Silibinin Inhibits the Hepatocellular Carcinoma in NDEA-Induced Rodent Carcinogenesis Model: An Evaluation through Biochemical and Bio-Structural Parameters

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Abstract

The present study was aimed to investigate the chemopreventive potential of Silibinin (SIB) against N-nitrosodimethylamine (NDEA)-induced hepatocellular carcinoma (HCC) in wistar rats. Thirty experimental animals were subjected to partial hepatectomy (PH) and after 24 hours of stabilization period a single dose of NDEA (100 mg/kg b.w., i.p) was administered to each animal followed by COCl2 (1 ml/kg b.w., s.c.). The effect of SIB (25 and 50 mg/kg/day, i.p) on NDEA-induced HCC was determined after 2 weeks of treatment (6th to 8th week after PH, in the promotional stage of tumor development). NDEA treatment to rats resulted in significant decrease in body weight and increase in liver weight along with levels of transaminases, γ-glutamyl transferase, lipoprotein, glycoproteins. Hepatic and serum malondialdehyde content, enzymatic and non-enzymatic antioxidant levels were also altered in HCC bearing animals without treatment. Bio-structural components (such as amide bands of proteins, symmetric phosphate stretching of nucleic acids, methylene chains in membrane lipids, methyl to methylene ratio of carbohydrates and proteins etc.) were marked in NDEA-treated groups of animals by analysing changes in carbohydrate, proteins, glycoproteins etc. in NDEA-treated groups of animals by analysing changes in carbohydrate, proteins, glycoproteins etc. of NDEA-treated and NDEA and SIB treated animals. SIB treatment could attenuate NDEA-induced hepatocarcinogenesis by improving the biochemical and bio-structural changes of the hepatic tissue near normal levels in a dose dependent manner. Taken together, this study reveals that SIB may have potential as a multi-functional drug candidate for cancer therapy.

Keywords: Liver cancer; NDEA; Silibinin; Biochemical; Bio-structural; FTIR

Introduction

Liver cancer is one of the most common malignancies worldwide, especially in Asia and Africa [1]. Hepatocellular carcinoma (HCC) accounts for about 80-90% of all cancers and ranks the fifth most common and the third most deadly cancer worldwide [2]. Major risk factors for liver cancer include hepatitis viral infection, food additives, alcohol, aflatoxins, industrial toxic chemicals and water pollutants, etc. [3].

N-nitrosodimethylamine (NDEA), is a well-known potent hepatocarcinogenic agent present in tobacco smoke, water, cured and fried meals, cheddar cheese, agricultural chemicals, cosmetics and pharmaceutical products [4]. It is an important environmental carcinogen produces reproducible tumor in the liver [5]. Administration of NDEA has been reported to generate lipid peroxidation and activate oxygen species during hepatocarcinogenesis [6]. Oxidative stress has recently been suggested to participate in both metabolism and carcinogenic actions of nitrosamine. Liver tumor promotion in rodents has been characterized most extensively in the rat model utilizing initiation with a nitrosamine, partial hepatectomy (PH), and subsequent promotion with polychlorinated aromatic hydrocarbons [7]. The possibility was raised that the tumor yield in the liver would be increased, if NDEA were given in the period of regeneration that followed a necrotizing dose of a hepatotoxin like CCl4, that was not full carcinogen by itself [8]. Taken together the use of NDEA for HCC animal model development is a potential tool which mimics the HCC in clinical findings.

Recent approach of chemoprevention serves as an attractive alternative to control malignancy. Flavonoids have been shown to act as scavengers of various oxidizing species, inhibit the growth of various cancer cell lines in vitro, and reduce tumor development in experimental animals [9,10]. Milk thistle (Silybum marianum) is the most ancient and extensively used medicinal plant for its beneficial effects on liver and other organs [11]. Silymarin, an extract isolated from its fruits and seeds, is known to provide a wide range of hepatoprotective effects, especially against diseases like hepatitis, cirrhosis and jaundice [12]. Marketed as Legalon or Flavonol, silymarin has been successfully applied in the therapy of various liver diseases. Moreover, highly efficient antitumour activities were also reported for Silymarin [13,14]. One of the most active constituents is Silibinin (SIB) [(2R,3R)-3,5,7-trihydroxy-2-[(2R*,3R*)-3-(4-hydroxy-3-methoxyphenyl)-2-hydroxymethyl-1,4-benzoxoan-6-y]-4-chromanone], which is composed of flavanone-3-ol and 1,4-benzoxodioxane ring systems (Figure 1). Silibinin, is consumed widely as a dietary supplement and it displays a remarkable spectrum of pharmacological activities like antioxidant, hepatoprotective, anti-inflammatory, antibacterial, anti-allergic, anti-mutagenic, antiviral, antineoplastic, anti-thrombotic and it displays a remarkable spectrum of pharmacological activities like antioxidant, hepatoprotective, anti-inflammatory, antibacterial, anti-allergic, anti-mutagenic, antiviral, antineoplastic, anti-thrombotic ects.

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and vasodilatory actions [15,16], affecting basic cell functions such as proliferation, differentiation and apoptosis. It possesses anticancer effect on human hepatocellular carcinoma cells [17] and also it produced antitumor efficacy in an orthotopic drafting of Hep-55.1C cells into the liver of C57BL/6j mice [18]. Based on this claim, we for the first time tried to evaluate the effect of SIB on NDEA-induced hepatocellular carcinogenesis model which represents all stages of carcinogenesis in vivo (Figure 2).

Materials and Methods

Animals

Wistar albino rats 50-day old were purchased from National Institute of Nutrition, Hyderabad, India and used for the study. Animals were maintained on standard pelleted diet and water ad libitum. Experiments were approved by the Animal Ethics Committees of Department of Pharmaceutical Technology and Sciences, Birla Institute of Technology University, India (621/02/ac/CPCSEA) and strictly performed according to the NIH and CPCSEA, India guidelines for the care and use of laboratory animals.

Chemicals

N-Nitrosodiethylamine was obtained from the Sigma Aldrich, USA. KBr (I.R. Grade), Silibinin (M.W.: 482.44g/mol) and other fine chemicals were purchased from the Sigma Aldrich, USA. Other chemicals and reagents in the study are of highest purity and standard which are commercially available.

Tumor induction and experimental design

HCC was induced by NDEA using the induction techniques given by Yadav et al. [5], Pound et al. [8] with some modifications. Briefly, PH was done to the animals. After 24 hours of stabilization a single dose of NDEA (100 mg/kg b.w., i.p) was administered to the animals. Phenobarbital sodium (PB, 0.05% w/v, P.O.) was given after PH, up to a single dose of NDEA (100 mg/kg b.w., i.p) was administered to the animals. Phenobarbital sodium (PB, 0.05% w/v, P.O.) was given after PH, up to 4 weeks of drinking water. CCl₄ (1 ml/kg b.w., s.c.) was administered twice a week to 1st week to 2nd week.

Tumor yield and size were stabilized after 6 weeks with the initiation of NDEA. The administration of SIB was done after 6 weeks of NDEA-treatment and continued up to 8 weeks (in the promotional stage of tumor development). Five experimental groups with six animals in each group were set up in this study as follows:

Group I: Animals with no treatment

Group II: PH was performed to the animals and received only 0.5% CMC (Vehicle)

Group III: HCC induced with NDEA (200 mg/kg b.w., i.p.) as described (after 24h stabilization of PH) and received only 0.5% CMC for the treatment period

Group IV: Animals with HCC were treated with SIB-25 (after 6 weeks)

Group V: Animals with HCC were treated with SIB-50 (after 6 weeks)

The animals in each group were weighted each week and the changes in the body weight were recorded. All the animals were starved overnight and sacrificed by cervical decapitation after the completion of 8th week.

Macroscopical documentation of tumor burden and sample preparation

After decapitation of the animals in each group, the livers were isolated and cleaned properly using phosphate buffer saline (PBS), weighted and observed morphologically for: foci, lesions and tumors. Blood was collected; the plasma and serum were separated by centrifugation. Liver specimens were cleared for surrounding fat, tumors. Blood was collected; the plasma and serum were separated by centrifugation. Liver specimens were cleared for surrounding fat, tumors. Blood was collected; the plasma and serum were separated by centrifugation. Liver specimens were cleared for surrounding fat, tumors. Blood was collected; the plasma and serum were separated by centrifugation. Liver specimens were cleared for surrounding fat, tumors. Blood was collected; the plasma and serum were separated by centrifugation. Liver specimens were cleared for surrounding fat, tumors. Blood was collected; the plasma and serum were separated by centrifugation. 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an extinction coefficient of 0.152 mM$^{-1}$ cm$^{-1}$ formed per milligram of protein. The protein content was estimated by the method of Lowry et al. [24]. Superoxide dismutase (SOD) activity was assessed by the nitroblue tetrazolium reduction method by Flohe and Otting et al. [25]. Catalase (CAT) activity was assayed by the method of Sinha [26] and ascorbic acid and α-tocopherol were also accessed [20]. Oxidation of glutathione by the enzyme was measured spectrophotometrically at 420 nm. The activity of GPx was expressed as micromoles glutathione oxidized per minute per milligram protein by Rotruck et al. [27]. Reduced glutathione (GSH), Glutathione reductase (GR) was estimated by the method of Moron et al. and glutathione-S-transferase (GST) [28].

The lipids in plasma was extracted and quantified by the method of Folch et al. [29]. Triglyceride was estimated using the method of Rice et al. [30], which is based on the method of Van Handle et al. [31]. Total cholesterol was estimated using the method of Parekh and Jung et al. [32]. Plasma lipoproteins were fractionated by dual precipitation technique of Sujatha and Sachandanam et al. [33]. Addition of heparin–magnesium to plasma, precipitated very low-density lipoproteins (VLDL-c), low-density lipoproteins (LDL-c), and high-density lipoproteins (HDL-c), which were left in the supernatant, and subsequently, the content was measured in the fraction. The protein bound hexose, protein bound hexosamine and protein bound sialic acid was estimated from the collected serum samples by the method of Nandave et al. [34].

**Histopathological and immunohistochemical studies**

For histopathological examination, liver tissues specimens from all groups were fixed in 10% neutral-buffered formalin. The histopathology of the tissue samples with Hematoxylin and eosin staining were carried out by the modified method of Pattanayak et al. [35]. To the paraffin groups were fixed in 10% neutral-buffered formalin. The histopathology of the tissue samples with Hematoxylin and eosin staining were carried out by the modified method of Pattanayak et al. [35] and the paraffin sections of the liver tissue, Ki67 immunolabeling was performed to assess cell proliferation [36], using a mouse monoclonal antibody of the tissue samples with Hematoxylin and eosin staining were carried out by the modified method of Pattanayak et al. [35]. To the paraffin sections of the liver tissue, Ki67 immunolabeling was performed to assess cell proliferation [36], using a mouse monoclonal antibody (Thermo Scientific, USA), and a three-step immunoperoxidase method.

**FT-IR spectroscopic analysis**

The FT-IR spectra in the 4000–400 cm$^{-1}$ region were recorded with a Schimatzu 8400S FT-IR Spectrometer equipped with an attenuated reflectance detector (ATR) detector. FTIR analysis was done according to the method of Palaniappan et al. [37] with some modifications. In brief, 3 mg lyophilized sample was triturated with 100 mg IR grade KBr and pelletted for standard FT-IR analysis. The spectrometer was continuously purged with dry standard FT-IR eliminate air. Water vapor and carbon dioxide. To improve the signal to noise ratio for each spectrum, 60 scans with a spectral resolution of ± 4 cm$^{-1}$ were averaged. Background spectra, which were collected under identical conditions, were subtracted from the sample spectra automatically. The frequencies for all sharp bands were accurate to 0.001 cm$^{-1}$. To eliminate the differences due to the non-uniformity of thickness of sample and the varying of intensity of light source, all spectra were subsequently calibrated. The frequencies for all sharp bands were determined accurately from the original base line-corrected spectra belonging to the corresponding four groups. Each observation was confirmed by taking at least three replicates. The sample was then weighed to get the corresponding weight of the sample. Therefore, it was possible to directly correlate the intensities of absorption bands to the concentration of the functional group. The spectra were analyzed using Schimatzu IRRsolution software.

**Statistical analysis**

Pharmacological data were analyzed by one-way analysis of variance followed by Bonferroni’s multiple comparison tests with equal sample size. The difference was considered significant when $p$ value $<$ 0.05. All the values were expressed as mean ± standard error mean (SEM).

**Results**

**SIB ameliorated the alteration in body weight and liver weight in NDEA-induced liver cancer**

NDEA treatment caused significant difference in body weight (b.w.) as compared with normal control and PH-control groups. SIB treatment in NDEA treated animals showed significant increase ($p<0.001$) in b.w. with respect to induced control in both treatment groups (Figure 3). NDEA treatment caused highly significant ($p<0.001$) increase in liver weight. SIB (25 mg/kg/day) administration caused significant ($p<0.05$) decrease and higher dose (SIB-50 mg/kg/day) caused complete normalization of liver weight (Figure 4). The representative images of the liver of all groups of rats are depicted in Figure 5.

**Antioxidant status and biochemical changes in HCC-rats were attenuated by SIB**

NDEA treated rats showed significant ($p<0.01$) increase in the AST, ALT, ALP and γ-GT levels in the serum (Figure 6) and tissue homogenate (Figure 7) as compared to the control group animals. SIB treatment produced significant ($p<0.05$) decrease in the liver marker levels in both treatment groups of animals. High dose treated animals showed more significant ($p<0.01$) decrease in the transaminase and γ-GT enzymes with respect to induced control group.

Table 1 represents the plasma lipoprotein cholesterol profile such as HDL-c, LDL-c, and VLDL-c levels of all groups along with TC and TG. The levels of HDL-c significantly ($p<0.001$) decreased in group III animals as compared with those in group I. The levels of VLDL-c and LDL-c significantly ($p<0.001$) increased in the same manner. However, significantly ($p<0.05$) decreased levels of VLDL-c, LDL-c and increased levels of HDL-c were observed in groups IV, and V animals as compared with those in group III animals. The TC and TG levels were also found

![Figure 3: Mean body weight (gms) of normal and different groups of animals for 8 weeks of experimental period. Comparisons: NDEA+SIB (25) and NDEA+SIB (50) groups of animals compared with Induced control (induced-ctrl). Values are expressed as Mean ± standard deviations. Significant: a<0.01.](image)
to be significantly increased in the Group III animals and brought back to normal levels in a dose dependent manner after the SIB treatment.

Table 2 shows activities of glycoproteins in the serum in all experimental groups. A significant (P<0.01) increase in activity of sialic acid, hexose and hexosamine were observed in the group III animals. After the treatment with SIB for 2 weeks, these alterations in glycoprotein levels significantly decreased in a concentration dependent manner (group IV and V) (Figure 8).

The activities antioxidants in serum and liver homogenates were depicted in Tables 3 and 4, respectively. The status of SOD, CAT, GSH, GR, GPx and GST were recorded to be significantly (p<0.001) increased in serum samples of NDEA-induced group as compared to control group I. Although the low dose SIB (25 mg/kg/day) treatment increased the antioxidant levels HCC mice, but a propound increase was observed with the high dose (50 mg/kg/day) treatment group of animals (Table 3). The similar findings were also recorded for the enzymic and non-enzymic antioxidant levels in liver tissue homogenates of all tested groups (Table 4). The levels of lid peroxidation in only NDEA-treated animals (group III) was significantly increased (p<0.01) with respect to group I animals and it was brought back to almost normal levels after 14 day treatment with SIB at a dose level of 50 mg/kg/day.

Figure 4: Mean liver weight (gm) of normal and different treatment groups after 8 weeks. Values are expressed as mean ± SEM for Six animals. Group I: Normal control; Group II: PH-control; Group III: NDEA; Group IV: NDEA+SIB (25 mg/kg/day); Group V: NDEA+SIB (50 mg/kg/day). Comparisons: a = groups II and III with group I; b = group IV and V with group III. Significant: *p<0.05; **p<0.01; ***p<0.001.

Figure 5: Effect of Silibinin (SIB) on liver marker enzymes in serum all tested group of animals. Values are expressed as mean ± SEM for Six animals. Group I: Normal control; Group II: PH-control; Group III: NDEA; Group IV: NDEA+SIB (25 mg/kg/day); Group V: NDEA+SIB (50 mg/kg/day). Comparisons: a = groups II and III with group I; b = group IV and V with group III. Significant: *p<0.05; **p<0.01; ***p<0.001.

Figure 6: Effect of Silibinin (SIB) on liver marker enzymes in tissue homogenate of all tested group of animals. Values are expressed as mean ± SEM for six animals. Group I: Normal control; Group II: PH-control; Group III: NDEA; Group IV: NDEA+SIB (25 mg/kg/day); Group V: NDEA+SIB (50 mg/kg/day). Comparisons: a = groups II and III with group I; b = group IV and V with group III. Significant: *p<0.05; **p<0.01; ***p<0.001.

Figure 7: Effect of Silibinin (SIB) treatment on lipid peroxidation in liver homogenate tissue preparation from normal and treatment groups of animals. Values are expressed as mean ± SEM for Six animals. Group I: Normal control; Group II: PH-control; Group III: NDEA; Group IV: NDEA+SIB (25 mg/kg/day); Group V: NDEA+SIB (50 mg/kg/day). Comparisons: a = groups II and III with group I; b = group IV and V with group III. Significant: *p<0.05; **p<0.01; ***p<0.001.
SIB-treatment customized the tissue architecture and hepatocytes proliferation in HCC

The histopathological examination of liver sections of NDEA-treated rats showed multiple nucleoli, hyperchromatic malignant nuclei, cellular infiltration, protein and cytoplasmic leakage (Figure 9) in comparison to the PH-control and normal control animals. A decrease in degenerative changes and cytoplasmic leakage was showed in SIB (25 mg/kg/day) and SIB (50 mg/kg/day) treated groups (Figure 9) groups. But the high dose revealed almost normal architecture comparison to the low dose treated group of animals.

The kinetics of hepatocytes proliferation was examined by Ki67-immunolabeling. A high proportion of hepatocytes were Ki67-positive (brown colored in Figure 10 (NDEA)). The rate of hepatocytes proliferation in the SB-treated animals progressively decreased thereafter (Figure 10 NDEA+SIB (25), SIB (50)). At the end of follow-up, the rate of hepatocytes proliferation had returned to basal levels in high dose treated groups of animals.

Changes in the bio-structural components has been altered by SIB in HCC-bearing rats

A complete scanning of the normal as well as other treated group samples was done. The general band assignments of the FTIR spectra of liver tissue on the basis of reported literature of Wistar rat for comparison among all groups were depicted in supplemental Table 1. The FT-IR spectra for the normal and PH-control group tissues (Figure 11a) showed no difference in spectral peak positions. The spectra of NDEA-induced group was compared with normal control group (Figure 11b), the spectra showed many changes in the intensities and position of peaks like peaks for amide I, amide II, amide A bands, olefinic band at 3010 cm\(^{-1}\), peak at 1401 cm\(^{-1}\) and 1452 cm\(^{-1}\) due to methyl group of protein, peaks at 1065 cm\(^{-1}\) and 1088 cm\(^{-1}\) etc. The changes in the peak position and intensities were decreased in the spectra of SIB treated group as compared to NDEA-induced group (Figure 11c). Changes in the peak intensities of amide I and amide II bands, reappearance of olefinic band with a shift to 3007 cm\(^{-1}\), change in peak near 1720 cm\(^{-1}\) of ester group, peak near 1024 cm\(^{-1}\) were observed. The spectra of NDEA+SIB (50 mg/kg/day) treated group was compared with NDEA-treated group (Figure 11d) were found with variations at numerous peaks such as, amide I and amide II bands, olefinic peak, amide A and B bands, band shift in peaks near 1024 cm\(^{-1}\). The FTIR spectra of SIB treated group have similarities with normal control group spectra.

Discussion

Rats treated with NDEA significantly reduce the body weight might be due to stress compared to control animals. The reduction in body weight of the animals in this study correlate with the decreased food intake observed during the experimental period which appeared to reduced metabolism and hepatotoxicity [38]. Liver damage caused by NDEA and CCl\(_4\) generally reflects instability of liver cell metabolism and reduced metabolism and hepatotoxicity [38]. Liver damage caused by NDEA and CCl\(_4\) generally reflects instability of liver cell metabolism and is usually accompanied by a rise in AST. Similarly, increase in ALP reflects pathological alteration in biliary flow and discharge of total bilirubin reflects a non-specific alteration in the plasma membrane integrity and/ or permeability. γ-GT is an enzyme in the hepatocyte plasma membrane, its liberation into serum indicates cellular damage to liver. Hence γ-GT is considered to be one of the best indicators of liver damage [39]. After partial hepatectomy only a slight to moderate increase in serum transaminase activity was recorded specifically with AST of liver tissue preparation. In patients with hepatocellular carcinoma high preoperative levels of ALT, AST and γ-GT indicates a significantly increased risk to develop tumor recurrence after

| Groups | Group I | Group II | Group III | Group IV | Group V |
|--------|---------|----------|-----------|----------|---------|
| TC (mg/dl) | 8.23 ± 0.8 | 8.55 ± 0.18\(^*\) | 18.22 ± 0.08\(^***\) | 14.35 ± 0.14\(^*\) | 9.32 ± 0.34\(^***\) |
| HDL-c (mg/g wet tissue) | 41.65 ± 1.07 | 45.24 ± 0.52\(^*\) | 22.95 ± 0.45\(^*\) | 30.08 ± 0.80\(^*\) | 42.38 ± 0.06\(^***\) |
| LDL-c (mg/g wet tissue) | 54.33 ± 0.44 | 60.50 ± 0.41\(^*\) | 132.28 ± 0.15\(^***\) | 104.41 ± 0.62\(^*\) | 69.40 ± 0.02\(^***\) |
| VLDL-c (mg/g wet tissue) | 18.32 ± 0.15 | 19.05 ± 0.32\(^*\) | 53.20 ± 1.90\(^***\) | 40.12 ± 0.14\(^***\) | 21.12 ± 0.05\(^***\) |
| TG | 93.40 ± 1.56 | 94.88 ± 1.01\(^*\) | 192.32 ± 1.57\(^***\) | 165.71 ± 1.20\(^***\) | 121.67 ± 1.34\(^***\) |

Values are expressed as mean ± SEM for Six animals. Group I: Normal control; Group II: PH-control; Group III: NDEA; Group IV: NDEA+SIB (25 mg/kg/day); Group V: NDEA+SIB (50 mg/kg/day). Comparisons: a = groups II and III with group I; b = group IV and V with group III. Significant: \(p<0.05\); \(p<0.001\).
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**Table 3: Effect of Silibinin (SIB) on serum antioxidant status of NDEA-induced liver cancer rats.**

| Groups | Group I | Group II | Group III | Group IV | Group V |
|--------|---------|---------|-----------|---------|---------|
| SOD (U/min/mg protein) | 8.62 ± 0.32 | 8.04 ± 0.64 | 4.45 ± 0.72 | 6.36 ± 0.87 | 8.10 ± 0.49 |
| CAT (U/mg protein) | 60.53 ± 1.23 | 58.23 ± 1.40 | 39.26 ± 1.67 | 47.66 ± 1.5 | 56.16 ± 1.62 |
| GPx (nmol NADPH oxidized/min/mg protein) | 92.45 ± 2.32 | 89.34 ± 1.24 | 43.05 ± 2.21 | 58.15 ± 1.13 | 72.34 ± 1.15 |
| GST (nmol CDNB conjugate/min/mg protein) | 179.43 ± 2.69 | 181.45 ± 5.12 | 92.82 ± 1.85 | 129.11 ± 2.32 | 162.18 ± 3.15 |
| GSH (nmol GSH/mg tissue) | 1.52 ± 0.12 | 1.48 ± 0.14 | 0.49 ± 0.09 | 0.85 ± 0.06 | 1.43 ± 0.12 |
| Ascorbic acid | 8.82 ± 0.13 | 8.12 ± 0.15 | 5.23 ± 0.19 | 6.69 ± 0.13 | 7.79 ± 0.08 |
| α-Tocopherol | 6.14 ± 0.19 | 5.95 ± 0.25 | 3.09 ± 0.12 | 4.12 ± 0.23 | 5.85 ± 0.15 |

Values are expressed as mean ± SEM for Six animals. Group I: Normal control; Group II: PH-control; Group III: NDEA; Group IV: NDEA+SIB (25 mg/kg/day); Group V: NDEA+SIB (50 mg/kg/day). Comparisons: a = groups II and III with group I; b = group IV and V with group III. Significant: *p<0.05; **p<0.01; ***p<0.001.

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**Table 4: Effect of Silibinin (SIB) treatment on liver oxidative stress indices in homogenate tissue preparation from normal and treatment groups of animals.**

| Groups | Group I | Group II | Group III | Group IV | Group V |
|--------|---------|---------|-----------|---------|---------|
| SOD (U/min/mg protein) | 8.47 ± 0.09 | 4.34 ± 0.078 | 2.09 ± 0.068 | 3.27 ± 0.043 | 4.03 ± 0.062 |
| CAT (U/mg protein) | 30.54 ± 0.53 | 28.61 ± 0.34 | 18.37 ± 0.29 | 23.42 ± 0.54 | 27.51 ± 0.58 |
| GPx (nmol NADPH oxidized/min/mg protein) | 91.2 ± 0.31 | 85.7 ± 0.31 | 58.7 ± 0.46 | 64.9 ± 1.47 | 82.4 ± 0.52 |
| GST (nmol CDNB conjugate/min/mg protein) | 387.60 ± 13.64 | 376.50 ± 11.3 | 174.20 ± 11.7 | 239.5 ± 4.8 | 368.3 ± 12.7 |
| GSH (nmol GSH/mg tissue) | 2.85 ± 0.18 | 2.23 ± 0.18 | 1.21 ± 0.22 | 1.68 ± 0.46 | 2.35 ± 0.21 |
| GR (nmol GR/mg tissue) | 3.20 ± 0.44 | 2.98 ± 0.31 | 1.97 ± 0.27 | 2.61 ± 0.40 | 3.07 ± 0.53 |

Values are expressed as mean ± SEM for Six animals. Group I: Normal control; Group II: PH-control; Group III: NDEA; Group IV: NDEA+SIB (25 mg/kg/day); Group V: NDEA+SIB (50 mg/kg/day). Comparisons: a = groups II and III with group I; b = group IV and V with group III. Significant: *p<0.05; **p<0.01; ***p<0.001.

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**Figure 9:** Histopathological observation of liver tissue in control and experimental groups of animals. NC: normal control; PHC: PH-control; NDEA: NDEA-induced control; NDEA+SIB (25): NDEA-induced animals treated with SIB (25 mg/kg/day); NDEA+SIB (50): NDEA-induced animals treated with SIB (50 mg/kg/day). The fibroadenoma of the rat hepatocytes was identified with hematoxylin and eosin stain (×40).

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**Figure 10:** Cell proliferation was assessed by Ki67 immunolabeling in the liver Normal, NDEA-treated and SIB treated animals. NDEA-Treated animals at the end of 8 week of induction revealed a large number of Ki67-labeled hepatocytes. In normal control (NC) and PH-control (PHC) group of animals showed the vast majority of hepatocytes Ki67-negative; 2 weeks of treatment with SIB reduced the Ki67 positive hepatocytes in liver in a dose dependent manner. Original magnification: ×40. Hepatocytes proliferation was measured as the proportion of Ki67-positive hepatocytes.

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As a terminal component of the non-reducing end of carbohydrate chains of glycoprotein, their implications in a variety of surface-related vital cell functions in numerous tissues including HCC are well documented. Hence, a pronounced increase in serum levels was recorded. Glycoproteins level was found to be significantly reduced after treatment with SIB (50 mg/kg/day). This study shows that SIB administration may inhibit glycoprotein synthesis in tumor cells [42].

The significant increase of hepatic GSH level in NDEA-treated rats liver is probably due to the simultaneous observed two-fold increase in the activities of γ-GT one of the principal enzymes involved in GSH formation [43]. Glutathione-S-transferases (GSTs) are a family of isoenzymes that play an important role in protecting cells from the cytotoxins and carcinogens. In addition, GSTs can bind to sequester intracellular toxins to prevent oxidative damage by an intrinsic organic peroxidase that converts toxic peroxidase to inactivated form [44]. These results indicate the ameliorative effect of SIB under cancer conditions. Moreover, GSH has a nucleophilic property that makes key

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**References**

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**Abstract**

Silibinin is an active constituent of milk thistle, a herbal supplement used for the treatment of hepatic disorders. The present study was undertaken to evaluate whether silibinin influences the development of hepatocellular carcinoma in NDEA-induced rodents. The results of the study showed that silibinin significantly inhibited cell proliferation and induced apoptosis in NDEA-induced hepatocellular carcinoma cells.

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**Keywords**

Silibinin, hepatocellular carcinoma, cell proliferation, apoptosis
role in the cellular protection from the oxidative damage. Furthermore, GSH is a cofactor of GST, which is responsible for detoxification of xenobiotics. GSH is regenerated by glutathione reductase from the oxidized glutathione. SIB has antioxidant potential which restores these enzymes. Ascorbic acid and α-tocopherol may also account for its potential anticancer effects. Additionally, we also observed that vitamin C and vitamin E levels were significantly increased in SIB-treated cancer-bearing rats.

Oxidative damage of the vital cellular constituents such as DNA, lipids and proteins and alterations in the signal transduction pathways that control the expression of genes required to execute cell death occurs in the liver tissue due to the formation of large amount of reactive oxygen species. As the present study represented, the increased level of MDA which was a biomarker for the oxidative stress in the liver of HCC bearing animals that could be result to the excessive generation of free radicals which are produced during the metabolism of NDEA or during the process of carcinogenesis [45]. Free radical scavenging activity of SIB is confirmed by the results obtained in our findings i.e. decreased level of MDA after drug treatment. SOD was reported as one of the most important enzymes among the enzymic antioxidant defense system. It scavenges the superoxide anion to form hydrogen peroxide, hence diminishing the toxic effect caused by free radicals. In the present study, the significantly decreased level of SOD as observed in HCC induced animals which might be due to the utilization of the enzyme to scavenge H$_2$O$_2$ radicals. CAT decomposes hydrogen peroxide and protects the tissue from highly reactive hydroxyl radicals [46] and it is thought to be the first line of defense against oxidative damage induced by carcinogen. The significantly decreased level of CAT activities were recorded in NDEA-induced HCC animals as compared to normal animals may be due to the utilization of this enzyme in the removal of hydrogen peroxide radicals caused by carcinogen administration [47]. These antioxidant enzymes have been increased with the treatment of SIB at a dose level of 50mg/kg/day for 2 weeks.

Research reports for cancer diagnosis by infrared spectroscopy have generally focused on some useful findings in molecular level (e.g. amide bands for proteins, symmetric phosphate stretching band of the phosphodiester groups of nucleic acids, methylene chains in membrane lipids, hydrogen bonding on the phosphodiester groups of nucleic acids, methyl to methylene ratio, glycosyl content and hydrogen bonding of C–OH groups in carbohydrates and protein etc.) [48]. The vibrational spectra of the protein are characterized by a set of absorption regions known as the amide region and the C–H region. The most widely studied regions are amide I, amide II, amide III and amide A regions. Absorbance at 1650-1654 cm$^{-1}$ region representing amide I region corresponding to the stretching C=O and bending C–N vibrational modes of the polypeptides and protein backbone and at 1540-1545 cm$^{-1}$ region assigned to the bending N–H and stretching C–N [49]. In the amide I band (1650-1655) of normal tissues (control group) (Figure 11a) the peak was found to be more intensified than that of NDEA induced cancerous tissue sample. Moreover, the difference between the peak intensity in the NDEA+SIB treated group is significant with respect to induced-
control (Figure 11). The peak shift is insignificant. Uniformity in the peak intensity at 1650-1655 cm\(^{-1}\) was observed in all samples of all the groups. The changes observed are due to the variation and alteration in the protein content and its irregular composition due to alteration in cancer tissue composition and make up of specific vibrational band specially assigned for amide I band. The amide I band primarily associates with a stretching motion of the C=O group. This band is sensitive to the environment of the peptide and also depends upon overall secondary structure of protein [50]. The strong band observed at 1659 cm\(^{-1}\) can be assigned to α-helical structure [51] and amide I band is due to inplane stretching of the C≡O bond, weakly coupled with C−N stretching and inplane N−H bending [50]. In the region of amide II band (1540-1545 cm\(^{-1}\)) the pattern and differences are similar to that of amide I, the peak intensity and position of bands are shifted with negligible contribution from O−H stretching but is also contributed by O−H stretching and both vibrations represents secondary structure of water soluble proteins [52]. The peak at 3290 cm\(^{-1}\) corresponds to the amide A that can generally be associated with N−H stretching of protein with negligible contribution from O−H stretching of intramolecular hydrogen bonding, since unbound water was removed from the system. Lastly in the amide B the peak at 3078 cm\(^{-1}\) is due to N−H stretching proteins of amide B proteins [37].

The sharp bands of amide I and amide II bands at 1650-1655 cm\(^{-1}\) and 1540-1545 cm\(^{-1}\) respectively are mainly used to indicate the relative concentration of the protein of biological tissues as these bands represents the amide groups of protein. The band at 1401 and 1452 arises mainly from symmetrical and asymmetrical CH\(^{2}\) bending modes, respectively of the methyl group of protein [53]. But a broad band is formed in this region (1401-1460 cm\(^{-1}\)) due to contributions from other bands by different other cellular components like nucleic acids and carbohydrates etc.. The intensity of these bands are higher in normal (Figure 11a) and NDEA+SIB-50 (Figure 11d) treated group than that of malignant tissue (Figure 11b). A significant variation in peak intensity in all the peaks and bands viz. 1260-1290, 1401, 1452, 1540-1545, 1650-1655 cm\(^{-1}\) are observed in the malignant tissue sample. The parameter differs greatly among all treatment group samples on the basis of protein components. Lipid form the major component of cell walls keeping biological media organized in their necessary compartments. In cancer, a very common stage of disease development is called metastasis, which is the complete separation of cancer affected cells, which invade other organs of the body. The main reason for irregular separation of the cells and their easy destruction relates to the quality of their lipid walls, so lipid also plays an important role [54]. The triglycerides contains lots of methyl, methylene and carbonyl, so the different of Fourier transform infrared spectroscopic spectra in normal and malignant tissue at those area were caused by the different contents of lipid substances in the tissue. In the frequency range 3400-2800 cm\(^{-1}\) known as fatty acid region with specific bands at 3300, 3010, 2958, 2925 and 2854 cm\(^{-1}\) corresponding to the stretching mode of OH and/or N−H, H==C==C−H, asymmetrical CH\(^{2}\) and both asymmetrical and symmetrical CH\(^{2}\) vibrations respectively changes were observed in this fatty acid region while using malignant samples. The band observed at 2920-2925 cm\(^{-1}\) and 2853-2855 cm\(^{-1}\) are due to asymmetric and symmetric stretching modes of the methylene chain in the membrane lipid respectively [51]. The weak band near 3010/3007 cm\(^{-1}\) in the normal control animal was assigned to the vibration of ==CH groups of oleic bands or unsaturated fatty acids which disappeared in NDEA induced animal tissue sample. A slight shift in the band at 1310 cm\(^{-1}\) was observed in malignant tissue as compared with normal tissue sample. The peak intensities of the band at 2853 cm\(^{-1}\) is higher in normal control group than that of malignant group sample. In malignant tissue sample the intensity of band at 2925 cm\(^{-1}\) was slightly enhanced but with a sharp peak. Taken together, it represents an increase in fatty acid content and/or acryl chain length. The band centered at 1738 cm\(^{-1}\) which was mainly assigned to >C≡O ester stretching vibration in phospholipids. An increase in intensity was observed indicating the accumulation of lipid in the NDEA induced group but band is submerged with the peak of amide band due to broadening of the amide bands and increased intensity. Moreover, the intense bands observed at 1466 cm\(^{-1}\) which are due to the CH\(^{2}\), asymmetrical bending vibration and CH\(^{2}\) symmetrical bending of the lipid. The band intensity was observed to be increased indicating increases in content of fatty acid chains. Further, the band at 1170 cm\(^{-1}\) and 1060 cm\(^{-1}\) which arises due in part of the ester C−O−C asymmetric and symmetric stretching vibrations in phospholipids and cholesterol esters respectively are increased for the malignant tissue and absent in the treatment group of animal tissues, which supports the biochemical finding of our experiment [49]. Major absorption in the spectra of lipid in the control tissue arises from C−C stretching (1117 cm\(^{-1}\)) and skeletal C−C stretching (1065 cm\(^{-1}\)) of lipids [53]. DNA and RNA also play important role in relation to protein structures as they carry information that determines protein structure. The main spectral features of nucleic acids in the infrared region are in plane double bond vibrations of the bases, and asymmetric and symmetric phosphate stretching located at 1750-1600 cm\(^{-1}\), 1230 cm\(^{-1}\) and 1100 cm\(^{-1}\), respectively. It is also noticeable that the intensity ratio of the signal located at 1055 cm\(^{-1}\) is the most significant difference between DNA and RNA [54]. In NDEA treated tissue sample, nucleic acids gives rise to a medium intensity peak at 1426 cm\(^{-1}\) and a band near 666 cm\(^{-1}\) which are respectively due to the rings breathing modes of DNA bases (alanine, guanine) and ring breathing modes of DNA bases (guanine and thymine) [55]. In malignant tissue the peak at 1220 cm\(^{-1}\) is greater than that of at 1240 cm\(^{-1}\) of the PO\(_{4}^{-}\) group in phosphodiester group of nucleic acids. In liver cancer many PO\(_{4}^{-}\) groups of nucleic acids are hydrogen bonded, in contrast to those of normal liver tissue. The band at 1082 cm\(^{-1}\) is mainly due to symmetrical phosphates (PO\(_{3}^{-}\)) stretching mode [47]. This band is found higher and stronger in malignant tissue than that in normal tissue. Changes were noted in treated groups and are noticeable which prove the bio-structural changes due to malignancy and are brought back to almost normal levels after the Silibinin treatment. Our work defines, SIB could be a useful and novel therapeutic drug to control HCC. Further preclinical and clinical trials are warranted to research the full potential of this important natural flavonoid analogue.

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We declare no conflict of interest.

Author contributions

SP Pattanayak and A Kumar performed the majority of the experiments.
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discussed the results and commented on the manuscript.

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