Hepatic $^{31}$P MRS in rat models of chronic liver disease: assessing the extent and progression of disease

I R Corbin, R Buist, J Peeling, M Zhang, J Uhanova, G Y Minuk

Background: Hepatic adenosine triphosphate (ATP) levels are an accurate reflection of functioning hepatic mass following surgical resections and acute liver injury. Objective: To determine whether hepatic ATP levels can serve as a non-invasive means of documenting progression of chronic liver disease to cirrhosis. Methods: In vivo phosphorus-31 magnetic resonance spectroscopy ($^{31}$P MRS) was performed in three animal models of chronic liver disease. Sixty-six adult Sprague-Dawley rats were subjected to either thioacetamide, carbon tetrachloride (CCL), or common bile duct ligation (CBDL) to induce liver disease (n=35, 21, and 10, respectively). Serial MRS examinations, blood samples, and liver biopsies (when appropriate) were obtained throughout and/or on completion of the study. Results: Over the course of the chronic liver disease, a progressive decrease in hepatic ATP levels was consistently observed in each model. The findings were most striking when end stage liver disease (cirrhosis) was established. The reduction in hepatic ATP levels correlated with significant changes in serum albumin concentrations (CCI, and CBDL models) and the extent of hepatocyte loss seen histologically (all models). Conclusion: The results of this study indicate that during progression of chronic liver disease to cirrhosis, there is a progressive reduction in hepatic ATP levels. In addition, changes in hepatic ATP levels correlate with changes in liver function and histology. Thus hepatic $^{31}$P MRS provides a non-invasive means of documenting the severity and progression of parenchymal and cholestatic models of chronic liver disease in rats.

MATERIAL AND METHODS

Experimental animals

Adult male Sprague-Dawley rats were maintained on Purina rat chow and water ad libitum until initiation of the study. All

Phosphorus-31 magnetic resonance spectroscopy ($^{31}$P MRS) is a radiological technique that provides direct biochemical information about the tissue under consideration. This technique permits non-invasive simultaneous detection and quantitation of several cytosolic phosphorus containing compounds involved in energy metabolism (adenosine triphosphate (ATP) and inorganic phosphate (Pi)) and membrane phospholipid metabolism (phosphomonoesters (PME) and phosphodiesters (PDE)).

Previous studies in our laboratory have demonstrated that hepatic ATP levels in particular accurately reflect the extent of hepatic disease and dysfunction following graded surgical resections and in animal models of acute liver disease. Reports by other groups have suggested that changes in PME resonance may also be indicative of the extent of disease. The aim of the present study was to determine whether levels of hepatic metabolites (ATP, Pi, PME, and/or PDE), as detected by quantitative $^{31}$P MRS, reflect the severity and progression of chronic liver disease to cirrhosis in rats.

Abbreviations: $^{31}$P-MRS, phosphorus-31 magnetic resonance spectroscopy; ATP, adenosine triphosphate; Pi, inorganic phosphate; PME, phosphomonoesters; PDE, phosphodiesters; TAA, thioacetamide; CCL, carbon tetrachloride; CBDL, common bile duct ligation; MDP, methylene diphosphonic acid; ROI, region of interest; TR, repetition time; TE, echo time; FOV, field of view; AST, aspartate aminotransferase; LCAR, liver cell area ratio; PE, phosphoethanolamine; PC, phosphocholine.
animals were kept in identical housing units on a 12 hour light- dark cycle. The number of rats assigned to each experimental group was based on published data regarding the consistency of the model employed, anticipated death rates, and number of analyses outlined in the experimental protocol. This study was approved by the University of Manitoba animal ethics committee.

Thioacetamide induced liver cirrhosis

Thioacetamide (TAA) cirrhosis was induced in 35 rats (150–250 g) by administering TAA (Sigma Chemicals, St Louis, Missouri, USA; 30 mg/100 ml) in their drinking water (150–250 g) by administering TAA (Sigma Chemicals, St

Carbon tetrachloride series

Stage 1 6 433 [12] 11 [0.5]
Stage 4 10 413 [11] 13 [1.0]
Common bile duct ligation series

Baseline 8 283 [7.0] —
Cholecystectomy 11 days 9 295 [7.0] —
26 days 9 344 [10]† —
46 days 7 376 [24]§ 20.0 [2.1]
Age matched controls 4 461 [12] 14.1 [0.9]

Values are means [SEM].
*p<0.05 versus stages 0 and 1; †p<0.05 versus stage 1; § p<0.05 versus baseline; ‡ p<0.05 versus baseline and age matched controls.

Thioacetamide was diluted in 0.5 ml of corn oil and doses were continuously adjusted on the basis of individual body weight, as described by Dupin and colleagues. All control rats underwent the same procedure, but received only corn oil intragastrically.

MRS examinations were performed on all animals 10–14 days after their last CCl4 or corn oil treatment. Following each MRS examination, animals were sacrificed, and blood and liver samples were collected.

Common bile duct ligation induced cirrhosis

Common bile duct ligation (CBDL) was used to produce secondary biliary cirrhosis in 10 rats (240–270 g). Briefly, under ether anaesthesia, a 4 cm incision was made just below the xiphoid process. The bile duct was isolated, a double ligation of the common bile duct was performed, and the bile duct was severed between the ligatures. The abdomen was subsequently closed and the animal allowed to recover.

Twelve isocaloric fed rats not exposed to TAA served as controls. Serial MRS examinations were also performed on this group. However, rats were only sacrificed at baseline and six months.

Carbon tetrachloride induced liver cirrhosis

This group consisted of 27 rats weighing 100–120 g. All animals had free access to water containing 0.35 g/l phenobarbital (Abbott Laboratories, Canada) starting two weeks prior to and continuing throughout carbon tetrachloride (CCl4) administration. CCl4 (Sigma Chemicals) was diluted in 0.5 ml of corn oil and doses were continuously adjusted on the basis of individual body weight, as described by Dupin and colleagues. Six control rats underwent the same procedure, but received only corn oil intragastrically.

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Spectroscopy. Localised MDP reference vial near the centre of the coil. A non-localised fully relaxed spectrum of the MDP reference was acquired for calibration in mmol/l; C = concentration of phantom solution used for calibration in mmol/l; I/I_p = corresponding signal integrals; N, N_p = corresponding number of signal averages; S, S_p = corresponding saturation factors calculated from measured T_1 times; I_µ = I_µ(p) = corresponding signal integral of reference sample.

Liver function

Sera were isolated from collected blood samples, and serum aspartate aminotransferase (AST) and albumin levels were measured using commercial kits (Sigma).

Histology and quantitative morphological analysis of liver tissue

Fixed tissue specimens were blocked in paraffin, cut, and stained with haematoxylin-eosin and van Gieson (collagen) stains. Slides were staged (0–IV) by a pathologist (blinded to the study groups) for hepatic fibrosis according to the following scale: stage 0, no fibrosis; stage I (mild fibrosis), fibrous expansion around portal tracts or central veins; stage II (moderate fibrosis), septa extending into the liver lobule; stage III (moderate fibrosis), bridging fibrosis (portal-portal, central-central, or portal-central linkage); and stage IV (cirrhosis), parenchymal nodules surrounded by fibrous septa and disturbed hepatic architecture.

Images of van Gieson stained sections were captured with a Spot Cooled Color Digital Camera and Spot Software v2.2 (Diagnostic Instruments, Inc., Sterling Heights, Michigan).

Table 3 Concentrations (mM) of hepatic phosphorylated metabolites in control rats and rats at various stages of thioacetamide induced chronic liver disease

<table>
<thead>
<tr>
<th>Stage</th>
<th>PME</th>
<th>Pi</th>
<th>PDE</th>
<th>ATP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.68 (0.17)</td>
<td>1.55 (0.07)</td>
<td>1.05 (0.09)</td>
<td>3.04 (0.12)</td>
</tr>
<tr>
<td>1</td>
<td>3.63 (0.40)</td>
<td>1.90 (0.28)</td>
<td>1.13 (0.15)</td>
<td>2.82 (0.04)</td>
</tr>
<tr>
<td>2</td>
<td>3.05 (0.17)</td>
<td>0.91 (0.07)*</td>
<td>1.23 (0.11)</td>
<td>2.61 (0.14)</td>
</tr>
<tr>
<td>3</td>
<td>3.03 (0.88)</td>
<td>1.21 (0.08)*</td>
<td>1.28 (0.12)</td>
<td>2.21 (0.17)*</td>
</tr>
<tr>
<td>4</td>
<td>2.55 (0.17)</td>
<td>0.94 (0.06)*</td>
<td>1.11 (0.09)</td>
<td>2.18 (0.15)*</td>
</tr>
</tbody>
</table>

Values are means (SEM). PME, phosphomonoesters; Pi, inorganic phosphate; PDE, phosphodiesters; ATP, adenosine triphosphate.

*p<0.05 versus stages 0 and 1; †p<0.05 versus stage 0.
RESULTS

TAA model

Animals in the TAA series tended to gain weight over the course of the disease, as rats at stages 2, 3, and 4 weighed more than those at stages 0 and 1 (table 1). Liver weights were also greater at stages 3 and 4 than at the preceding stages.

Table 2 provides the results of serum AST and albumin determinations at various stages of disease. Similar to the reports of others, levels of serum AST and albumin did not differ with stage of disease. However, LCAR decreased with progressive disease reaching significantly lower levels at stages 2, 3, and 4.

Representative sections of liver tissue and corresponding localised 31P MR spectra from rats with normal livers (stage 0) and those with stages 2, 3, and 4 of TAA induced chronic liver disease are provided in fig 1. In addition to the fibrosis and cirrhosis traditionally described for late stages of chronic liver disease, regions of ductular cholangiocellular proliferation were frequently present in TAA treated rats with stages 3 and 4 disease.

Hepatic 31P MR spectra from rats with normal livers (stage 0), and stages 1 and 2 disease were similar. Once disease progressed to stages 3 and 4, a significant decrease in the signal of phosphorylated metabolites was seen in the 31P MR spectra. Concentrations of the various phosphorylated metabolites are presented in table 3. Hepatic ATP levels decreased with progression of disease such that significantly lower levels were documented once rats progressed to stages 3 and 4. Levels of Pi fluctuated with progression of disease but significantly lower levels were detected at stages 2, 3, and 4 compared with levels at stages 0 and 1. PDE levels displayed a downward trend with disease progression while PDE levels remained unchanged.

Correlation analysis (table 4) revealed no significant associations between these hepatic phosphorylated metabolite levels and serum AST but Pi levels did correlate with serum albumin concentrations (r=−0.48, p<0.004). Significant correlations also existed between the LCAR index and hepatic ATP (r=0.56, p<0.001) and PME (r=0.46, p<0.01) levels.

CCL model

Body and liver weights among rats exposed to CCL, were similar to those of controls (table 1) as were serum AST concentrations (table 5). However, serum albumin concentrations in rats with stage 4 disease were significantly lower than in rats with stage 1 disease (30.2 (0.6) v 35.2 (1.2) g/l, respectively; p<0.05). Stage 4 livers also had a lower LCAR index than those at stage 1 (83.9 (1.2) v 98.6 (0.2)% respectively; p<0.05).

### Table 4

<table>
<thead>
<tr>
<th>Correlation (r)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serum AST</td>
<td></td>
</tr>
<tr>
<td>PME</td>
<td>0.01</td>
</tr>
<tr>
<td>Pi</td>
<td>−0.02</td>
</tr>
<tr>
<td>PDE</td>
<td>−0.10</td>
</tr>
<tr>
<td>ATP</td>
<td>0.01</td>
</tr>
<tr>
<td>Serum albumin</td>
<td></td>
</tr>
<tr>
<td>PME</td>
<td>−0.21</td>
</tr>
<tr>
<td>Pi</td>
<td>−0.48</td>
</tr>
<tr>
<td>PDE</td>
<td>0.09</td>
</tr>
<tr>
<td>ATP</td>
<td>−0.25</td>
</tr>
<tr>
<td>LCAR</td>
<td></td>
</tr>
<tr>
<td>PME</td>
<td>0.46</td>
</tr>
<tr>
<td>Pi</td>
<td>0.29</td>
</tr>
<tr>
<td>PDE</td>
<td>−0.12</td>
</tr>
<tr>
<td>ATP</td>
<td>0.56</td>
</tr>
</tbody>
</table>

AST, aspartate aminotransferase; LCAR, liver cell area ratio; PME, phosphomonoesters; Pi, inorganic phosphate; PDE, phosphodiesters; ATP, adenosine triphosphate.
Animals treated for 8–9 weeks with CCl₄ had complete cirrhosis (stage 4) while those treated with corn oil alone displayed non-specific histological changes. Presented in fig 2 are representative histological sections and hepatic ³¹P MR spectra from cirrhotic and control rats. Table 6 shows concentrations of hepatic phosphorylated metabolites in CCl₄ treated rats and controls. Similar to TAA experiments, animals with stage 4 disease had decreased hepatic ATP levels compared with rats with stage 1 disease. Hepatic Pi and PME levels demonstrated a trend towards lower levels with increasing severity of disease but this did not reach statistical significance. PDE levels remained unchanged.

Correlations between hepatic phosphorylated metabolites, serum AST, and albumin concentrations and LCAR in CCl₄ treated rats are presented in table 7. Hepatic ATP levels correlated with both serum albumin (r=0.53, p<0.02) and LCAR (r=0.63, p<0.006).

**CBDL model**

As shown in table 1, animals in the CBDL series followed a similar trend to those described for the TAA group in that rats with more advanced disease (days 26 and 46) weighed more than those at baseline or with early disease (day 12). Age matched controls weighed more than their day 46 cholestatic counterparts. Liver weights were similar between the two groups (table 1). Significant elevations in serum AST and reductions in serum albumin concentrations and the LCAR index occurred in cholestatic rats over the course of the disease (table 8).

Representative sections of liver tissue and the corresponding hepatic ³¹P MR spectra from a control rat and a rat with chronic cholestasis are displayed in fig 3. At 46 days post bile duct ligation, hepatic lesions which included marked hepatocyte necrosis, inflammation, bile duct proliferation, and fibrosis, were in keeping with biliary cirrhosis. A summary of the levels of hepatic phosphorylated metabolites documented during the course of the chronic cholestatic liver disease is presented in table 9. Hepatic ATP levels progressively decreased, with significantly lower levels occurring at 47 days.

### Table 6

<table>
<thead>
<tr>
<th>Stage</th>
<th>PME (mM)</th>
<th>Pi (mM)</th>
<th>PDE (mM)</th>
<th>ATP (mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.61(0.39)</td>
<td>0.94(0.11)</td>
<td>0.90(0.16)</td>
<td>3.33(0.20)</td>
</tr>
<tr>
<td>4</td>
<td>3.35(0.18)</td>
<td>1.09(0.06)</td>
<td>0.81(0.08)</td>
<td>2.71(0.10)*</td>
</tr>
</tbody>
</table>

Values are means (SEM).
PME, phosphomonoesters; Pi, inorganic phosphate; PDE, phosphodiesters; ATP, adenosine triphosphate.
*p<0.05 versus stage 1.

### Table 7

<table>
<thead>
<tr>
<th>Correlation (r)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serum AST</td>
<td></td>
</tr>
<tr>
<td>PME</td>
<td>0.04</td>
</tr>
<tr>
<td>Pi</td>
<td>0.13</td>
</tr>
<tr>
<td>PDE</td>
<td>0.01</td>
</tr>
<tr>
<td>ATP</td>
<td>0.26</td>
</tr>
<tr>
<td>Serum albumin</td>
<td></td>
</tr>
<tr>
<td>PME</td>
<td>0.00</td>
</tr>
<tr>
<td>Pi</td>
<td>−0.34</td>
</tr>
<tr>
<td>PDE</td>
<td>0.19</td>
</tr>
<tr>
<td>ATP</td>
<td>0.53</td>
</tr>
<tr>
<td>LCAR</td>
<td></td>
</tr>
<tr>
<td>PME</td>
<td>0.25</td>
</tr>
<tr>
<td>Pi</td>
<td>−0.24</td>
</tr>
<tr>
<td>PDE</td>
<td>0.29</td>
</tr>
<tr>
<td>ATP</td>
<td>0.63</td>
</tr>
</tbody>
</table>

AST, aspartate aminotransferase; LCAR, liver cell area ratio; PME, phosphomonoesters; Pi, inorganic phosphate; PDE, phosphodiesters; ATP, adenosine triphosphate.

### Table 8

<table>
<thead>
<tr>
<th>Time</th>
<th>Serum AST (U/l)</th>
<th>Serum albumin (g/l)</th>
<th>LCAR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>73.9 (18.4)</td>
<td>48.2 (1.4)</td>
<td>—</td>
</tr>
<tr>
<td>12 days</td>
<td>237 (29)*</td>
<td>42.0 (2.3)</td>
<td>—</td>
</tr>
<tr>
<td>27 days</td>
<td>217 (38)*</td>
<td>33.5 (2.8)</td>
<td>—</td>
</tr>
<tr>
<td>46 days</td>
<td>325 (98)*</td>
<td>27.5 (1.9)*</td>
<td>70.7 (5.8)*</td>
</tr>
<tr>
<td>Aged matched controls</td>
<td>33.0 (5.4)</td>
<td>39.4 (1.1)§</td>
<td>96.0 (0.7)</td>
</tr>
</tbody>
</table>

AST, aspartate aminotransferase; LCAR, liver cell area ratio.
*p<0.05 versus aged matched controls; †p<0.05 versus baseline, 12 days, and aged matched controls; §p<0.05 versus baseline and 12 days; ‡p<0.05 versus baseline and 46 days.

**Figure 3** Representative histological section of liver and corresponding hepatic ³¹P magnetic resonance spectrum from (A) a control rat and (B) a rat with cholestatic (common bile duct ligation) induced cirrhosis. Van Gieson, ×40 (see methods for description of histological staging). PME, phosphomonoesters; Pi, inorganic phosphate; PDE, phosphodiesters; ATP, adenosine triphosphate. PCr, phosphocreatine resonance arising from abdominal wall muscle.
Chronic liver disease can result from various causes which operate through different pathophysiological pathways and elicit distinct patterns of hepatic injury. However, the general course and outcome of chronic hepatic injury, as described by progressive fibrosis and eventually cirrhosis, remains constant. In a similar manner, the present study reports consistent alterations in hepatic metabolism throughout the course of hepatocellular and cholestatic chronic liver disease in rats. Animals subjected to TAA, CCl4, and CBDL each model. This disparity may be explained by the different histological features present. Specifically, CCl4 administration produced the typical pattern of cirrhosis with bridging fibrotic septa, disorganised parenchymal architecture, regenerative nodules, and mild perportal bile ductal proliferation. Although the same features were present in the TAA model, TAA exposed rat livers also contained multiple cholangiolobomas. In the CBDL model, a different pattern of cirrhosis was present where extensive bile ductal proliferation extended beyond perportal regions and replaced much of the normal parenchyma. Given that the LCAR index includes areas covered by both parenchymal and non-parenchymal cells and that luminal space occupies much of the area enclosed by bile ducts, the disparity observed in the hepatic ATP levels could reflect differences in viable hepatocyte populations. It is important to note that the differences between the various models should not affect the results of serial examinations within the same model or individual subjects within the group.

Another possible explanation relates to altered hepatic bioenergetics, namely increased energy expenditure as liver disease progresses. With the reduction in total volume of viable liver tissue, residual hepatocytes must expend more energy to maintain normal hepatic function and engage in compensatory liver regeneration. Eventually, the remnant hepatocyte population is incapable of meeting the increasing demands and both energy depletion and hepatic insufficiency ensue. Supporting this explanation were the decreases in serum albumin concentrations and hepatic ATP levels in CCl4 treated and CBDL rats. That serum albumin concentrations were maintained during TAA induced chronic liver disease is in keeping with the findings of other investigators who reported no or few changes in liver function tests in TAA treated animals. Further studies are required to examine the compensatory mechanism in this model.

Disturbed hepatic bioenergetics has also been ascribed to the capillarisation of hepatic sinusoids during the development of cirrhosis. In normal livers, the sieve-like structure of the sinusoidal endothelium and the freely accessible perisinusoidal space allow for rapid and high exchange of substrates and nutrients between the vascular compartment and hepatocytes. During fibrogenesis and the development of cirrhosis, a barrier of connective tissue and extracellular matrix is deposited in the perisinusoidal space. By limiting hepatocyte access to nutrients, high energy substrates, and oxygen, this barrier may impair hepatic energy metabolism.

The magnitude of hepatic ATP levels at end stage disease varied considerably between the models of chronic liver disease, being highest in CCl4 treated rats (ATP 2.71 mM), lowest in CBDL rats (ATP 1.66 mM), and intermediate in TAA treated rats (ATP 2.18 mM), despite similar levels of LCAR in each model. This disparity may be explained by the different histological features present. Specifically, CCl4 administration produced the typical pattern of cirrhosis with bridging fibrotic septa, disorganised parenchymal architecture, regenerative nodules, and mild perportal bile ductal proliferation. Although the same features were present in the TAA model, TAA exposed rat livers also contained multiple cholangiolobomas. In the CBDL model, a different pattern of cirrhosis was present where extensive bile ductal proliferation extended beyond perportal regions and replaced much of the normal parenchyma. Given that the LCAR index includes areas covered by both parenchymal and non-parenchymal cells and that luminal space occupies much of the area enclosed by bile ducts, the disparity observed in the hepatic ATP levels could reflect differences in viable hepatocyte populations. It is important to note that the differences between the various models should not affect the results of serial examinations within the same model or individual subjects within the group.

An alternative explanation for differences in absolute ATP levels relates to the heterogeneity of the liver lobule and patterns of zonal injury induced by the various models. Portal hepatocytes within zone 1 of the liver lobule have sufficiently high oxygen tension that they are capable of generating...
energy by both glycolytic and oxidative metabolism, whereas the less aerobic periportal hepatocytes predominantly utilise glycolytic pathways of energy generation.\(^{12,13}\) Having access to both aerobic and anaerobic pathways, and thereby a selection of fatty acid and carbohydrate substrates, periportal hepatocytes are generating more energy on a per mole basis than those in the perivenous region.\(^{14,15}\) Hence one would predict that lesions specific to zone 1 of the liver lobule would create a greater bioenergetic disturbance than lesions localised in zone 3. The results from the present study support this hypothesis as BDCL injury predominantly involves zone 1 while CCl\(_4\) involves zone 3 and TAA is a more diffuse injury, involving zone 1–3 hepatocytes.

Inorganic phosphate, another marker of tissue bioenergetics, displayed a trend towards lower levels with more advanced stages of chronic liver disease. However, significant decreases were only detected among TAA treated rats. As with hepatic ATP, lower levels of hepatic Pi likely result from reduced hepatic PI mass. However, unlike ATP, these changes are attenuated by certain metabolic activities within the functioning remnant liver. Specifically, increased energy expenditure perpetuates the hydrolysis of high energy phosphate bonds which in turn liberates inorganic phosphate species. Accumulation of Pi due to enhanced metabolic activity and reduced recycling back to purine/pyrimidine moieties would in turn contribute to the Pi signal. Indeed, increases in Pi have been observed during high energy activities such as liver regeneration following partial hepatectomy.\(^{16,17}\)

Information regarding phospholipid membrane metabolism may also be obtained from the PME and PDE resonances in the \(^{31}\)P MR spectrum. Both resonances are multiplet components containing contributions from several metabolites.\(^{18}\) The PME resonance consists of membrane phospholipid precursors, phosphoethanolamine (PE), and phosphocholine (PC), and several phosphorylated glycolytic (G) intermediates. Conversely, PDE resonance is made up of metabolites involved in phospholipid membrane degradation, GPC, and GPE, as well as a signal arising from the phospholipid bilayers of the endoplasmic reticulum.\(^{19}\) An increase in PME levels accompanied by a decrease in PDE levels has traditionally been interpreted to reflect increased phospholipid membrane turnover due to enhanced cell proliferation.\(^{19}\) Previous studies in human patients with cirrhosis have reported increased ratios of hepatic PME/ATP and PME/PDE.\(^{20}\) Additional high resolution MRS experiments performed on tissue extracts have detected transthyretin (TTR) and inositol in hepatic PE and PC and reductions in GPE and GPC occur within the cirrhotic liver.\(^{19}\) These findings are interpreted to reflect enhanced cell turnover as the cirrhotic liver attempts to regenerate.\(^{18,19}\)

Contrary to previous reports, in this study PME levels did not increase nor did PDE levels decrease in any of the models employed. These findings raise the possibility that hepatic phospholipid membrane activity may differ in rat models of cirrhosis versus cirrhosis in humans. An alternative explanation relates to differences in the field strength at which the present study was performed compared with previous studies as PDE resonance is known to contain a magnetic field dependent component.\(^{19}\)

In conclusion, the results of the present study indicate that hepatic ATP levels correlate with biochemical evidence of hepatic dysfunction and histological evidence of loss of functioning hepatocytes and progressive disease. The results also support the concept that regardless of the aetiology, progressive liver disease has a significant effect on hepatic bioenergetic integrity. Given these observations, hepatic \(^{31}\)P MRS holds promise as a non-invasive means of documenting the extent and progression of liver disease.

ACKNOWLEDGEMENTS

This work was supported by grants from the Health Sciences Centre Foundation and the Canadian Liver Foundation. Financial assistance from the Multimedia Advanced Computational Infrastructure (MACI) project is appreciated. Special thank you to Dr Sahar Al-Haddad from the Department of Pathology for staging histological sections.

Authors' affiliations

I R Corbin, G Y Minuk, Section of Hepatology, Department of Medicine, and Department of Pharmacology and Therapeutics, University of Manitoba, Winnipeg, Canada

R Buist, Department of Radiology, University of Manitoba, Winnipeg, Canada

J Peeling, Department of Pharmacology and Therapeutics, and Department of Radiology, University of Manitoba, Winnipeg, Canada

M Zhang, J Uhanova, Section of Hepatology, Department of Medicine, University of Manitoba, Winnipeg, Canada

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In vivo 31P MRS and chronic liver disease


