

Without reference to clinical or MR spectroscopic data, cytologic analysis of the aspirate after MR spectroscopic analysis was attempted. However, cellular detail was compromised by autolytic changes, and this approach was not pursued. Therefore, to verify fine-needle biopsy sampling accuracy, a single pathologist (P.R.) separately performed histopathologic assessment in tissue specimens removed from the aspiration sites of the MR spectroscopic specimens (see Specimen Collection). These tissue specimens were thawed; fixed in a mixture of formalin, acetic acid, and alcohol; embedded in paraffin; sectioned at 7  $\mu\text{m}$ ; stained with hematoxylin and eosin according to standard protocols; and reviewed by the pathologist under the light microscope without access to the clinical or MR spectroscopic data. Tissue preservation, the abundance of epithelial cells relative to stroma, and the presence of potentially confounding factors such as fat and inflammatory cells were reported in addition to the principal diagnosis.

### Other Clinical Correlations

Comparisons were made with findings of other preoperative diagnostic investigations, which included physical examination, mammography, and fine-needle aspiration cytologic analysis (separate specimen than that in MR spectroscopy).

## RESULTS

### Sample Collection

The problem of high levels of MR-measurable fat in the solid breast tissue was successfully overcome with fine-needle aspiration biopsy. The resultant improvement in spectral resolution due to the reduction in exogenous fat was confirmed by means of histopathologic analysis (data not shown).

In 207 of the 218 fine-needle biopsy specimens obtained, sufficient cellular material was collected for adequate MR assessment under the chosen ex-

perimental conditions. Eleven specimens were discarded for technical reasons (see Materials and Methods, Proton MR Spectroscopy, Data analysis).

### Benign Lesions versus Invasive Carcinoma

Invasive carcinoma was identified by means of resonances at 3.25 ppm that were attributable to choline-containing metabolites (Fig 3). A discrimination between invasive carcinoma ( $n = 82$ ) and normal or benign tissue ( $n = 106$ ) was made on the basis of the intensity of the 3.25 ppm resonance standardized to the resonance intensity at 3.05 ppm, indicating contributions from creatine, phosphocreatine, or lysine ( $P < .001$ , Mann-Whitney  $U$  test) (Fig 2). A receiver operating characteristic curve calculated by using this intensity ratio is shown in Figure 4.

Of 106 benign or normal samples, 102 had an MR spectroscopic ratio of less than 1.7. Four false-positive findings were obtained in three palpable fibroadenomas (fine-needle aspiration cytologic analysis had been performed in none of them) and in one moderate ductal hyperplastic lesion. The diagnoses were based on correlative histopathologic findings.

Fine-needle biopsy in four of 82 carcinomas had an MR spectroscopic ratio of less than 1.7. Correlative histopathologic findings in specimens from the aspiration site showed that one specimen had only benign fibrocystic changes in this region. The other three specimens were confirmed as invasive carcinoma, but with a marked inflammatory cell infiltrate.

Two specimens with phyllodes tumors were studied. The first was multifocal and had a ratio of more than 1.7, and the second was from a single mass and had a ratio of 1.6. Phyllodes tumors are classified as fibroepithelial proliferations with variable biologic activity. Their behavior ranges from benignity through a propensity to local recurrence to blood-borne metastasis. Both phyllodes tumors were excluded from all statistical analyses.

### Carcinoma in Situ

The MR spectroscopic ratios for all samples reported as DCIS on routine hospital histopathology reports are shown in Figure 5. These were grouped according to the correlative histopathologic findings. No in situ disease was detected in the correlative histopathologic analysis of the six samples denoted "benign." Ductal cells had breached the basement membrane

(<1 mm) at one or more foci in the entirety of each of the four DCIS specimens denoted "microinvasion." This group, as well as two specimens of high-grade DCIS with extensive comedonecrosis had ratios of more than 1.7. Specimens that contained only DCIS (10 high grade, one low grade) all had ratios of at most 1.7, which is indicative of a low ratio of choline to creatine and lysine, similar to that in benign lesions.

### Clinical Correlations

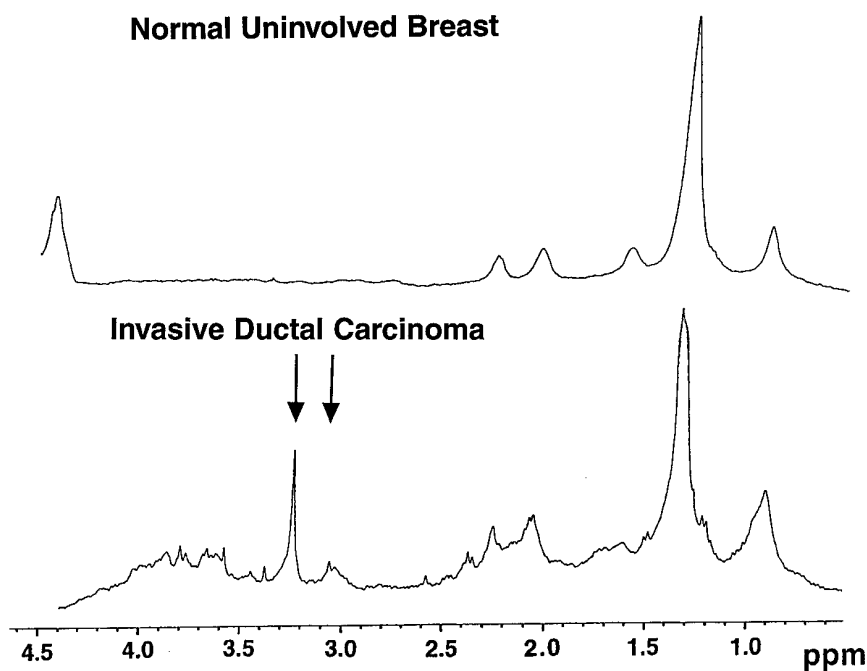
All cases that were mammographically suspicious ( $n = 56$ ), mammographically negative ( $n = 23$ ), or nondiagnostic ( $n = 14$ ) or that had atypical or suspicious fine-needle aspiration biopsy cytologic findings ( $n = 25$ ) were accurately categorized at MR spectroscopy as benign or malignant, as confirmed with histopathologic analysis of tissue excised from the aspiration site.

MR spectroscopic findings in fine-needle biopsy specimens correlated with the final histologic diagnosis of benign lesions in 96% of cases (Table 2); yet, biopsy was performed because of clinical (34%) or mammographic features (45%) or because of fine-needle aspiration biopsy cytologic analysis results (31%). MR spectroscopic findings in fine-needle biopsy specimens correlated with a malignant histologic diagnosis in 95% of cases (Table 2). While biopsy for all the malignant lesions studied was indicated with the triple assessment, no single preoperative modality was an improvement on MR spectroscopy in the identification of malignancy (physical examination, 84%; mammography, 82%; fine-needle aspiration cytologic analysis, 92%).

### DISCUSSION

When compared with the histopathologic analysis, the peak intensity ratio in MR spectroscopy of fine-needle biopsy specimens has a sensitivity and specificity for the differentiation of invasive carcinoma from benign breast lesions of 95% and 96%, respectively. The increase in the ratio observed in carcinoma tissues is most likely due to elevated choline metabolite levels in malignant compared with benign tissues. This is consistent with a higher rate of cellular replication, specifically with increased phospholipid synthesis and membrane turnover (12).

Although triple assessment followed by open biopsy has an overall sensitivity that approaches 100%, it



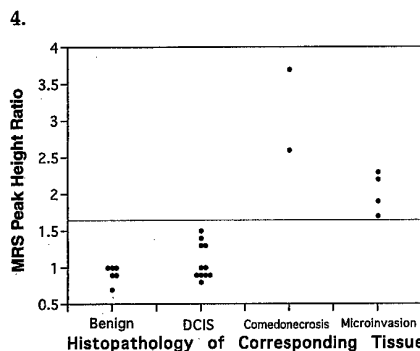
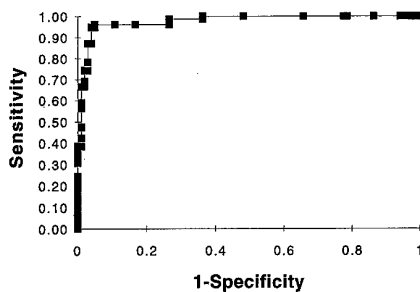
**Figure 3.** One-dimensional proton MR spectra (256 acquisitions) in fine-needle biopsy specimens obtained in a patient who underwent mastectomy. Spectra for a normal uninvolved breast and a breast with invasive ductal carcinoma. The distinction between normal breast and invasive carcinoma is based on an increase in the *N*-trimethyl resonance at 3.25 ppm normalized to that of creatine at 3.05 ppm (peaks indicated by arrows).

entails a large number of open biopsies for benign disease. This is especially the case when equivocal or suspicious mammographic findings are followed by either atypical or suspicious fine-needle aspiration cytologic or benign cytologic findings that are incongruous with clinical or radiologic findings. In our study, all atypical or suspicious fine-needle aspiration cytologic results in subsequently confirmed benign specimens had a benign MR spectroscopic ratio. While the MR spectroscopic findings were obtained in ex vivo aspirate, MR spectroscopy performed before cytologic analysis in in vivo aspirates may well be a valuable adjunct because it improves the specificity. Therefore, MR spectroscopy in fine-needle biopsy specimens could reduce the number of biopsies performed in benign lesions and could lead to a more conservative approach, such as continued observation or surveillance with repeat fine-needle aspiration cytologic analysis and MR spectroscopy. Used as a complementary modality to triple assessment, MR spectroscopy in fine-needle biopsy specimens may also provide further diagnostic confidence when open biopsy is requested for patient reassurance only.

MR spectroscopy in fine-needle biopsy specimens clearly distinguished pure DCIS without comedonecrosis or

microinvasion (MR spectroscopy ratio,  $\leq 1.7$ ) from invasive carcinoma. However, even when DCIS specimens contained comedonecrosis or a few foci of microinvasion, the specimen was categorized in the invasive category with MR spectroscopy in every case. This may demonstrate the selective sampling of necrotic cells or invasive disease in the MR spectroscopic fine-needle biopsy specimens but could also indicate chemical changes that occur in cells that progress from in situ to frankly invasive before morphologic manifestation. Pure DCIS was not distinguished from benign lesions on the basis of the MR spectroscopic ratio; however, more spectral information is available for comparison of the two groups, and this is being investigated. In particular, specific chemical differences characteristic of pure DCIS may be identified with two-dimensional MR spectroscopy. Alternatively, multivariate analysis as previously reported for thyroid neoplasms (22), yet to be undertaken, is likely to improve sensitivity and specificity.

Seventy-eight of the 82 invasive carcinomas had an MR spectroscopic ratio of greater than 1.7. Of the four false-negative specimens, one aspiration sample was found not to contain invasive carcinoma. The remaining three samples all had a marked inflam-



4. Receiver operating characteristic curve of the data from Figure 2 ( $n = 188$ ) calculated from the MR spectroscopic ratios of all specimens. The ratios were ranked, and both the sensitivity and the specificity were calculated for all ratios. (5) MR spectroscopic (MRS) ratios in fine-needle biopsy specimens reported as containing DCIS ( $n = 23$ ) at postoperative histologic analysis. Data are grouped on the basis of the final correlative histopathologic findings.

matory infiltrate, which, if sampled, may have accounted for a ratio of less than 1.7. In all the remaining carcinoma specimens, which includes those that were mammographically negative or had nondiagnostic fine-needle aspiration cytologic analysis results, MR spectroscopy correctly indicated malignancy.

In this study, fine-needle biopsy specimens for MR spectroscopy were collected intraoperatively from the exposed lesion to ensure accurate sampling. If MR spectroscopy in fine-needle biopsy specimens were used as a preoperative diagnostic modality, a sampling error could be introduced, similar to that experienced with fine-needle aspiration cytologic analysis, which would reduce the sensitivity and specificity recorded here. For example, in this patient sample, 14 of 143 cytology reports were nondiagnostic or insufficient. Further studies will directly compare MR spectroscopy with cytology in the same aspirate at the time of clinical assessment.

The potential clinical use of MR spectroscopy in fine-needle biopsy specimens is to complement triple assessment procedures, which would

**Table 2**  
Diagnosis with MR Spectroscopy of Fine-Needle Biopsy Specimens Compared with Histopathologic Diagnosis of Tissue Samples

MR Spectroscopic Finding	Histopathologic Finding (N = 188)	
	Invasive Carcinoma	Normal or Benign
Positive*	78	4
Negative†	4	102

Note.—The sensitivity of MR spectroscopy was 95% (78 true-positive findings of 82 total findings), the specificity was 96% (102 true-negative findings of 106 total findings), the positive predictive value was 95% (78 true-positive findings of 82 total findings), and the negative predictive value was 96% (102 true-negative findings of 106 total findings).

\* MR spectroscopic ratio of at least 1.7.  
† MR spectroscopic ratio of less than 1.7.

reduce the number of unnecessary biopsies in benign lesions. Management of breast lesions varies, however, from country to country. In Australia, fine-needle biopsy is routinely used as part of the triple assessment; thus, introducing MR spectroscopy as a fourth modality would not alter management. In the United States, core biopsy is used more often. Core biopsy has two potential areas of usefulness, namely, to demonstrate an invasive focus within an area of DCIS and to histologically confirm radiologically suspected benign lesions. It is anticipated that MR spectroscopy in fine-needle biopsy specimens will be able to address both these questions as or more accurately than core biopsy, which would obviate the more invasive procedure. A core biopsy specimen may contain high levels of fat, which makes it unsuitable for MR spectroscopic analysis. Thus, in countries such as the United States, the choice of biopsy procedure will need to be reassessed and the re-introduction of fine-needle biopsy will need to be measured against MR spectroscopy, with the improved sensitivity and specificity.

Furthermore, it is likely that the technical obstacles to in vivo spectroscopy of the breast will be overcome. It has been shown in at least one U.S. site that the diagnostic chemical information reported here is available in vivo. Considerable research and development are required, however, before such techniques will be in routine clinical use.

MR spectroscopy in ex vivo fine-needle biopsy specimens may (a) complement triple assessment and reduce

the number of performances of unnecessary biopsy of benign lesions and (b) obviate open biopsy before the definitive therapy of invasive lesions by increasing the diagnostic specificity of the cytologic analysis. Preoperative diagnosis of breast lesions with proton MR spectroscopy thereby offers potential benefits in management by reducing the potential morbidity related to biopsy and by allaying anxiety due to an equivocal diagnosis. ■

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# BREAST CANCER AND MAGNETIC RESONANCE SPECTROSCOPY

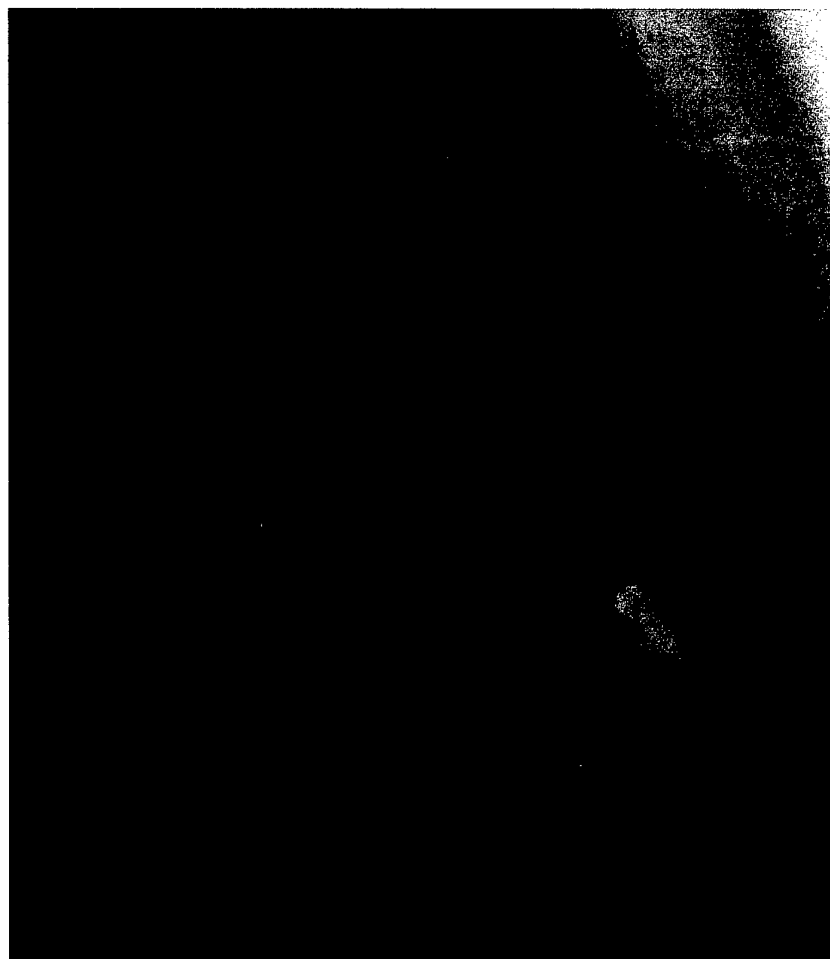
*Proton magnetic resonance spectroscopy (MRS), which reports alterations to cellular chemistry, could monitor the development of breast tumours.*

BY CAROLYN E MOUNTFORD

Earlier diagnosis and more effective management of breast cancer have led to improvement in breast cancer patient outcomes [1,2]. However combining physical examination, mammography and fine needle aspiration cytology (known as triple assessment) — the most sensitive way of diagnosing pre-operative clinical and radiographically detected breast lesions [3,4] — is flawed. Triple assessment has a high probability of detecting all malignant lesions but its sub-optimal specificity results in uncertainty, needing open biopsy (surgical intervention) to exclude malignancy.

Physical examination has limitations due to individual variation in breast consistency, the site and size of the lesion (less than 1cm is usually palpable), and the presence of a diffuse versus discrete tumour. Screening mammography guidelines ensure that about one benign lesion is biopsied for every malignant lesion detected [3]. Even so, 10–40% of palpable breast cancers are missed by mammography alone, especially in women under 50 in whom radiographically dense breast tissue may mask changes associated with malignancy [4,5].

The golden standard for diagnosis, histopathology, relies on alterations to cellular morphology and tissue architecture. Fine needle aspiration (FNA) cytology has a sampling error of about 1–15% [6], partly explaining its variable sensitivity. While the complete sensitivity of FNA is 81–97% [7], this includes atypical and suspicious diagnoses that typically lead to histological confirmation of cancer by open biop-



The cornerstone of breast cancer diagnosis — triple assessment — might not be the only way of monitoring and diagnosing this disease. What part can magnetic resonance spectroscopy play?

sy in 50–80% of cases [8].

We have investigated the possibility that a new method, proton magnetic resonance spectroscopy (MRS) which reports on alterations to cellular chemistry, could monitor the development of breast tumours (Figure 1). MRS detects pools of chemicals that are mobile on the MR time scale. Therefore, the technology reports not on the total chemical content of the cells but on pools of chemicals that are active at a particular stage of development. By reporting such alterations to cellular chemistry that often do not manifest morphologically and therefore cannot be seen under the light microscope, MRS may provide a robust and accurate way of diagnosing breast cancer.

A technology like MRS, which monitors cellular chemistry correlating with different cell behaviour, could offer both independent and objective assessment of breast tissue. The potential then exists to identify a predisposition towards, or early features of, breast cancer and therefore offer interventions aimed at reducing tumour development. MRS is one diagnostic method that has been successfully applied to monitor tumour development and progression in other organs [7, 9–12].

Proton MRS can distinguish pre-invasive from invasive cervical cancer with a sensitivity and specificity of 98% and 94%, respectively [7]. It also distinguishes genuinely benign from malignant follicular lesions in human thyroid [12] and discriminates degrees of loss of cellular differentiation in ovarian tumours [11].

Preliminary investigations of excised breast tissue by 1-D and 2-D proton MRS detected increased levels of glycerophosphocholine and phosphocholine in invasive breast carcinoma compared with benign fibroadenomas [15]. Specimens of benign fibrocystic disease were characterised by an absence of resonances from choline, amino acids and other metabolites. However, we had problems obtaining adequate spectral resolution from excised breast due to the high adipose content of the tissue (Figure 2). The intense broad MR resonances from this fat often masked other diagnostic resonances in the 1-D spectrum. This problem is largely overcome by applying a  $T_2$  filter (Carr-Purcell-Meiboom-Gill sequence) during data collection [13] and/or with post-acquisitional data processing [14].

A simpler remedy was to optimise specimen collection. Collection methods substantially affect the amounts of exogenous

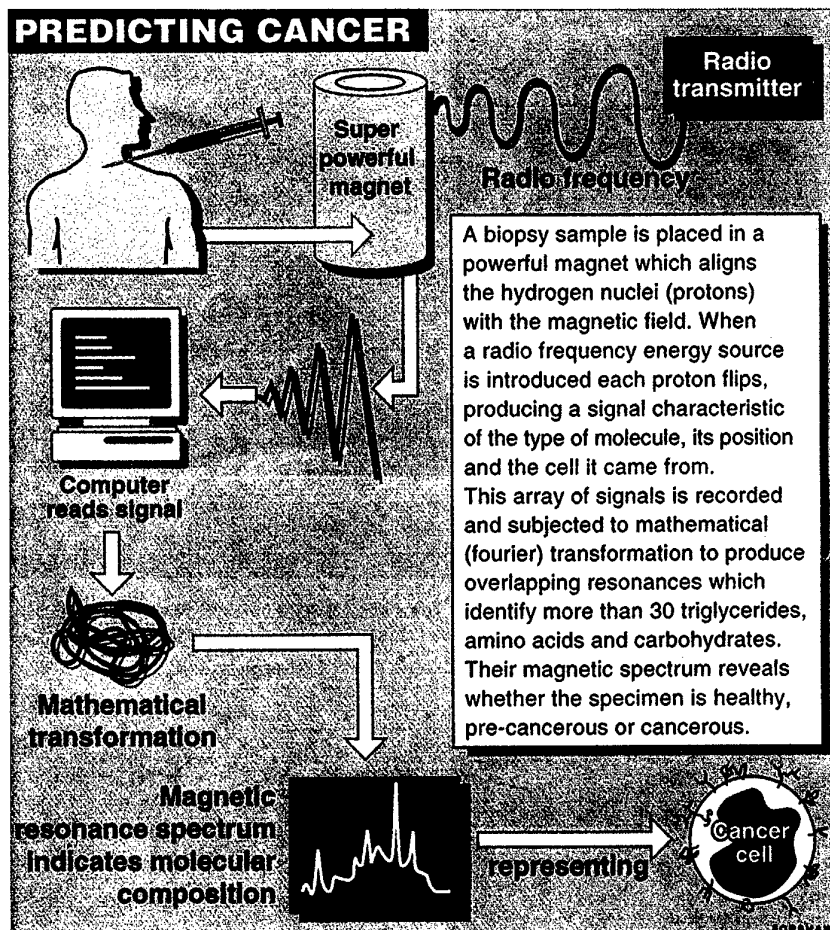


Figure 1. Predicting cancer with magnetic resonance spectroscopy (MRS).

fat sampled. FNA biopsy methods developed for thyroid sampling [12] provided cellular material adequate for assessment by MRS with reduced fat levels compared with excised tissue (Figure 2).

### The study

Over 250 patients took part in the study [15], with a summary of histological diagnoses shown in Table 1. Fine needle aspiration biopsies (FNB) were taken from the breast and examined by MRS and then conventional histology. Comparisons were made to other pre-operative diagnostic investigations including physical examination, mammography and FNB cytology. Invasive cancer was identified by the presence of choline-containing metabolites. MRS discriminated between invasive cancer and normal or benign tissue based on the amount of choline when standardised to the creatine, phosphocreatine and lysine present in the same sample. MRS on FNB,

when compared with the histopathological diagnosis, has a sensitivity and specificity for distinguishing invasive carcinoma from benign breast lesions of 95% and 96% respectively, based on the 1-D peak intensity ratio of 3.25/3.05ppm (Figure 3 and Table 2). This data has now been sent to the National Research Council of Canada for a team of mathematicians to produce an algorithm to allow a robust, non subjective diagnosis independent of human involvement [14]. Preliminary outcomes place the sensitivity and specificity close to 99% [1–6].

All samples reported as ductal carcinoma-in situ (DCIS) by routine hospital histopathology ( $n = 21$ ), were grouped according to the correlative histopathology on the MR specimen. MRS subcategorised DCIS into two categories. In category A (high choline to creatine/lysine ratio) were four DCIS samples where ductal cells had breached the basement mem-



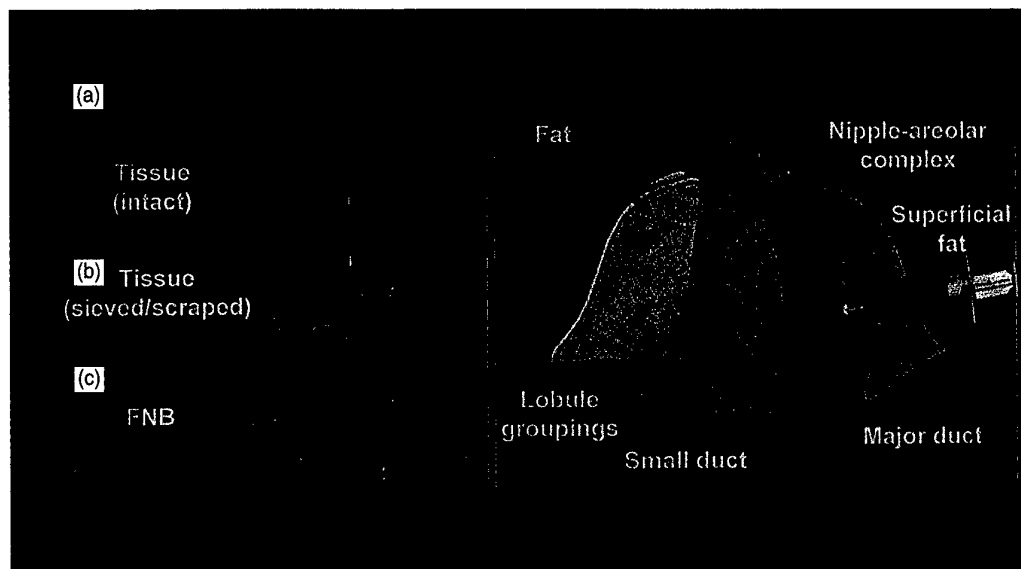


Figure 2. MRS on human breast (ex vivo). 8.5 Tesla MRS spectra obtained from (a) breast tissue from a histologically diagnosed invasive tumour; (b) same tissue as (a) but dissociated mechanically; and (c) FNA biopsy from a patient with invasive breast cancer.

brane (under 1mm) in one or more focus and microinvasion was identified in another four samples. This group of eight as well as two samples of high grade DCIS with extensive comedo necrosis were malignant by MR criteria. Group B containing DCIS (10 high grade, 1 low grade) all had a low choline to creatine/lysine ratio similar to that obtained for benign lesions.

Therefore, MRS on FNB clearly distinguished pure DCIS without comedo necrosis or microinvasion from invasive carcinoma. However, even when DCIS specimens contained comedo necrosis or a few foci of

microinvasion, MRS ranked the specimen in the invasive category in every case. This may indicate chemical changes occurring in cells progressing from in situ to frankly invasive before morphological manifestation. Pure DCIS was not distinguished from benign lesions based on the 1-D 3.25/3.05ppm ratio.

MRS on FNB may therefore complement triple assessment and reduce the need for unnecessary biopsy of benign lesions, while obviating the need for open biopsy before definitive therapy of invasive lesions by increasing diagnostic specificity of cytology. Pre-operative diagnosis of breast lesions by proton MRS therefore offers potential benefits in patient management by reducing potential morbidity related to biopsy and allaying anxiety due to equivocal diagnosis.

However, a most exciting aspect of this program is the subcategorisation of DCIS where some lesions already are committed to malignancy but are not detectable by light microscopy.

### Acknowledgements

The multi-disciplinary nature of this project involved surgeons, pathologists, scientists and technologists from the Institute for Magnetic Resonance Research based at the University of Sydney. These include Bruce Barraclough, Peter Barry, Michael Bilous, Sinead Doran, Susan Dowd, David Gillett, Cynthia Lean, Wanda

<b>Benign</b>	
Fibrocystic changes	68
Fibroadenoma	15
Ductal hyperplasia (mild/florid)	9
Fat necrosis	4
Sclerosing adenosis	2
Radial scar	2
Atypical ductal hyperplasia	2
Duct ectasia	2
Miscellaneous	2
<b>Total</b>	<b>106</b>
Phyllodes tumour 2	
<b>Ductal carcinoma in-situ</b>	
DCIS (high grade)	10
DCIS (low grade)	1
DCIS (comedo necrosis)	2
DCIS + microinvasion	4
<b>Total</b>	<b>17</b>
<b>Invasive carcinoma</b>	
Ductal carcinoma (NST)	66
Ductal carcinoma (NST), EIC positive	7
Lobular carcinoma	5
Tubular carcinoma	4
<b>Total</b>	<b>82</b>

Table 1. Summary of histological subtypes of FNB samples. DCIS = Ductal carcinoma in situ; NST = no special type; EIC = extensive intraductal component. Histopathology according to dominant findings on correlative histopathology samples.

## BREAST FNB

### Benign vs Infiltrating Carcinoma

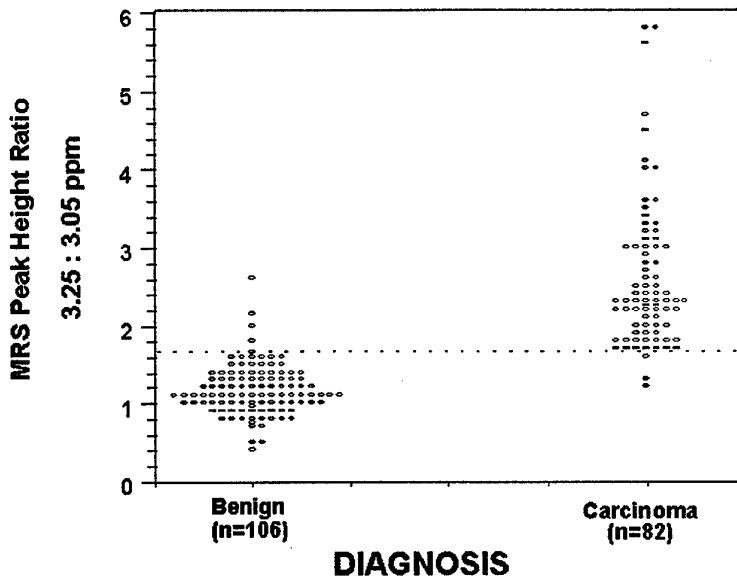


Figure 3. Plot of ratio of intensity of resonances at 3.25 and 3.05ppm measured from MR spectra as shown in Figure 2. Benign and invasive lesions (unequivocal) are compared. Data are grouped on the basis of the final histopathology of tissue specimens taken from the aspiration site.

	Invasive carcinoma	Normal/benign	
<b>MRS (FNB) positive</b>	78	4	PPV 95%
Ratio 1.7	(TP)	(FP)	(78/82)
<b>MRS (FNB) negative</b>	4	102	NPV 96%
Ratio under 1.7	(FN)	(TN)	(102/106)
	<b>Sensitivity 95%</b>	<b>Specificity 96%</b>	<b>Total=188</b>
	(78/82)	(102/106)	

Table 2. Test result probabilities for diagnosis by MRS on FNB compared with histological diagnosis on tissue. TP = true positive; FN = false negative; FP = false positive; TN = true negative; PPV = positive predictive value; NPV = negative predictive value; Sensitivity or true-positive rate = frequency of positive test result (ie. MRS ratio 1.7) in those with malignant disease; Specificity or true-negative rate = frequency of negative test result (MRS ratio under 1.7) in those without malignant disease as judged by histopathology of breast tissue excised from the aspiration site.

Mackinnon and Peter Russell.

Carolyn Mountford is executive director of the Institute of Magnetic Resonance Research at the University of Sydney.

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