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Treatment of Albino Rats with Oltipraz (4-MethyL-5-PyrazinyL-3H-1,2-Dithiole-3-Thione Protects against Doxorubicin-Induced Cardiotoxicity

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Abstract

Doxorubicin is an anthracycline group of antibiotics that is frequently used in the treatment of various human neoplasia clinically. However, its adverse effect on the human heart is of major concern and limits its full clinical utilization. The present study was undertaken to alleviate the doxorubicin-induced myocardial toxicity by oltipraz an Nrf-2 inducer in albino rats. The albino rats were orally administered with 10 mg/kg body weight of oltipraz daily for three days before treatment with 15 mg/kg body weight of doxorubicin. The doxorubicin-induced myocardial stress indicated by an increase in the CK-MB activity, and lipid peroxidation accompanied by a reduction in the glutathione, glutathione-s-transferase, catalase and superoxide dismutase in the rat heart. The administration of 10 mg/kg oltipraz for three days before doxorubicin treatment reduced the CK-MB activity and lipid peroxidation significantly followed by the significant elevation in the activities of glutathione-s-transferase, catalase and superoxide dismutase and glutathione in the rat heart. Our study demonstrates that oltipraz an Nrf-2 inducer reduced doxorubicin-induced myocardial stress in the rats.

Keywords

Rat; Myocardial stress; Oltipraz; CK-MB; Glutathione-s-transferase; Lipid peroxidation

Introduction

Anthracyclines rank among the most effective anti-cancer drugs ever developed. The first anthracyclines were isolated from the pigment-producing *Streptomyces peucetius* in the early 1960s and were named doxorubicin and daunorubicin [1]. The anthracyclines (including doxorubicin, daunomycin, epirubicin, and idarubicin) are one of the most clinically useful groups of anticancer chemotherapeutics. These drugs are routinely employed in combination regimes with other groups of drugs in which each drug generally exhibits a different mechanism of action to increase tumor cell kill and minimize chemotherapy-induced resistance [2]. Doxorubicin is clinically used in the treatment of breast cancer, bladder cancer, childhood solid tumors, lymphomas, myeloblastic leukemia, neuroblastoma, ovarian cancer, small cell lung cancer, soft tissue sarcomas and HIV-associated Kaposi's sarcoma [3-9].

The cancer patients undergoing doxorubicin therapy develop life-threatening myocardial toxicity after long-term survival and this limits the clinical application of doxorubicin [8,10]. The metabolism of doxorubicin leads to the formation of doxorubicin deoxyaglycone, doxorubicin hydroxyaglycone, doxorubicinol, doxorubicinol aglycone, and doxorubicin-semiquinone, which trigger cardiotoxicity in the patients undergoing doxorubicin therapy [3,11-13]. The doxorubicin uses multiple mechanisms to induce cardiotoxicity however production of reactive oxygen species and subsequent lipid peroxidation, calcium dysregulation, and intervention in energy transfer lead to heart failure [14]. The doxorubicin produces free radicals in the cell mitochondria and their exacerbation in the presence of iron is the most widely accepted mechanism of doxorubicin-induced cardiomyopathies [15,16]. The ROS interact with mitochondrial DNA, proteins and lipid and disrupt the mitochondrial function of cardiomyocytes leading to toxic effects. In addition, the scarcity of an antioxidant system in the heart also adds to the toxicity of doxorubicin [17]. Doxorubicin not only adversely affects the heart but it produces toxic effects on the brain, bone marrow, lung, liver, kidneys, and ovaries [18,19].

Oltipraz is a dithiol derivate (4-Methyl-5-pyrazinyl-3H-1,2-dithiole-3-thione) and a potent anthelmintic drug that was originally used to treat intestinal worms. Clinical trials in different countries have proven its effectiveness against *Schistosoma mansoni* and *Schistosoma hematobium* [20-22]. Oltipraz was later found to prevent, cancers of blood, bladder, colon, liver, kidney, lung, stomach, pancreas, breast, skin and trachea in rodents. The phase 1 and phase II clinical trials have been also conducted for cancer chemoprevention, where volunteers administered with a single oral dose of 123, 250, 500 or 1000 mg/m^2 were well tolerated whereas administration of high doses of oltipraz for 8 weeks showed adverse toxic effects in the form of tingling, numbness, and pain in the fingertips and extremities [21,23]. The oltipraz has been found to be active against HIV and hepatitis B viruses [24,25]. It has been found to protect against hepatotoxicity induced by acetaminophen, carbon tetrachloride, and aflatoxin B

[20,26,27]. Oltipraz has been found to protect against liver cirrhosis and fibrosis in humans and rats and hepatocytes in vitro. Oltipraz also protected against the high glucose-induced oxidative stress in cultured rat RSC96 cells [32]. Oltipraz protected rats against alloxan and streptozotocin-induced diabetes mellitus. The dexrazoxane has been used as a cardioprotective agent against the anthracyclines including the doxorubicin-induced cardiotoxicity clinically for more than the last 25 years however, its adverse effects such as neutropenia, nausea, alopecia, mucositis, and vomiting, increase in hepatic transaminases and increased urinary excretion of iron and zinc are of major clinical concern [34]. This indicates the need to search for newer paradigms that can protect against the doxorubicin-induced cardiotoxicity with minimum/no adverse side effects. Therefore, the present study was undertaken to study the cardioprotective potential of oltipraz in rats treated with doxorubicin.

Materials and Methods

Chemicals

Doxorubicin (DOX) was procured from Biochem Pharmaceutical Industries, Mumbai, India. Ethylenediaminetetraacetic acid (EDTA), phenazine methosulphate (PMS), nitroblue tetrazolium (NBT), nicotinamide adenine dinucleotide reduced (NADH), glutathione reductase, thiobarbituric acid (TBA), trichloroacetic acid (TCA), 5,5-dithio2-nitrobenzoic acid (DTNB), glutathione reduced (GSH), 1-chloro,2,4-dinitrobenzene (CDNB), *tert*-butyl-hydroperoxide tetraethoxypropane were purchased from Sigma Aldrich Chemical Co. Bangalore, India. Potassium dihydrogen phosphate, disodium hydrogen phosphate, hydrogen peroxide, dipotassium hydrogen phosphate and other routine chemicals were supplied by Merck India Limited, Mumbai, India. Oltipraz (OLT) was a kind gift from Canopus Biopharma. Baybush, Straffan, Co. Kildare, Ireland.

Animal care and handling

Six to eight weeks old albino rats weighing 45-60 grams were procured locally and acclimatized to laboratory conditions before designing the experiment. The rats were cared for and handled following the recommendations of the World Health Organization, Geneva, Switzerland, INSA (Indian National Science Academy, New Delhi, India), and the NIH, USA Guide for the Care of Laboratory Animals, 2011. The animals were kept in sterilized polypropylene cages bedded with sterile paddy husk (procured locally) and had free access to standard rodent diet and water. The Animal Ethics Committee of the Mizoram University, Aizawl, India approved the study.

Preparation of oltipraz

The oltipraz is sparingly soluble in water therefore it was dissolved in 0.5% carboxymethylcellulose in sterile physiological saline (SPS), whereas doxorubicin was dissolved in sterile distilled water.

Experimental

The cardioprotective effect of oltipraz was studied by dividing the animals into the following groups according to the treatment:

- **Sterile physiological saline**: The animals were administered with 0.5% carboxymethylcellulose orally in sterile physiological saline.
- **Oltipraz**: Animals of this group were orally administered once daily with 10 mg/kg body weight oltipraz consecutively for three days.
- **Doxorubicin**: Animals of this group were administered with a single dose of 15 mg/kg body weight of doxorubicin intraperitoneally.
- **Oltipraz + Doxorubicin**: Animals of this group were orally administered with oltipraz 10 mg/kg body weight once daily consecutively for three days. One hour after the last administration of oltipraz, 15 mg/kg body weight of doxorubicin was administered intraperitoneally.

Thirty hours after the administration of doxorubicin, the animals from all the groups were killed by cervical dislocation. The animals were dissected and blood was collected by cardiac puncture and allowed to stand on ice for 30 minutes and the serum was collected for the estimation of creatine kinase isoenzyme (CK-MB). Immediately after blood collection, the hearts were perfused with cold phosphate buffered saline (PBS) blot dried and homogenized in PBS for the estimation of antioxidants and lipid peroxidation (LOO).

CK-MB

The activity of CK-MB was measured in the serum of rats using a commercially available kit (Coral Clinical Systems, Goa, India) according to the manufacturer's protocol. The absorbance of the samples was read at 340 nm using an autoanalyzer.

Total proteins

The protein contents were determined using the modified method of Lowry.

Glutathione

The measurement of glutathione concentration was carried out by the modified method [35], where the proteins were precipitated by 25% TCA, and centrifuged and the supernatant was mixed with 0.2 M sodium phosphate buffer (pH 8.0) and 0.06 mM DTNB. The mixture was allowed to stand for 10 minutes at room temperature and the absorbance of the sample/s was read against the blank at 412 nm in a UV-VIS double beam spectrophotometer and the GSH concentration has been calculated from the standard curve.

Glutathione-S-transferase

Glutathione-S-transferase (GST) was determined by mixing the tissue homogenate with 0.1 M potassium phosphate buffer, 1 mM EDTA, glutathione reductase, 10 mM GSH, and 12 mM *tert*-butyl-hydroperoxide and left for 10 min at 37°C in a water bath [36]. The absorbance was read against the blank at 340 nm using a double beam UV-VIS spectrophotometer.

Catalase

The catalase activity was assayed by the catalytic reduction of hydrogen peroxide as a measure of

catalase activity as described earlier [37] where hydrogen peroxide was added to the sample, mixed and incubated at 37°C in a water bath. The decomposition of hydrogen peroxide was monitored every 0, 5, 10 and 30 seconds by recording the absorbance against the blank at 240 nm using a UV-VIS double beam spectrophotometer.

Superoxide dismutase

The SOD activity was estimated using nitroblue tetrazolium (NBT) [38]. The tissue homogenate sample was mixed with NBT, phenazine methosulphate and NADH. The reaction was stopped by adding acetic acid. The colour formed at the end of the reaction was extracted into n-butanol and measured at 560 nm against the blank using a UV-VIS double beam spectrophotometer.

Lipid peroxidation (LOO)

The lipid peroxidation was estimated according to the modified method [39] where the tissue homogenate was mixed with trichloroacetic acid (15%), thiobarbituric acid (0.375%), and butylated hydroxytoluene (0.01%) in 0.25 N HCl and the mixture was incubated at 95°C for 25 min. The mixture was brought to room temperature, centrifuged at 8,000 g, the supernatant collected and the absorbance was recorded at 535 nm against the blank using a UV-VIS double beam spectrophotometer. The lipid peroxidation has been determined against a standard curve prepared with tetraethoxypropane. For all biochemical estimations, duplicate samples were used from each animal for various estimations listed above and a minimum of five animals was used for each concurrent group.

Statistical Analysis

The significance between the treatments was determined using the Student's 't' test and one-way ANOVA with the application of Tukey's posthoc test for multiple comparisons. A p value of <0.05 was considered statistically significant. Origin Pro 8.5 (Origin Lab Corporation, Northampton, MA, USA) was used for statistical analyses.

Results

The results are represented as mean ±standard error of the mean in (Table 1) and (Figure 1-6).

Creatinine Kinase-MB

The creatinine kinase is an indicator of cardiotoxicity. The CK-MB activity in the non-drug treated rat heart was 39.61±3.66 IU. Oltipraz alone treatment non-significantly reduced the CK-MB activity in the serum to 28.30±1.67 IU (Table 1). Doxorubicin alone treatment significantly increased CK-MB activity (102.18±5.90 IU) when compared to spontaneous level by 2.6 folds (Table 1, Figure 1). Oltipraz administration before doxorubicin treatment significantly reduced the CK-MB activity (67.93±5.92 IU), by 1.5 folds (Table 1, Figure 1).

Treatment	Mean± Standard error of the mean					
	CK-MB (IU/mg protein)	Glutathione (nmol/mg protein)	Glutathione-S-transferase (nmol/mg protein)	Catalase (U/mg protein)	Superoxide dismutase (nmol/mg protein)	Lipid peroxidation (nmol/mg protein)
Sterile Saline	39.61±3.66	20.85±0.25	21.55±2.35	0.25±0.02	13.62±1.23	2.33±0.33
Oltipraz	28.30±1.67	19.00±0.5	19.00±2.121	0.24±0.038	14.27±1.61	2.75±0.05
Doxorubicin	102.17±5.90*	3.43±0.57*	2.96±0.05*	0.10±0.001*	2.059±0.84*	11.33±1.66*
Oltipraz + Doxorubicin	67.93±5.92$^{\#}$	16.33±0.68$^{\#}$	16.33±0.68$^{\#}$	0.20±0.010$^{@}$	12.96±2.13$^{\#}$	3.933±0.3$^{\#}$
*p< 0.001 When compared to control. $^{\#}$p< 0.001, $^{@}$p <0.05 When compared to doxorubicin alone treatment. N=5.						

Table 1: Alteration in the biochemical profile of albino rat serum/heart treated with oltipraz for three consecutive days before 15 mg/kg body weight doxorubicin administration.

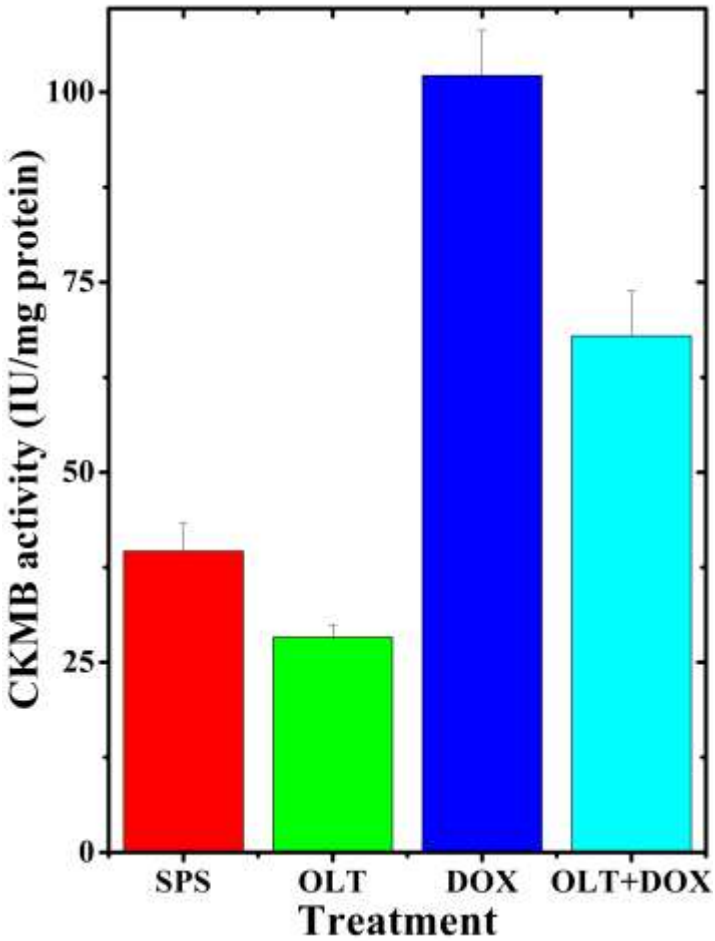

Figure 1: Alteration in the doxorubicin-induced CK-MB activity in the rat serum by oltipraz.

Glutathione

The level of glutathione in the untreated heart of rats was 20.85±0.25 nmol/mg protein. Oltipraz alone treatment did not significantly alter the GSH concentration when compared to non-drug treated control (Table 1). Doxorubicin alone treatment resulted in a significant decrease in the glutathione (3.43±0.57 nmol) concentration, which was 6-fold lower than the untreated control (Table 1, Figure 2). Oltipraz treatment before doxorubicin administration caused a significant rise in the glutathione concentration when compared to doxorubicin treatment alone (16.33±0.68 nmol), which was 4.8 fold higher than the latter (Table 1, Figure 2).

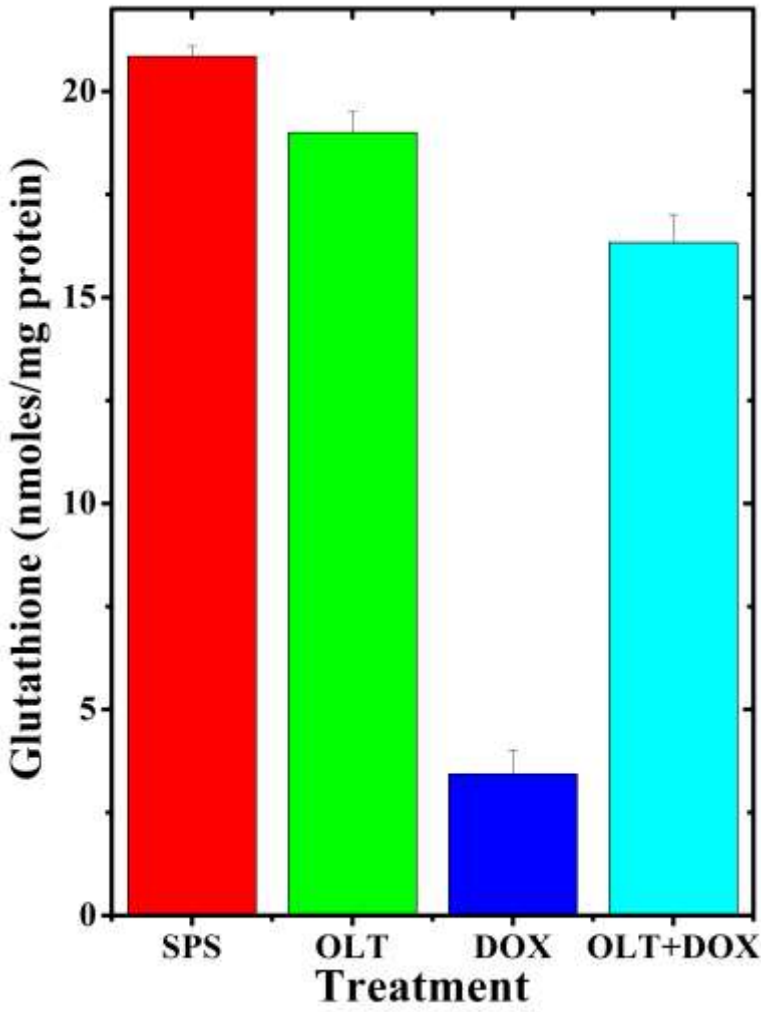

Figure 2: Alteration in the doxorubicin-induced glutathione concentration in the rat heart by oltipraz.

Glutathione-S-Transferase

The activity of glutathione-s-transferase (GST) in the untreated rat heart was 21.55±2.35 nmol/mg protein. Oltipraz alone treatment did not show significnt changes in the GST activity as compared to control (Table 1). Administration of doxorubicin resulted in a drastic but significant reduction in the GST activity, which reduced to 2.964±0.045 (Table 1 and Figure 3). Treatment of rats with oltipraz before doxorubicin administration resulted in a significant elevation in the glutathione-S-transferase activity (16.33±0.676 nmol), which was 5.5 fold higher when compared to doxorubicin treatment alone (Table 1, Figure 3).

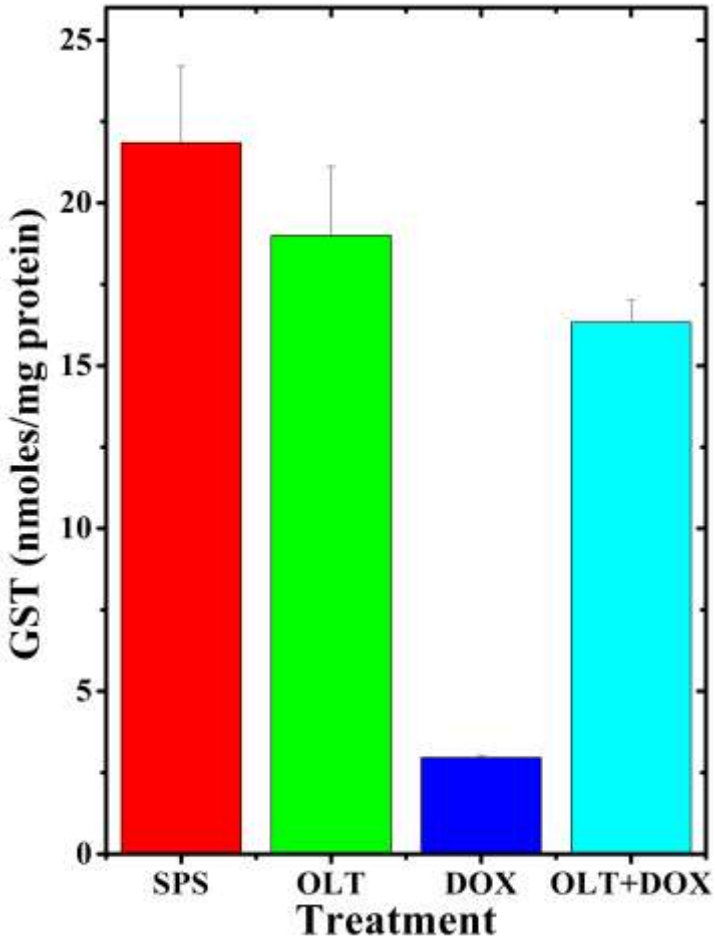

Figure 3: Alteration in the doxorubicin-induced glutathione-s-transferase activity in the rat heart by oltipraz.

Catalase

The catalase activity of the untreated rat heart was 0.25±0.02 U/mg protein. The oltipraz alone treatment did not alter the catalase activity significantly when compared to the spontaneous activity (Table1). Doxorubicin alone treatment significantly reduced the catalase activity (0.10±0.001) as compared to non-drug treated controls (Table 1, Figure 4). Oltipraz treatment elevated the catalase

activity significantly when compared to doxorubicin treatment alone (Table 1, Figure 4). Administration of oltipraz before doxorubicin treatment led to a 2 fold rise in the catalase activity (Table 1).

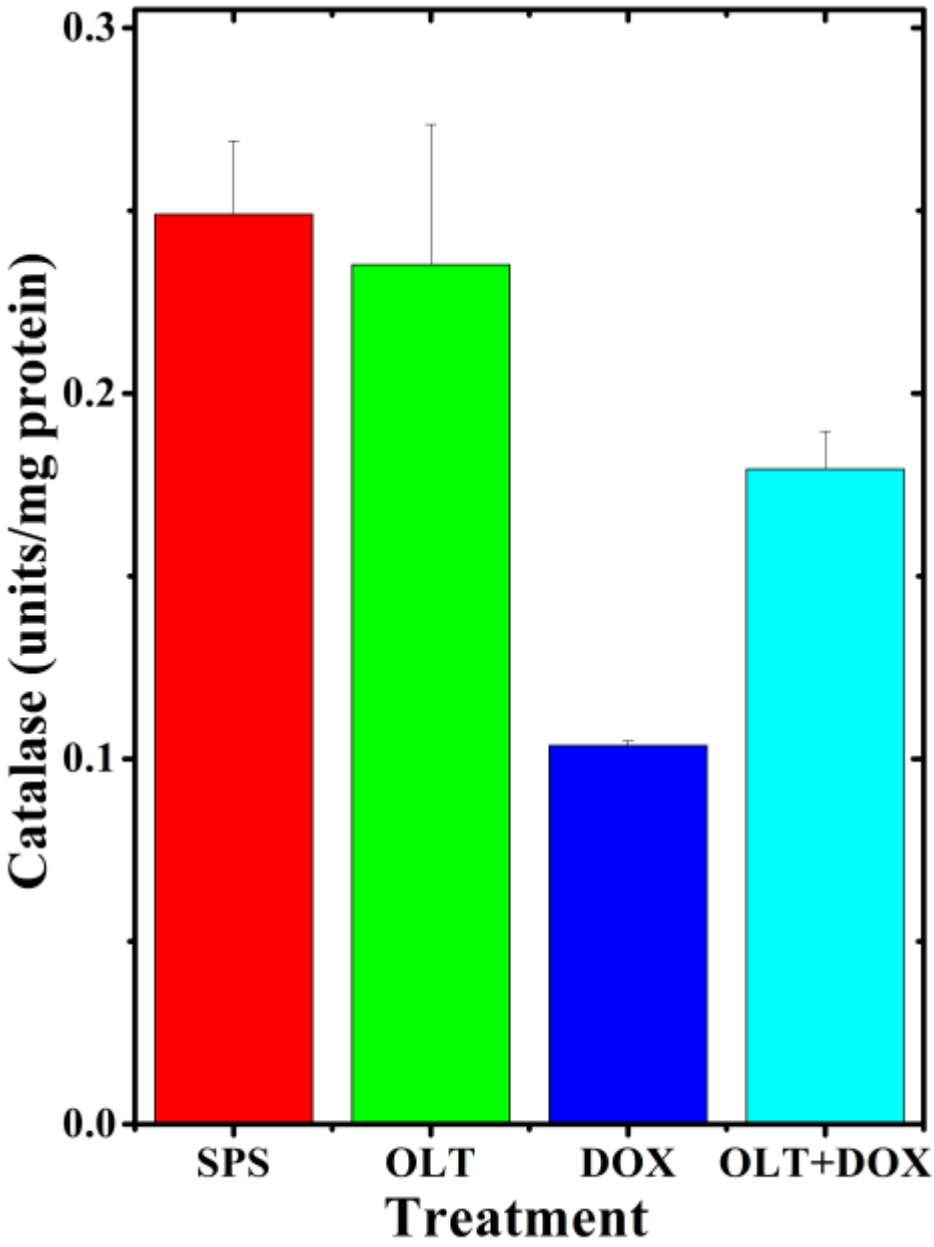

Figure 4: Alteration in the doxorubicin-induced catalase activity in the rat heart by oltipraz.

Superoxide Dismutase

The activity of SOD in the non-drug treated hearts of rats was 13.62±1.23 nmol/mg protein and treatment of rats with oltipraz alone did not significantly (14.27±1.60 nmol) change this activity (Table 1). Doxorubicin alone treatment also showed a significant decrease in the SOD activity (2.06±0.84 nmol), which was almost 6.3-fold lower than that of non-drug treated control (Table 1,Figure 5). Oltipraz

treatment before doxorubicin administration elevated the SOD activity, which reached to almost normal level (12.96±2.13 nmol) in the Oltipraz+doxorubicin treated group (Table 1, Figure 5).

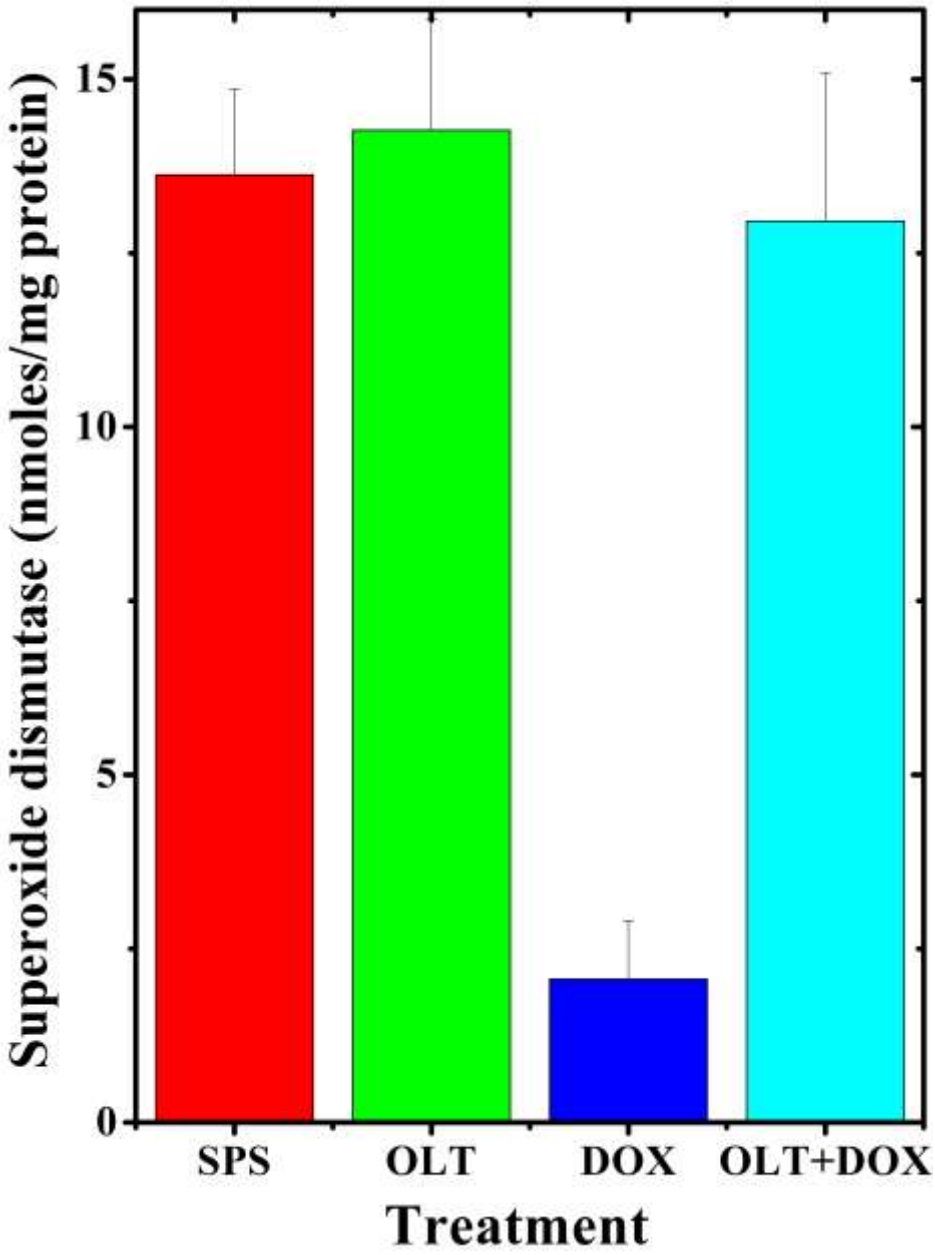

Figure 5: Alteration in the doxorubicin-induced superoxide dismutase activity in the rat heart by oltipraz.

Lipid Peroxidation

The results of the present study showed that the rate of lipid peroxidation in the untreated rat heart is 2.33±0.33 nmol/mg protein. Oltipraz alone treatment did not show significant alteration in the lipid peroxidation when compared to control (Table1, Figure 6). The doxorubicin alone treatment raised the

level of lipid peroxidation (11.33±1.66 nmol) significantly when compared to the untreated control. This rise in lipid peroxidation after doxorubicin treatment was 4.9-fold higher when compared to non-drug treated control (Table 1). Administration of oltipraz before doxorubicin treatment significantly reduced lipid peroxidation (3.93±0.29 nmol), which was 2.9-fold lower as compared to doxorubicin treatment alone (Table 1,Figure 6).

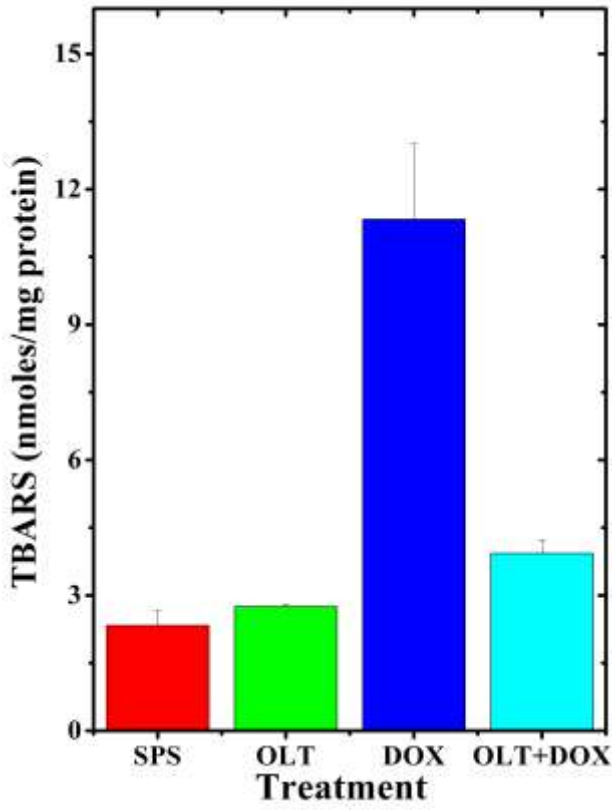

Figure 6: Alteration in the doxorubicin-induced lipid peroxidation in the rat heart by oltipraz.

Discussion

Cardiotoxicity is an important health concern for patients receiving doxorubicin for the treatment of cancer because it is expressed after many years of doxorubicin administration and remains a life-long threat. In recent years, several mechanisms have been suggested for doxorubicin-induced cardiotoxicity, however, the free radical theory is still the most accepted mechanism. Doxorubicin binds to cardiolipin present abundantly in the mitochondrial membrane leading to its accumulation in the mitochondria of the cardiomyocytes [40]. The quinone moiety of doxorubicin undergoes univalent reduction into a semiquinone radical, which is autoxidized in the presence of molecular oxygen to re-form the parent quinone radical and the superoxide anion as a free radical. This is a repetitive cyclic process that continually forms superoxide anions. The paucity of enzymes that passivate free radicals in the heart is the main cause of doxorubicin-induced cardiotoxicity [17]. The redox cycling of quinone moiety is catalyzed by the enzyme flavin dehydrogenase and other proteins including complex 1 of the electron

transport chain located in the mitochondria and NADPH oxidase-2 present in the cardiac membrane [41]. The doxorubicin interacts with iron to form doxorubicin iron complexes resulting in the cycling of iron between Fe^{3+} and Fe^{2+} increasing ROS production including the hydroxyl radical, a highly toxic species via Fenton and Haber-Weiss reactions triggering toxic effects [42].

The administration of doxorubicin-induced cardiotoxicity in the rats, indicated by a rise in the CK-MB activity by 2.6 folds. The elevated serum levels of CK-MB have been considered as a reliable marker of doxorubicin-induced cardiotoxicity [43]. The doxorubicin has been reported to increase the activity of CK-MB in mice, rats, and rabbits earlier [44-53]. The administration of rats with oltipraz reduced serum levels of CK-MB indicating that it protected the heart against the toxic effect of doxorubicin. Oltipraz has been reported to protect rats against isoproterenol-induced heart failure [54]. Earlier a polyherbal preparation, antarth, *Agele marmelos* (bael), naringin, hesperidin, ellagic acid, carvedilol metformin, berberine, vanillic acid and chia seed oil have been reported to protect mice, rats and rabbits against the doxorubicin-induced cardiotoxicity by reducing CK-MB activity and increasing antioxidants [44-53]. The iron chelator dexrazoxane (ICRF-187) has been used to reduce doxorubicin-induced cardiotoxicity in mice, rats, rabbits, dogs, swine, and humans [55-57]. However, it is associated with hematological toxicities like neutropenia, leukopenia, anemia, thrombocytopenia and bone marrow suppression in patients [56]. The administration of dapsone has been reported to protect against doxorubicin-induced myocardial toxicity in rats by reducing CK-MB activity and elevating superoxide dismutase activity in the hearts of rats [58].

There has been a causal relationship between doxorubicin-induced lipid peroxidation and cardiotoxicity [59] [14]. The doxorubicin accelerated lipid peroxidation in the heart tissue and oltipraz attenuated the lipid peroxidation in the rat heart. The antarth, bael, naringin, hesperidin and metformin have been reported to reduce lipid peroxidation in mice and rat hearts earlier [44,48–50,53]. Similarly, berberine treatment decreased lipid peroxidation in cultured cardiomyocytes [52]. The chia seed oil and dapsone have been reported to reduce doxorubicin-induced lipid peroxidation in rat serum and heart homogenate [45,58].

The exact mechanism of protection afforded to rat hearts by oltipraz is not known. The doxorubicin-induces reactive oxygen species and removal of reactive oxygen species and attrition in lipid peroxidation by oltipraz may be responsible for its cardioprotective effect. The neutralization of doxorubicin-induced free radicals by oltipraz may have protected rat hearts against the doxorubicin-induced toxicity of rats. This would have been made possible by increasing glutathione, glutathione-s-transferase, catalase and superoxide dismutase by oltipraz in the present study. Oltipraz has been reported to be a potent inducer of phase-II detoxifying enzymes earlier [20,60]. The oltipraz is reported to suppress NF-κB and activate Nrf-2 that may have increased the antioxidant status by elevating glutathione, glutathione-s-transferases, glutathione peroxidases, catalases and superoxide dismutases in the rat heart and protected against the doxorubicin-induced cardiotoxicity. The doxorubicin treatment has been reported to increase the expression of TNF-α in the rat heart [58], whereas oltipraz suppressed the activation of tumor necrosis factor (TNF-α) and interleukin (IL-1β) in the rat heart earlier [54] and a similar action cannot be ruled out in the present study.

Conclusion

The doxorubicin administration induced cardiotoxicity in the rat hearts as evidenced by the increased CK-MB activity and lipid peroxidation. The oltipraz pretreatment reduced doxorubicin-induced CK-MB activity and lipid peroxidation indicating that it protected against cardiotoxicity. The increased levels of glutathione, glutathione-s-transferase, catalase and superoxide dismutase seem to alleviate doxorubicin-induced free radical production and protect rat heart against the doxorubicin-induced toxic effects, which may be due to the suppression of NF-κB, TNF-α, and IL-1β and elevation of Nrf-2.

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References

1. Arcamone F, Cassinelli G, Fantini G, Grein A, Orezzi P, et al. Adriamycin, 14 hydroxydaimomycin, a new antitumor antibiotic from S. Peucetius var. caesius. Biotechnol Bioeng. 11:1101-10.
2. Carter SK. (1975) Adriamycin: a review. J Natl Cancer Inst. 55:1265-74.
3. Minotti G, Menna P, Salvatorelli E, Cairo G, Gianni L. (2004) Anthracyclines: Molecular advances and pharmacologie developments in antitumor activity and cardiotoxicity. Pharmacol Rev. 56:185-229.
4. Carvalho C, Santos R, Cardoso S, Correia S, Oliveira P, et al. (2009) Doxorubicin: The Good, the Bad and the Ugly Effect. Curr Med Chem. 16:3267-85.
5. Volkova M, Russell R. (2011) Anthracycline Cardiotoxicity: Prevalence, Pathogenesis and Treatment. Curr Cardiol Rev. 7:214-20.
6. Tam K. (2013) The roles of doxorubicin in hepatocellular carcinoma. ADMET DMPK. 1:29-44.
7. Meredith AM, Dass CR. (2016) Increasing role of the cancer chemotherapeutic doxorubicin in cellular metabolism. J Pharm Pharmacol. 68:729-41.
8. Henriksen PA. (2018) Anthracycline cardiotoxicity: An update on mechanisms, monitoring and prevention. Heart. 104:971-7.
9. Ishihara A, Hatakeyama S, Suzuki J, Amano Y, Sasahara T, et al. (2019) Histological evidence for the cardiac safety of high-dose pegylated liposomal doxorubicin in a patient with HIV-associated Kaposi sarcoma: A case report and literature review. BMC Infect Dis. 19:1-6.
10. De Angelis A, Urbanek K, Cappetta D, Piegari E, Ciuffreda LP, et al. (2016) Doxorubicin cardiotoxicity and target cells: a broader perspective. Cardio-Oncology. 2.
11. Minotti G, Recalcati S, Mordente A, Liberi G, Calafiore AM, et al. (1998) The secondary alcohol metabolite of doxorubicin irreversibly inactivates aconitase/iron regulatory protein-1 in cytosolic fractions from human myocardium. FASEB J. 12:541-52.
12. Licata S, Saponiero A, Mordente A, Minotti G. (2000) Doxorubicin metabolism and toxicity in human myocardium: Role of cytoplasmic deglycosidation and carbonyl reduction. Chem Res Toxicol. 13:414-20.
13. Kalyanaraman B. (2020) Teaching the basics of the mechanism of doxorubicin-induced cardiotoxicity: Have we been barking up the wrong tree? Redox Biol. 2020:29.
14. Wenningmann N, Knapp M, Ande A, Vaidya TR, Ait-Oudhia S. (2019) Insights into doxorubicin-induced cardiotoxicity: Molecular mechanisms, preventive strategies, and early monitoring. Mol Pharmacol. 96:219-32.

15. Ichikawa Y, Ghanefar M, Bayeva M, Wu R, Khechaduri A, et al. (2014) Cardiotoxicity of doxorubicin is mediated through mitochondrial iron accumulation. J Clin Invest. 124:617-30.
16. Luu AZ, Chowdhury B, Al-Omran M, Teoh H, Hess DA, et al. (2018) Role of endothelium in doxorubicin-induced cardiomyopathy. JACC Basic to Transl Sci. 3:861-70.
17. Agunbiade TA, Zaghlol RY, Barac A. (2019) Heart failure in relation to anthracyclines and other chemotherapies. Methodist Debakey Cardiovasc J. 15:243-9.
18. Tacar O, Sriamornsak P, Dass CR. (2013) Doxorubicin: An update on anticancer molecular action, toxicity and novel drug delivery systems. J Pharm Pharmacol. 65:157-70.
19. Mazzotta M, Giusti R, Iacono D, Lauro S, Marchetti P. (2016) Pulmonary fibrosis after pegylated liposomal doxorubicin in elderly patient with cutaneous angiosarcoma. Case Rep Oncol Med. 2016:8034832.
20. Benson AB. (1993) Oltipraz: A laboratory and clinical review. J Cell Biochem. 53:278-91.
21. Zhang Y, Munday R. (2008) Dithiolethiones for cancer chemoprevention: Where do we stand? Mol Cancer Ther. 7:3470-9.
22. Yagishita Y, Gatbonton-schwager TN, McCallum ML, Kensler TW. (2020) Current landscape of NRF2 biomarkers in clinical trials. Antioxidants. 9:716.
23. Kensler TW, Groopman JD, Sutter TR, Curphey TJ, Roebuck BD. (1999) Development of cancer chemopreventive agents: Oltipraz as a paradigm. Chem Res Toxicol. 12:113-26.
24. Prochaska HJ, Chavan SJ, Baron P, Polsky B. (1995) Oltipraz, a novel inhibitor of human immunodeficiency virus type 1 (HIV-1) replication. J Cell Biochem. 59:117-25.
25. Chi WJ, Lin-Shiau SY, Boone CW, Kelloff GJ, Lin JK. (1998) Oltipraz, a novel inhibitor of hepatitis B virus transcription through elevation of p53 protein. Carcinogenesis. 19:2133-8.
26. Davies MH, Schnell RC. (1991) Oltipraz-induced amelioration of acetaminophen hepatotoxicity in hamsters. II. Competitive shunt in metabolism via glucuronidation. Toxicol Appl Pharmacol. 109:29-40.
27. Ma X, Chang Y, Zhang Y, Muhammad I, Shi C, et al. (2018) Effects of C2-Ceramide and oltipraz on hepatocyte nuclear factor-1 and glutathione S-transferase a1 in acetaminophen-mediated acute mice liver injury. Front Pharmacol. 9:1009.
28. Bae SK, Lee SJ, Kim T, Kim JW, Lee I, et al. (2006) Pharmacokinetics and therapeutic effects of oltipraz after consecutive or intermittent oral administration in rats with liver cirrhosis induced by dimethylnitrosamine. J Pharm Sci. 95:985-97.
29. Kim SG, Kim YM, Choi YH, Lee MG, Choi JY, et al. (2010) Pharmacokinetics of oltipraz and its major metabolite (RM) in patients with liver fibrosis or cirrhosis: Relationship with suppression of circulating TGF-B1. Clin Pharmacol Ther. 88:360-8.
30. Kim SG, Kim YM, Choi JY, Han JY, Jang JW, et al. (2011) Oltipraz therapy in patients with liver fibrosis or cirrhosis: A randomized, double-blind, placebo-controlled phase II trial. J Pharm Pharmacol. 63:627-35.
31. Zhang Y, Ma B, Hao S, Wang J, Zhang R, et al. (2021) Drug-induced liver injury: Oltipraz and C2-ceramide intervene HNF-1α/GSTA1 expression via JNK signaling pathway. J Appl Toxicol.
32. Jiang Z, Bian M, Wu J, Li D, Ding L, et al. (2020) Oltipraz prevents high glucose-induced oxidative stress and apoptosis in rsc96 cells through the Nrf2/NQO1 signalling pathway. Biomed Res Int. 2020:5939815.
33. Bae SK, Kim JY, Yang SH, Kim JW, Kim T, et al. (2006) Pharmacokinetics of oltipraz in rat models of diabetes mellitus induced by alloxan or streptozotocin. Life Sci. 78:2287-94.
34. Langer SW. (2014) Dexrazoxane for the treatment of chemotherapy-related side effects. Cancer Manag Res. 6:357-63.
35. Moron MS, Depierre JW, Mannervik B. (1979) Levels of glutathione, glutathione reductase and glutathione S-transferase activities in rat lung and liver. Biochim Biophys Acta. 582:67-78.
36. Habig W, Pabst M, Jakoby W. (1974) Glutathione S-transferases. The first enzymatic step in mercapturic acid formation. J Biol Chem. 249:7130-7139.

37. Aebi H. (1984) Catalase in Vitro. Methods Enzymol. 105:121-6.
38. Fried R. (1975) Enzymatic and non-enzymatic assay of superoxide dismutase. Biochimie. 57:657-60.
39. Gelvan D, Saltman P. (1990) Different cellular targets for Cu- and Fe-catalyzed oxidation observed using a Cu-compatible thiobarbituric acid assay. Biochim Biophys Acta. 1035:353-60.
40. Gorini S, De Angelis A, Berrino L, Malara N, Rosano G, et al. (2018) Chemotherapeutic drugs and mitochondrial dysfunction: Focus on doxorubicin, trastuzumab, and sunitinib. Oxid Med Cell Longev. 2018:7582730.
41. Doroshow JH, Esworthy RS, Chu FF. (2020) Control of doxorubicin-induced, reactive oxygen-related apoptosis by glutathione peroxidase 1 in cardiac fibroblasts. Biochem Biophys Reports. 21:100709.
42. Gammella E, Maccarinelli F, Buratti P, Recalcati S, Cairo G. (2014) The role of iron in anthracycline cardiotoxicity. Front Pharmacol. 5:25.
43. Kemp M, Donovan J, Higham H, Hooper J. (2004) Biochemical markers of myocardial injury. Br J Anaesth 93:63-73.
44. Abdel-Raheem IT, Abdel-Ghany AA. (2009) Hesperidin alleviates doxorubicin-induced cardiotoxicity in rats. J Egypt Natl Canc Inst. 21:175-84.
45. Ahmed AZ, Mumbrekar KD, Satyam SM, Shetty P, D'Souza MR, et al. (2021) Chia seed oil ameliorates doxorubicin-induced cardiotoxicity in female Wistar rats: an electrocardiographic, biochemical and histopathological approach. Cardiovasc Toxicol. 21:533-42.
46. Ajmal K, Sharif M, Afzal A, Khan TB, Ajmal M. (2015) Early detection of doxorubicin-induced cardiotoxicity and its prevention by carvedilol. Int J Basic Clin Pharmacol. 4:278-83.
47. Baniahmad B, Safaeian L, Vaseghi G, Rabbani M, Mohammadi B. (2020) Cardioprotective effect of vanillic acid against doxorubicin-induced cardiotoxicity in rat. Res Pharm Sci. 15:87-96.
48. Jagetia GC, Reddy TK, Malagi KJ, Nayak BS, Naidu MBR, et al. (2005) Antarth, a polyherbal preparation protects against the doxorubicin-induced toxicity without compromising its antineoplastic activity. Phyther Res. 2005:19.
49. Jagetia GC, Reddy TK. (2014) The grape fruit flavonone naringin protects mice against doxorubicin-induced cardiotoxicity. J Mol Biochem. 3:34-49.
50. Jagetia GC, Venkatesh P. (2015) An indigenous plant bael (Aegle marmelos (l.) correa) extract protects against the doxorubicin-induced cardiotoxicity in mice. Biochem Physiol. 4:163.
51. Warpe VS, Mali VR, Arulmozhi S, Bodhankar SL, Mahadik KR. (2015) Cardioprotective effect of ellagic acid on doxorubicin induced cardiotoxicity in wistar rats. J Acute Med. 5:1-8.
52. Xiong C, Wu YZ, Zhang Y, Wu ZX, Chen XY, et al. (2018) Protective effect of berberine on acute cardiomyopathy associated with doxorubicin treatment. Oncol Lett. 15:5721-9.
53. Zilinyi R, Czompa A, Czegledi A, Gajtko A, Pituk D, et al. (2018) The cardioprotective effect of metformin in doxorubicin-induced cardiotoxicity: The role of autophagy. Molecules. 23:1884.
54. Tang Y, Guo M, Ma XY, Sun WP, Hao MH, et al. (2018) Oltipraz attenuates the progression of heart failure in rats through inhibiting oxidative stress and inflammatory response. Eur Rev Med Pharmacol Sci. 22:8918-23.
55. Imondi AR. (1998) Preclinical models of cardiac protection and testing for effects of dexrazoxane on doxorubicin antitumor effects. Semin Oncol. 4:22-30.
56. Tahover E, Segal A, Isacson R, Rosengarten O, Grenader T, et al. (2017) Dexrazoxane added to doxorubicin-based adjuvant chemotherapy of breast cancer: A retrospective cohort study with a comparative analysis of toxicity and survival. Anticancer Drugs. 28:787-94.
57. Kopp LM, Womer RB, Schwartz CL, Ebb DH, Franco VI, et al. (2019) Effects of dexrazoxane on doxorubicin-related cardiotoxicity and second malignant neoplasms in children with osteosarcoma: a report from the Children's Oncology Group. Cardio-Oncology. 5:1-12.

58. Sheibani M, Nezamoleslami S, Faghir-Ghanesefat H, Emami A hossein, Dehpour AR. (2020) Cardioprotective effects of dapsone against doxorubicin-induced cardiotoxicity in rats. Cancer Chemother Pharmacol. 85:563-71.
59. Julicher RHM, Sterrenberg L, Bast A, Riksen ROWM, Koomen JM, et al. (1986) The role of lipid peroxidation in acute doxorubicin-induced cardiotoxicity as studied in rat isolated heart. J Pharm Pharmacol. 38:277-82.
60. Miao W, Hu L, Kandouz M, Batist G. (2003) Oltipraz is a bifunctional inducer activating both phase I and phase II drug-metabolizing enzymes via the xenobiotic responsive element. Mol Pharmacol. 64:346-54.