Energy-modulating vitamins – a new combinatorial therapy prevents cancer cachexia in rat mammary carcinoma

Selvanathan Saravana Perumal1, Palanivelu Shanthi2 and Panchanadham Sachdanandam1*

1Department of Medical Biochemistry and 2Department of Pathology, Dr AL Mudaliar Post Graduate Institute of Basic Medical Sciences, University of Madras, Taramani Campus, Chennai 600 113, India

(Received 29 October 2004 – Revised 23 January 2005 – Accepted 25 January 2005)

Mitochondria are the major intracellular organelles producing ATP molecules via the electron transport chain. Cancer cells have a deviant energy metabolism, and a high rate of glycolysis is related to a high degree of dedifferentiation and proliferation. The overall net ATP production is diminished with cancer, which ultimately leads to cancer cachexia. The present study was designed to investigate the altered energy metabolism in cancer cells and to enhance ATP production in the normal host cell metabolism by enhancing the activities of mitochondrial enzymes, using energy-modulating vitamins, and thus prevent cancer cachexia. Female Sprague–Dawley rats were selected for the experimental study. Mammary carcinoma was induced by the oral administration of 7,12-dimethylbenz[a]anthracene (25 mg/kg body weight), and treatment was started by the oral administration of the energy-modulating vitamins riboflavin (45 mg/kg body weight per d), niacin (100 mg/kg body weight per d) and coenzyme Q10 (40 mg/kg body weight per d) for 28 d. Mitochondria were isolated from the mammary gland and liver of all four groups, and the Krebs cycle and oxidative phosphorylation enzymes were assayed. In mammary carcinoma-bearing animals, the activities of the Krebs cycle and oxidative phosphorylation enzymes were significantly decreased. These activities were restored to a greater extent in animals treated with energy-modulating vitamins. From these experimental results, one may hypothesize that the combination therapy of energy-modulating vitamins could be of major therapeutic value in breast cancer.

Breast cancer: Energy-modulating vitamins: Mitochondrial enzymes: Cancer cachexia

Mitochondria are the major intracellular organelles producing ATP molecules via the electron transport chain (ETC), which is essential for major metabolic processes such as biosynthesis, active transport and DNA repair (Singh, 2000). Under normal aerobic conditions, the cells derive their energy primarily from oxidative phosphorylation via oxidation through the Krebs cycle. In cancerous conditions, the cancer cells use an anaerobic energy cycle, meaning that they do not depend upon O2 to sustain themselves (Pederson, 1978; Baggetto, 1992). This more primitive method of energy production found in cancer cells uses a fermentation cycle that requires more glucose than the cycle of a normal cell.

An enormous amount of the waste product lactic acid is produced during this kind of energy production (Schwartz, 1992). Because of the immense glucose needs of the cancer cell, the liver is stimulated by messages from the cancer cells to utilize an enzyme to convert the lactic acid waste back into more glucose (Baggetto, 1992; Waterhouse, 1974). Hence, the metabolism of carbohydrate must proceed via anaerobic glycolysis (Golshani-Hebroni & Bessman, 1997). Most of the energy demand is met by the production of ATP through glycolysis via substrate-level phosphorylation. This high glycolytic rate is important for rapidly proliferating cancer cells, not only as a major energy source, but also to provide such cells with precursors for nucleotide and lipid biosynthesis (Parry & Pedersen, 1983). In intact glycolytic tumour cells, only 10% of the pyruvate enters a truncated Krebs cycle (Parlo & Coleman, 1984). This results in a decline in the overall net ATP production in the host cells because of the downregulation of activity of the Krebs cycle enzymes, resulting in a loss of body weight that consequently leads to cancer cachexia (Tayek, 1992; Tisdale, 1997).

The ultimate goal of anti-neoplastic therapy is to cure cancer, thus allowing recovery. Unfortunately, non-specific cytotoxicity resulting from anti-neoplastic therapy remains a serious complication during cancer treatment, and the treatment of patients suffering from cancer cachexia becomes even more problematic. Body-wasting prior to chemotherapeutic treatment reduces expected patient survival (DeWys et al. 1980), and there is evidence that chemotherapy may directly contribute to the cachexia observed during cancer, further complicating the treatment of this disease and the patient’s subsequent recovery (Le Bricon et al. 1995).

One of the hallmarks of cancer treatment is the frequent ability to achieve remission that is inevitably followed by relapse. Nutritional therapy is a key component in the treatment of cancer cachexia and in actually helping to control malignant disease in some situations (Ogilvie & Vail, 1996). There is increasing evidence that a variety of micronutrients appear to have significant

Abbreviations: BSA, bovine serum albumin; CoQ10, coenzyme Q10; DMBA, 7,12-dimethyl benz[a]anthracene; EMV, energy-modulating vitamin; ETC, electron transport chain.

* Corresponding author: Dr P. Sachdanandam, fax +91 44 24926709, email psachdanandam2000@yahoo.co.in
anti-cancer activity (Bradlow & Sepkovic, 2002). Hence, current interest focuses on supplementation with energy-modulating vitamins (EMV; riboflavin, niacin and coenzyme Q10 (CoQ10)) for the more effective management of breast cancer. Riboflavin, in its active coenzymic forms such as FMN and FAD, participates in oxidation–reduction reactions in numerous metabolic pathways and in energy production via the respiratory chain (McCormick, 1999; Powers, 1999). Niacin and its co-factors, NAD and NADP, are essential for a variety of oxidation–reduction reactions that comprise tissue respiration (Cervantes-Laurean et al. 1999; Powers, 1999). The protective effect of nicotinamide may result from its action as a free-radical scavenger and its effects on inhibition of the enzyme poly ADP-ribose synthetase and on the repletion of NAD levels inside the cell (Jacobson & Jacobson, 1999; Powers, 1999). CoQ10 is an essential electron and protein carrier in ATP synthesis in the mitochondrial inner membrane. Besides its well-established role in energy production in aerobic organisms, CoQ10 is required for transmembrane electron transport that activates signals in the cell to stimulate cell growth (Ernster, 1977; Jolliet et al. 1998).

Our aim was to increase the amount of ATP produced via the ETC for normal host cell metabolism by enhancing the activities of the Krebs cycle and oxidative phosphorylation enzymes. For this, we made EMV available as co-factors in ETC intermediates, driving the reaction forward and preventing cancer cachexia in 7,12-dimethyl benz[a]anthracene (DMBA) induced mammary carcinoma-bearing rats.

Materials and methods

Animals

Female Sprague–Dawley albino rats between 50 and 55 d of age were obtained from the National Institute of Nutrition, Hyderabad, India. The animal room was well ventilated, and the animals had 12 ± 1 h day–night schedule throughout the experimental period. The animals were housed in large, spacious, hygienic cages and were given food and water ad libitum during the course of the experiments. The temperature was between 27°C and 37°C. The studies were performed with the approval of the Institutional Animal Ethical Committee, and the care of the animals and the facility were in accordance with institutional guidelines.

Experimental design

The rats were divided into four groups, each of which contained six animals. Normal healthy controls (group I) received a single dose of olive oil (1 ml) at the age of 8 weeks and then, after 3 months, 0.5 ml olive oil/d orally by gastric intubation for 28 d. Mammary carcinoma (group II) was induced with 25 mg/ml DMBA (Sigma Chemical Co., St Louis, MO, USA) in the experimental rats at 8 weeks of age, through gastric intubation (Sujatha et al. 1999). After 3 months, mammary carcinoma was confirmed by histological examination. Mammary carcinoma-induced rats were treated with the EMV riboflavin (45 mg/kg body weight per d), niacin (100 mg/kg body weight per d) dissolved in water and CoQ10 (40 mg/kg body weight per d) dissolved in olive oil, continued for 28 d daily via gastric intubation (group III). Drug control animals received the EMV in the same dosage as the animals in group III. The former animals were maintained on a normal diet and water for 3 months prior to drug ingestion (group IV).

The animal groups were formed at the same time. Other treatments were extended over time as mentioned in the text. At the termination of the study, i.e. after 3 months and 28 d, the animals from all four groups were fasted overnight and sacrificed by cervical decapitation. Mammary gland and liver were immediately excised from the animals and weighed. Carcinomatous tissues were dissected free of grossly necrotic and haemorrhagic areas, as well as of connective tissue or normal tissue. Portions weighing approximately 300 mg were cut, placed into plastic snap-cap vials and quickly frozen in liquid N2. The vials were placed in a deep-freezer at −72°C and stored until assayed. At the time of assay, small pieces of tissue were obtained for microscopic confirmation of the diagnosis; the remainder were homogenized and used for biochemical assays.

Estimation of energy-modulating vitamin status

Riboflavin status. The most sensitive method for determining riboflavin status is measurement of the activity of erythrocyte glutathione reductase, an enzyme requiring FAD as a coenzyme. Fasting venous blood samples were collected at the end of each week. The erythrocyte glutathione reductase activity coefficient was determined according to the method of Bayoumi & Rosalki (1976) and was calculated as the ratio of total stimulated activity in the presence of FAD in vitro to basal unstimulated activity.

Niacin status. Niacin levels in venous heparinized blood were determined according to the procedure developed by Shibata et al. (1987). This method measures free nicotinamide as well as nicotinamide derived from NAD and NADP. Blood samples were collected and stored at −20°C until analysis. Nicotinamide and the internal standard 1-methyl nicotinamide (Sigma Chemical Co.) were separated on a reversed-phase C-18S column (250 × 4.6 mm internal diameter; Phenomenex, Macclesfield, Cheshire, UK). The injection volume was 100 μl. The column was eluted isocratically at a flow rate of 1.00 ml/min at room temperature with 97% 10 mM KH2PO4, 2.5% acetonitrile and 0.5% tetrahydrofuran at pH 4.5. The eluent was monitored with an electrochemical detector (Dionex PS80 pump, and a Dionex UVD170S UV; Dionex (UK) Ltd, Macclesfield, Cheshire, UK).

Coenzyme Q10 status

CoQ10 plasma concentrations were determined by HPLC with UV detection, as derived from the paper by Morita & Folkers (1993). The sample (5–20 μl) was chromatographed on a reversed-phase C18 HPLC column (250 × 4.6 mm; Phenomenex) using a mobile phase consisting of 0.7% NaClO4 in ethanol–methanol–70% HClO4 (900:100:1, v/v/v) at a flow rate of 1.2 ml/min. The eluent was monitored with an electrochemical detector (Dionex PS80 pump, and a Dionex UVD170S UV; Dionex (UK) Ltd).

HPLC

HPLC was performed with an Ultracarb 5-μm C18 column (250 × 4.6 mm; Phenomenex) connected to a Dionex ASI-100 automated sample injector, a Dionex PS80 pump and a Dionex UVD170S UV detector (Dionex (UK) Ltd). Data were processed by Chromeleon software (Dionex (UK) Ltd).
Isolation of mitochondria from mammary gland

Mammary glands were removed and cooled in 0.3 M sucrose-EDTA, pH 7.4, on ice. All subsequent steps were carried out at 0–4°C. As much external connective tissue was removed as possible, and the tissues were blotted dry, weighed and minced very finely with small scissors. The tissue was then homogenized in a Potter-Elvehjem homogenizer (Sigma Chemical Co.) using two passes with a loose pestle and two passes with a tight pestle. The homogenate was strained through four layers of 10-gauge cheesecloth, and the filtrate was centrifuged at 900 g for 5 min. The supernatant was centrifuged at 11 500 g for 10 min to sediment the mitochondria. The mitochondrial pellet was washed twice in 5 ml sucrose-EDTA medium. At each step, the upper fatty layer was carefully removed by aspiration, and the walls of the tubes were carefully wiped clean. The final mitochondrial pellet was suspended at 10 mg mitochondrial protein/ml sucrose-EDTA/1% bovine serum albumin (BSA) medium. The purity of the mitochondria was assessed by estimating succinate dehydrogenase activity (Slater & Bonner, 1952). Mitochondrial protein was estimated by the method of Lowry et al. (1951).

Isolation of mitochondria from tumour mammary gland

Tumour cells were identified by the appearance of a red mass under the epithelial layer of the mammary pad. Tumour mitochondria were isolated by the modified method of Senior et al. (1975). A tumour portion was removed carefully from the mammary pad and placed immediately in 0.3 M sucrose-EDTA, pH 7.4, at 0°C. All subsequent steps were carried out at 0–4°C. Necrotic tissue was removed, and the tumour tissue was chopped into small pieces, weighed and washed three times with 40 ml chilled sucrose-EDTA solution. The tumour tissue was then homogenized directly in five volumes of 0.3 M sucrose-EDTA/1% BSA, pH 7.4, in a Potter-Elvehjem homogenizer. The homogenate was then treated in the same way as the homogenate from normal mammary gland (as above). BSA is necessary to obtain functional mitochondria from the tumour.

Isolation of mitochondria from liver

Animals (experimental and controls) were decapitated, and mitochondria were isolated from the liver of all four groups using differential centrifugation according to the method of Johnson & Lardy (1967). All operations were carried out at 0–4°C. A 10% (w/v) homogenate was prepared in 0.05 M Tris-HCl buffer, pH 7.4 containing 0.25 M sucrose. The homogenates were centrifuged at 600 g for 10 min, and the supernatants obtained were then centrifuged at 15 000 g for 5 min. Then the pellets were washed with 10 ml Tris-HCl (pH 7.8) containing 0.25 M sucrose and finally resuspended in the same buffer.

Estimation of mitochondrial Krebs cycle enzymes

Isocitrate dehydrogenase. The enzyme activity was assayed according to the method of King (1965), with slight modification. The reaction mixture containing 0.1 ml Tris-HCl, 0.2 ml trisodium iso-citrate, 0.3 ml manganese chloride, 0.2 ml mitochondrial suspension and 0.2 ml NADP (0.2 ml water for control) was added. After 60 min of incubation, 1 ml DNPH was added, followed by 0.5 ml EDTA, and the mixture was kept at room temperature for 20 min. Then 10 ml NaOH was added, and the colour developed was read at 390 nm. A standard containing α-ketoglutarate was run simultaneously.

α-Ketoglutarate dehydrogenase. The activity of α-ketoglutarate dehydrogenase was assayed by the method of Reed & Mukherjee (1969). To the reaction mixture containing 0.15 ml phosphate buffer, 0.1 ml each of thiamine pyrophosphate, MgSO₄, α-ketoglutarate and potassium ferrocyanide were added. The total volume was made up to 1.2 ml with water, and 0.2 ml mitochondrial suspension was added and incubated at 30°C for 20 min. Next, 1 ml TCA was added and centrifuged. Then, 0.2 ml mitochondrial suspension was added to the control after the addition of TCA. Volumes of 0.1 ml potassium ferrocyanide, 1 ml dianaph and 0.5 ml ferric ammonium sulphate-dianaph reagent were added to the supernatant and then incubated at 25°C for 20 min. The colour developed was measured at 540 nm. A standard containing potassium ferrocyanide was run simultaneously.

Succinate dehydrogenase. The activity of succinate dehydrogenase was assayed according to the method of Slater & Bonner (1952). The reaction mixture, containing 1 ml phosphate buffer, 0.1 ml EDTA, 0.1 ml BSA, 0.3 ml sodium succinate and 0.2 ml potassium ferrocyanide, was made up to 2.8 ml with water. The reaction was started by the addition of 0.2 ml mitochondrial suspension. The change in optical density was recorded at 15 s intervals for 5 min at 420 nm. A standard containing potassium ferrocyanide was run simultaneously.

Malate dehydrogenase. The enzyme activity was assayed by the method of Mehler et al. (1948). To 0.3 ml buffer, 0.1 ml NADH and 0.1 ml oxaloacetate were added, the total volume being made up to 2.9 ml with water. The reaction was started by adding 0.1 ml mitochondrial suspension. The change in optical density was measured at 350 nm in intervals of 15 s for 5 min using a spectrophotometer. A standard containing potassium ferrocyanide was run simultaneously.

Estimation of mitochondrial oxidative phosphorylation enzymes

NADH dehydrogenase. The activity of NADH dehydrogenase was determined according to the method of Minakami et al. (1962), with slight modification. The reaction mixture contained 1 ml phosphate buffer, 0.1 ml potassium ferricyanide, 0.1 ml NADH and 0.2 ml mitochondrial suspension. The total volume was made up to 3 ml with water. A control was also treated similarly without NADH. The change in optical density was measured at 420 nm as a function of time for 3 min at 15 s intervals.

Cytochrome c oxidase. Cytochrome c oxidase activity was assayed according to the method of Wharton & Tzagoloff (1967), with slight modification. The reaction mixture consisted of 0.1 ml phosphate buffer, 0.07 ml ferrocychrome c and 0.83 ml water. The blank was oxidized with 0.01 ml potassium ferricyanide. The reaction was then initiated by the addition of 0.01 ml mitochondrial suspension. The decrease in absorbency was measured at 550 nm every 15 min.

Estimation of cellular constituents

Extraction of nucleic acids. The nucleic acids were extracted by the method of Schneider (1957). Known amount of tissues were homogenized in 5.0 ml ice-cold distilled water using the Potter-Elvehjem homogenizer with a Teflon pestle. A volume of
5.0 ml 5 % TCA was added to the homogenate, and this was kept in ice for 30 min to allow the complete precipitation of proteins and nucleic acids. The mixture was centrifuged and the precipitate obtained washed three times with ice-cold 10 % TCA. This was then treated with 95 % ethanol to remove lipids. The final precipitate was heated at 90°C for 15 min with occasional shaking, which facilitated the quantitative separation of nucleic acids from protein. The supernatant after centrifugation was used for the estimation of DNA and RNA.

DNA. DNA was estimated by the method of Burton (1956). A known volume of the nucleic acid extract was made up to 3·0 ml with 1 m perchloric acid. This was mixed with 2·0 ml diphenylamine reagent. A reagent blank and standards were also carried out concurrently. This was kept in a boiling water bath for 10 min, and the blue colour developed was read at 640 nm in a photochem colorimeter.

RNA. RNA was estimated by the method of Rawal et al. (1977). Aliquots of nucleic acid extracts were made up to 2·0 ml with 5 % TCA. To this, 3·0 ml orcinol-ferric chloride reagent was added and mixed well. The tubes were heated in a boiling water bath for 20 min. Reagent blank and standards were also treated in the same way. The tubes were cooled, and the colour developed was measured at 640 nm using a photochem colorimeter.

Statistical analysis

Values are expressed as means with their standard deviations for six rats in each group, and the significance of the differences between mean values was determined by one-way ANOVA followed by the Student’s Newman Keuls for multiple comparisons using the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA) computer package. Values of \( P<0.05 \) were considered to be significant.

Results

Fig. 1 shows the body weight changes of the control and experimental rats. A growth curve was drawn between the initial and the final body weight. Initially, there was no significant change in the body weight of the control and experimental rats. Finally, however, there was a sharp drop in the body weight of the mammary carcinoma-bearing rats when compared with normal control rats. EMV-treated rats showed a gradual increase in their body weight when compared with untreated rats. Drug control rats showed an increase in their body weight but not to significant levels when compared with normal rats.

Table 1 depicts the EMV status in the blood of control and experimental rats. EMV deficiencies were observed in the mammary carcinoma-bearing rats. On combinatorial therapy, successful improvement in the status of riboflavin, niacin and CoQ_{10} (EMV) were observed.

The activities of mitochondrial Krebs cycle enzymes (isocitrate dehydrogenase, \( \alpha \)-ketoglutarate dehydrogenase, succinate dehydrogenase and malate dehydrogenase) and oxidative phosphorylation enzymes (NADH dehydrogenase and cytochrome c oxidase) in the mammary gland and liver mitochondria of control and experimental rats are depicted in Tables 2, 3 and 4. The activities of the Krebs cycle and oxidative phosphorylation enzymes are significantly \( (P<0.05) \) reduced in mammary carcinoma-bearing animals when compared with control rats. The activities of these enzymes were significantly restored to nearly normal on treatment with EMV (group III animals). In drug control (group IV) rats, there was a slight increase in the activities of Krebs cycle and oxidative phosphorylation enzymes, but not to significant levels when compared with normal (group I) rats.

Table 5 represents the levels of cellular constituents (DNA and RNA) in the mammary gland and liver of the control and experimental rats. A significant \( (P<0.05) \) increase in the levels of DNA and RNA observed in mammary carcinoma-bearing rats (group II) was returned to nearly control levels upon EMV combinatorial therapy treatment (group III).

Discussion

The goal of the experiment was to focus on cancer cachexia and to move toward a consensus statement on the role of EMV in prevention and treatment of breast cancer. The biochemical changes in the activities of various enzymes reflect the extent of metabolic alterations caused by the tumour.

In mammary carcinoma-bearing rats, there was a sharp decline in body weight. Weight loss is one of the most frequent adverse systemic effects of malignancy (DeWys et al. 1980). A decline in food intake relative to energy expenditure is the fundamental physiological derangement leading to cancer-associated weight loss (Pain et al. 1984; Mulligan & Tisdale, 1991). Combinatorial therapy-extended rats showed a significant increase in their body weight when compared with the untreated tumour-induced
animals. This positive modulation could be attributed to the presence of co-factors in the combinatorial therapy that participate in the ETC to enhance ATP production, thereby improving body weight in the host tissue to prevent cancer cachexia.

Cancer patients are frequently malnourished, and micronutrient deficiency is an important and understudied problem (Inculet et al. 1987, Shike & Brennan, 1993). In our study, EMV status was found to be significantly decreased in carcinoma-bearing rats. During treatment with EMV, the levels of EMV were found to be normalized. Several studies indicate that supplementation with riboflavin inhibits tumour growth in experimental animals and possibly in man, but the precise mechanisms involved have not been elucidated (Kensler et al. 1941; Wahrendorf et al. 1988). Niacin is one of the nutrients that appears to be deficient in many cancers (Inculet et al. 1987) and in chemotherapy patients (Dreizen et al. 1990). Biochemically and nutritionally, cancer patients would have an impaired biosynthesis of CoQ 10, and the subsequent deficiency of CoQ 10 could be a dominant biochemical dysfunction. It is therefore expected that many cancer patients will have abnormally low levels of CoQ 10 in their blood and tissue (Folkers et al. 1993, 1997). Exogenous CoQ10 administration via the nutrition may help to increase the

Table 1. Effect of energy-modulating vitamins (EMV) on the status of riboflavin, niacin and coenzyme (CoQ10) in the blood of control and experimental rats
(Values expressed as means with their standard deviations for six rats)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Group I (control)</th>
<th>Group II (DMBA induced)</th>
<th>Group III (DMBA induced + EMV)</th>
<th>Group IV (control + EMV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riboflavin (EGRAC)</td>
<td>1.09 ± 0.089</td>
<td>0.71 ± 0.056**</td>
<td>0.92 ± 0.081*</td>
<td>1.12 ± 0.094</td>
</tr>
<tr>
<td>Niacin (μg/ml)</td>
<td>42.6 ± 3.29</td>
<td>27.4 ± 2.11**</td>
<td>36.1 ± 2.98*</td>
<td>43.7 ± 3.62</td>
</tr>
<tr>
<td>CoQ10 (μg/ml)</td>
<td>21.9 ± 2.38</td>
<td>14.2 ± 1.27**</td>
<td>19.1 ± 1.69*</td>
<td>23.1 ± 2.19</td>
</tr>
</tbody>
</table>

DMBA, 7,12-dimethyl benz[a]anthracene; EGRAC, erythrocyte glutathione reductase activation coefficient. Comparisons were made between *groups I and II, **groups II and III, and *groups I and IV.

* P< 0.05.

Table 2. Effect of energy-modulating vitamins (EMV) on the activities of Krebs cycle enzymes in the mammary gland mitochondria of control and experimental rats
(Values expressed as means with their standard deviations for six rats)

<table>
<thead>
<tr>
<th>Parameters (Units/mg protein)</th>
<th>Group I (control)</th>
<th>Group II (DMBA induced)</th>
<th>Group III (DMBA induced + EMV)</th>
<th>Group IV (Control + EMV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isocitrate dehydrogenase†</td>
<td>531.9 ± 39.62</td>
<td>389.55 ± 21.79**</td>
<td>515.48 ± 32.37*</td>
<td>540.07 ± 34.59</td>
</tr>
<tr>
<td>α-Ketoglutarate dehydrogenase‡</td>
<td>174.06 ± 11.98</td>
<td>99.74 ± 7.91*</td>
<td>140.66 ± 10.71*</td>
<td>179.19 ± 12.01</td>
</tr>
<tr>
<td>Succinate dehydrogenase§</td>
<td>236.11 ± 19.15</td>
<td>159.32 ± 11.72**</td>
<td>210.65 ± 16.92*</td>
<td>241.55 ± 19.02</td>
</tr>
<tr>
<td>Malate dehydrogenase†</td>
<td>3572 ± 96.12</td>
<td>2378 ± 84.56**</td>
<td>3096 ± 99.07*</td>
<td>3609 ± 89.92</td>
</tr>
</tbody>
</table>

DMBA, 7,12-dimethyl benz[a]anthracene. Comparisons were made between *groups I and II, **groups II and III, and *groups I and IV.

† nmol α-ketoglutarate dehydrogenase liberated/min/mg mitochondrial protein; ‡ μmol ferrocyanide liberated/min/mg mitochondrial protein; § μmol succinate oxidized/min/mg mitochondrial protein; k nmol NADH oxidized/min/mg mitochondrial protein.

* P< 0.05.

Table 3. Effect of energy-modulating vitamins (EMV) on the activities of Krebs cycle enzymes in the liver mitochondria of control and experimental rats
(Values expressed as means with their standard deviations for six rats)

<table>
<thead>
<tr>
<th>Parameters (Units/mg protein)</th>
<th>Group I (control)</th>
<th>Group II (DMBA induced)</th>
<th>Group III (DMBA induced + EMV)</th>
<th>Group IV (Control + EMV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isocitrate dehydrogenase†</td>
<td>726.88 ± 42.13</td>
<td>484.17 ± 35.11**</td>
<td>689.59 ± 41.21**</td>
<td>731.59 ± 48.20</td>
</tr>
<tr>
<td>α-Ketoglutarate dehydrogenase‡</td>
<td>152.72 ± 12.01</td>
<td>96.65 ± 68.44**</td>
<td>138.34 ± 10.22*</td>
<td>161.06 ± 12.31</td>
</tr>
<tr>
<td>Succinate dehydrogenase§</td>
<td>78.44 ± 8.78</td>
<td>42.14 ± 4.57**</td>
<td>69.42 ± 5.09*</td>
<td>82.37 ± 9.00</td>
</tr>
<tr>
<td>Malate dehydrogenase†</td>
<td>277.88 ± 21.58</td>
<td>178.51 ± 12.27**</td>
<td>259.22 ± 22.41*</td>
<td>311.47 ± 27.64</td>
</tr>
</tbody>
</table>

DMBA, 7,12-dimethyl benz[a]anthracene. Comparisons were made between *groups I and II, **groups II and III, and *groups I and IV.

* P< 0.05.
protective effect of CoQ10 in breast tissue, especially in women in the high-risk group (Jolliet et al. 1998). Furthermore, CoQ10 has been shown to extend the lifespan of laboratory animals (Sarter, 2000). Our findings are also consistent with the above reports.

Most cancers probably start with an interruption of the Krebs cycle that arrests aerobic metabolism and forces the cell to revert back to anaerobic metabolism. In the present study, mammary carcinoma-induced rats showed a significant reduction in the activities of the Krebs cycle enzymes. Reductions in the activities of Krebs cycle enzymes prove the defect in the aerobic oxidation of pyruvate that might cause the low production of ATP molecules; this observation tallies with that by Hennipman et al. (1988).

Isocitrate dehydrogenase requires NAD and NADP as electron acceptors in the citric acid cycle to produce ATP molecules via oxidative phosphorylation (Damle et al. 1971). α-Ketoglutarate dehydrogenase requires five coenzymes for its activity: thiamine pyrophosphate, lipoic acid, FAD, coenzyme A and NAD (Greenhouse & Lehninger, 1977). In the cancerous condition, the supply of these co-factors is inadequate. On EMV supplementation, these enzyme activities were significantly elevated; which could be due to the availability of co-factors FAD, NAD and NADP from riboflavin and niacin in the treatment regimen.

Succinate dehydrogenase is an integral part of the inner mitochondrial membrane and is directly linked to the ETC. The oxidation of succinate to produce FADH2 molecules that directly transfer the electrons to ubiquinone results in the generation of two ATP molecules (Tchen & van Milligan, 1960). Malate dehydrogenase is an oxidoreductase and a highly stereospecific NAD-requiring enzyme that specifically catalyses an important reaction in the Krebs cycle, which is important in cellular metabolism and energy production (Dietzen & Davis, 1993). When cancer was present, the activities of these enzymes were found to be reduced. On EMV treatment, these enzyme activities were significantly elevated, which could be mainly due to the supply of NAD through niacin.

The enzymes located in the mitochondria catalyse the oxidation of a number of substrates via the Krebs cycle, yielding reducing equivalents. These reducing equivalents are channelled through the respiratory chain for the synthesis of ATP, the energy currency of the cell produced by oxidative phosphorylation, which provides the energy needed for many cellular functions. The processes leading to the Krebs cycle and the Krebs cycle itself proceed in a way that produces two very simple forms of proton donor, NADH and FADH2. These then react with O2 to yield electrons in the inner membrane, and these in turn carry out the work of oxidative phosphorylation with the help of CoQ.

### Table 4. Effect of energy-modulating vitamins (EMV) on the activities of oxidative phosphorylation enzymes in the mammary gland and liver mitochondria of control and experimental rats

<table>
<thead>
<tr>
<th>Parameters (Units/mg protein)</th>
<th>Group I (control)</th>
<th>Group II (DMBA induced)</th>
<th>Group III (DMBA induced + EMV)</th>
<th>Group IV (control + EMV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Mammary gland</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NADH dehydrogenase†</td>
<td>15·06</td>
<td>0·92</td>
<td>9·33</td>
<td>0·63**</td>
</tr>
<tr>
<td>Cytochrome c oxidase‡</td>
<td>3·64</td>
<td>0·14</td>
<td>1·97</td>
<td>0·10**</td>
</tr>
<tr>
<td>Liver</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NADH dehydrogenase†</td>
<td>27·59</td>
<td>1·72</td>
<td>14·03</td>
<td>1·01**</td>
</tr>
<tr>
<td>Cytochrome c oxidase‡</td>
<td>7·02</td>
<td>0·34</td>
<td>3·22</td>
<td>0·30**</td>
</tr>
</tbody>
</table>

DMBA, 7,12-dimethyl benz[a]anthracene.
† μmol NADH oxidized/min/mg mitochondrial protein; ‡ optical density × 10−2/min/mg mitochondrial protein.
Comparisons were made between a groups I and II, b groups II and III, and c groups I and IV.
* P< 0.05.

### Table 5. Effect of energy-modulating vitamins (EMV) on the levels of cellular constituents in the mammary gland and liver of control and experimental rats

<table>
<thead>
<tr>
<th>Parameters (mg/g wet tissue)</th>
<th>Group I (control)</th>
<th>Group II (DMBA induced)</th>
<th>Group III (DMBA induced + EMV)</th>
<th>Group IV (control + EMV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Mammary gland</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNA</td>
<td>3·92</td>
<td>0·21</td>
<td>5·16</td>
<td>0·60**</td>
</tr>
<tr>
<td>RNA</td>
<td>1·82</td>
<td>0·11</td>
<td>2·64</td>
<td>0·19**</td>
</tr>
<tr>
<td>Liver</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNA</td>
<td>5·08</td>
<td>0·39</td>
<td>6·14</td>
<td>0·42**</td>
</tr>
<tr>
<td>RNA</td>
<td>2·17</td>
<td>0·28</td>
<td>3·29</td>
<td>0·31**</td>
</tr>
</tbody>
</table>

DMBA, 7,12-dimethyl benz[a]anthracene;
Comparisons were made between a groups I and II, b groups II and III, and c groups I and IV.
* P< 0.05.
and the cytochromes (Williamson & Copper, 1980; Tzagoloff, 1982). DMBA-treated animals showed a decline in their level of ATP production that might be due to the inhibition of Krebs cycle and oxidative phosphorylation enzymes. The inhibition of these enzymes may affect mitochondrial substrate oxidation, resulting in a reduced oxidation of substrates, a reduced rate of transfer of reducing equivalents to molecular O₂ and the depletion of energy production.

NADH dehydrogenase, a flavin-linked dehydrogenase, constitutes complex I of the ETC, which passes electrons from NADH to CoQ. Cytochrome c oxidase (complex IV) donates electrons directly to molecular O₂. The significant decline in the activities of these key oxidative phosphorylation enzymes in cancer would result in the inhibition of electron flow from NADH to O₂. The decrease in activity of NADH dehydrogenase may be due to a depletion of reducing equivalents such as NADH and NADPH (Pederson, 1978; Baggetto, 1993).

The relative concentrations of NAD and NADH are important in regulating energy metabolism. When the NAD:NADH ratio is high, the rate of Krebs cycle increases. However, the activity of this cycle is slowed down when the NAD:NADH ratio is low because of an insufficient NAD concentration for normal enzymatic function and the reoxidation of NADH coupled to ATP formation. Intracellular levels of the NAD can be effectively increased by the addition of the NAD precursors nicotinic acid and nicotineamide from niacin through EMV supplementation. In addition, CoQ₁₀ enhances the activity of ETC complexes and produces a large amount of ATP because it enhances the activity of ubiquinone complex, which serves as a highly mobile electron carrier between the flavoproteins and cytochromes of the ETC (Ernster, 1977).

The major mechanism involved in cancer cells reverting back to aerobic metabolism, and thus back to normal cells, has three basic stages: enhancement of the Krebs cycle, of the respiratory chain enzyme activities and of O₂ transport to the cells. On EMV supplementation, these enzyme activities were significantly increased, which clearly indicates the reversal of cancer cells to normal ones. This effect could be due to the supply of co-factors (FMN, FAD, NAD, NADP and CoQ) by EMV, which participate in oxidation–reduction reactions in numerous metabolic pathways and enhance the activity of the Krebs cycle and respiratory chain enzymes (Koroshetz et al. 1997; Powers, 1999). One would expect the anaerobic metabolism to cause the breast cancer owing to the lack of CoQ₁₀. When the latter was replenished, aerobic metabolism would restart and the cancer cells revert to normal cells (Lockwood et al. 1994). Although glycolysis provides some of the ATP needed by the cell, the major generation of ATP occurs during oxidative phosphorylation in the mitochondria of mammalian cells, as electrons are transferred from NADH, FADH to O₂ by a series of electron-carriers. NADH is converted to NAD with the concomitant conversion of ADP to ATP (Coper & Neubert, 1964). In addition to their central role in energy metabolism, EMV supply the necessary co-factors that function as coenzymes in critical biochemical reactions facilitating ATP production. EMV play a diverse and critical role in many metabolic pathways and are thus vital in supplying energy and maintaining the integrity of the surrounding normal cells, preventing cancer cachexia.

DNA damage is a sensitive indicator and a potential biological target for many initiators of carcinogenesis (Shang Zhang et al. 1991). Persistent basal DNA damage may reflect higher exposure to carcinogens and deficient DNA repair (Rajeswari et al. 2000). Higher levels of DNA adduct and oxidative base lesions have been reported in the normal adjacent and tumour tissues of breast cancer patients (Li et al. 1999). These findings suggest that an accumulation of DNA damage may contribute to breast carcinogenesis. The binding of DMBA to cellular DNA indicates the DMBA–DNA interactions and is responsible for initiation of carcinogenic processes. Hence, the determination of DNA content plays an important role in tumorigenesis (Lin et al. 2001). RNA levels were also found to be increased in the cancerous condition; as DNA and RNA are directly related to each other, the abnormal increased content of DNA may lead to an increased transcription that leads to the increased RNA content of tumour cells. Palani et al. (1999) have reported an increased amount of DNA and RNA in fibrosarcoma-bearing rats. Our findings are also in line with the above reports.

With EMV combinatorial therapy, the levels of DNA and RNA were found to be nearly normal, which hints at the anti-tumour property of the drugs that inhibits the progression of tumour growth, as the size of the tumour is well correlated with the tumour’s DNA content in malignant conditions. The inhibitory activity on tumour growth may be due to the multiple co-factors present in the drug. Pangrekar et al. (1993) reported that riboflavin could reduce carcinogen–DNA interaction. Niacin (co-factor NAD) is important in modulating ADP ribose polymer metabolism, cyclic ADP ribose synthesis and stress response proteins, such as p53, following DNA damage. Understanding how NAD metabolism is regulated in human subjects has important implications for developing both prevention and treatment strategies against carcinogenesis (Jacobson, 1993; Jacobson & Jacobson, 1993; Jacobson et al. 1999). Folkers et al. (1993) reported several case histories of cancer patients with prolonged survival on therapy with CoQ₁₀. More recent findings substantiate the view that supplementation with CoQ₁₀ can cause a complete regression of tumours in advanced breast cancer, including one patient with numerous metastases to the liver (Lockwood et al. 1994, 1995; Diamond et al. 1997).

In conclusion, the above findings indicate that net ATP production was diminished in tumour-bearing animals, which ultimately leads to cancer cachexia. Treatment with EMV enhanced the activities of the Krebs cycle enzymes, and oxidative phosphorylation as a consequence enhanced ATP production. This increased amount of ATP was utilized by normal cells for their routine metabolism, reducing the cancer cachexia. In addition, the anti-carcinogenic and anti-proliferative effects of EMV suppress tumour cell proliferation. This suggests that the new combination of EMV could be of major therapeutic value in breast cancer management.

Acknowledgements

Financial assistance from the University Grant Commission (UGC) Major Research Project, New Delhi, India is gratefully acknowledged.

References


