Interaction Toxicity Study between P-glycoprotein Inhibitor (Captopril) and Inducer (Spironolactone) with Their Substrate (Lovastatin) in Male Rats

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A B S T R A C T

An interaction toxicity study was performed to evaluate and compare the effect of P-glycoprotein (P-gp) inhibitor (captopril) and inducer (spironolactone) on their common substrate (lovastatin) that were done by comparing LD50 of the acute study with their chronic form then with those combined therapeutic doses administered for 90 days. Therefore, isobolographic analysis and chronicity index were used as the parameters for this study. Forty rats were allocated into five groups according to the used treatment into: captopril, spironolactone, lovastatin, captopril + lovastatin and spironolactone + lovastatin using up and down method to determine their acute exposure LD50 while ninety rats were used to perform the chronic stage of the study divided equally into six groups according to daily dosing regimen as following G1 - control group administered distilled water orally; G2 - administered captopril 0.7 mg/kg BW orally; G3-administered spironolactone 1.4 mg/kg BW orally; G4-administered lovastatin 0.57 mg/kg BW orally; G5-administered spironolactone 1.4 mg/kg BW orally andLovastatin 0.57 mg/kg BW, G6-administered captopril 0.7 mg/kg BW andLovastatin 0.57 mg/kg BW orally. The results of isobolographic analysis showed that the sort of interaction between P-gp inhibitor (captopril) and lovastatin alone and as combined administration showed to be antagonistic after acute administration while it was synergistic after chronic administration; for P-gp inducer, spironolactone and lovastatin were additive after acute administration and antagonistic after chronic administration. Chronicity index results showed that both captopril and lovastatin accumulated after administered each alone and showed more accumulation after their combined administration while the chronicity index for P-gp inducer (spironolactone) and lovastatin showed less total concentration in the body burden after their combined administration than alone one. In conclusion, it seems that P-gp inhibitor (captopril) causes accumulation of itself and substrate (lovastatin), while P-gp inducer (spironolactone) causes reduction on the body burden of itself as well as lovastatin possibly due to their effects on the kinetics of the body and this may affect the efficacy and safety of drugs.

K e y w o r d s: p-glycoprotein, inducer, inhibitor, substrate, LD50

I N T R O D U C T I O N

Adenosine triphosphate (ATP)-binding cassette (ABC) transporters are highly expressed in tumor cells, as well as in organs involved in absorption and secretion processes, mediating the ATP-dependent efflux of compounds, both endogenous substances and xenobiotics, including drugs. Their expression and activity levels are modulated by the presence of inhibitors, inducers and/or activators (1). The first known human ABC transporter was
P-gp, which confers multidrug resistance (MDR) to anticancer drugs (2). P-gp is an ATP-dependent efflux pump encoded by the MDR1 gene in humans, known to mediate multidrug resistance of neoplastic cells to cancer therapy (3). P-gp plays an important role in drug transport in many organs. In the gut, P-gp pumps drugs back into the lumen, leading to decrease their absorption whereas P-gp transports medications into the urine to be excreted from the body in kidneys (4).

Drug-drug interactions between substrates and P-gp inhibitors can modify the drug’s pharmacokinetics by increasing bioavailability and organ uptake leading to more adverse drug reactions and toxicities. Possibly, coadministration of substrates for P-gp and P-gp-inducing agents may lead to a reduction in the levels of plasma drug and consequently reduce the effect of the treatment (5).

P-gp modulation -mediated transport has significant pharmacokinetic P-gp substrates implications. Changes in substrate pharmacokinetics may have the potential to alter the duration and magnitude of pharmacodynamics. It is important to understand P-gp modulation in order to predict the degree of which P-gp modulation may affect that substrate, minimize adverse effects or to get benefit from modulation of specific therapeu tic advantage (6).

Captopril is an angiotensin-converting enzyme (ACE) inhibitor which was initially approved to treat high blood pressure and can be used alone or in combination with other antihypertensive drugs (7). The benefits of captopril in hypertension and heart failure result primarily from suppression of the renin-angiotensin-aldosterone system (RAAS) (8) and captopril causes many side effects including renal insufficiency, renal failure, nephrotic syndrome, polyuria, oliguria and urinary frequency as well as angina pectoris, myocardial infarction, Raynaud syndrome and congestive heart failure (9, 10).

Statins are a widely prescribed class of drugs that decrease cholesterol. Their mechanism of action is primarily via inhibition of HMG-CoA (hydroxymethylglutaryl-coenzyme A) reductase and the rate-limiting enzyme in the cholesterol biosynthesis pathway (11). Many side effects of statin drugs that can be more serious sometime including new-onset type 2 diabetes mellitus, hepatotoxicity, renal toxicity, and other conditions (12).

Spironolactone is an aldosterone antagonist, and a potassium-sparing diuretic are used for treatment of hyperaldosteronism and edematous states including congestive heart failure and liver cirrhosis (13). It causes common undesirable effects (>10%): CNS disturbances (drowsiness, lethargy, confusion, headache, fever, ataxia and/or fatigue), GI disturbances including anorexia, dyspepsia, nausea, vomiting, peptic ulceration and/or colic (14).

The aim of this study was to investigate and compare the interaction between P-gp inducer spironolactone (SN) or inhibitor captopril (CP) with its common substrate lovastatin (LV) after acute and chronic administration in rats and to determine the possibility of existence accumulation or not after chronic administration of three drugs.

**Materials and Methods**

**Animals and Conditions**

A total of one hundred and thirty adult male albino rats were obtained from animal house of college of veterinary Medicine, University of Baghdad. They aged over 3 months and weighed 200-250 g. were used to perform different studies. They were fed standard pellet diet and drank tap water. The animals were left in special cages with good conditions in the animal house of College of veterinary medicine for two weeks for adaptation; maintained with standard condition at 10 / 14 h light-dark cycle, temperature at 20-25 °C in an air-conditioned room; and bed was mulch that changed twice weekly. Ethical approval was gotten from the care and use animal committee of the college of veterinary medicine/ university of Baghdad to start the work.

The procedures used in this study were reviewed and approved by the scientific committee at the University of Baghdad’s College of Veterinary Medicine in compliance with animal welfare ethical standards.

Forty mature, local breed rabbits, about 1.5-2 kg in weight of both sexes were used in this study, managed under the same conditions. Partial injury to semimembranosus muscle tendon was induced. Rabbits were divided into five equal groups; four of them (A, B, D, E) were irradiated with low-power laser at 5, 8, 15, 21 days postoperatively, whereas group (C) was left without irradiation and was considered as a control.

**Assessment of Median Lethal Dose (LD50)**

Forty rats were allocated into five groups according to the used treatment (captopril, spironolactone, lovastatin, captopril+lovastatin and spironolactone+lovastatin) using up and down method to determine their orally acute LD50. The drugs of this study were purchased from Y.S.P. Industries- Malaysia for lovastatin, Actavis-UK for spironolactone, and Medochemie-Cyprus for captopril.

Ranges of doses of LD50 Study were 3600-4400 mg/kg for captopril, 900-1100 mg/kg for spironolactone, and 4400-6000 mg/kg for lovastatin. The solution of the captopril dose was prepared by dissolving 1 tablet of captopril (50 mg) to 143 mL distill water to get concentration of (0.35 mg/mL) and to be given at dose volume 0.2 mL/100 g. of body weight of the animal. The dosing solution of spironolactone was also prepared by dissolving 1 tablet of spironolactone (100 mg) to143 mL distill water to get concentration of (0.7 mg/mL) and was...
given at dose volume 0.2 mL/100 g. of body weight of the animal. The dosing solution of lovastatin was prepared by dissolving 1 tablet of lovastatin (40 mg) to 138 mL distill water to prepare concentration of (0.29 mg/mL) and was given at dose volume 0.2 mL/100 g. of body weight of the animal.

Toxicity study was conducted according to the up and down method. This experiment was rendering for dosing of rats in singly of sequence at twenty four-hour intervals, together with dose of the initial set at "the toxicologist's best estimation of the LD$_{50}$". Then the dose after each death was lowered; next each survival, the dose was raised, according to a prespecified progression factor of dose. If a death follows up an initial trend of raising doses of 10-20% or by constant factors a survival follows up an initial direction of lowering dose with an equivalent ratio, three additional animals were tested following an equivalent dose adjustment pattern then test was ended. The LD$_{50}$ were determined depending on Up and Down method and calculated by using the subsequent equation (15, 16):

$$\text{LD}_50 = X_f + K_d$$

Where, $X_f$ = final dose administered, $K$=constant factor, and $d=$ variation between levels of dose.

**Chronic Study**

Ninety rats were used in the study of chronic administration, in which animals were divided equally into six groups according to oral daily doses regimen as following G1, control group, administered distilled water; G2, administered captopril at 0.7 mg/kg BW; G3, administered spironolactone at 1.4 mg/kg BW; G4, administered lovastatin at 0.57 mg/kg BW; G5, administered spironolactone at 1.4 mg/kg BW and lovastatin at 0.57 mg/kg BW; G6-administered captopril at 0.7 mg/kg BW and lovastatin at 0.57 mg/kg BW.

**Isobolographic Study**

Isobolographic analysis and chronicity index ordinarily were used to determine the interaction sort of the three drugs, during which a line draw to affix the LD$_{50}$ of every 2 drugs studied in isobolograph and a point of intersection determined by draw of lines vertically from the LD$_{50}$ values of everycombined drug.

The conclusion of interaction of drugs decided accordingly to the position of the spot of the two drugs joined LD$_{50}$ line. If the spot was besides right, it meant there was an antagonistic effect >1, besides left, meant potentiation or synergistic effect <1, but on the road=1, it meant there was an additive effect between the 2 drugs. The type of interaction estimated consistent with the subsequent equation (17):

$$\frac{a}{A} + \frac{b}{B} = 1$$

Where, a and b are chronic or acute (combined) LD$_{50}$ of drug 1 and 2, respectively; and A and B are chronic or acute (alone) LD$_{50}$ of drug 1 and 2, respectively.

**Chronicity Index**

Chronicity index considered as the possibility measurement of accumulation of the drug after its chronic administration supporting comparison of the ratio of LD$_{50}$ values after acute and chronic administration to the drugs consistent with the equation:

$$\text{Chronicity index} = \frac{\text{LD}_{50} \text{ after acute dose}}{\text{LD}_{50} \text{ after 3 months administration of sublethal dose}}$$

If a value exceeded one, the accumulation possibility existed (18).

**RESULTS**

**Acute Toxicity Study of P-gp Inhibitor and Substrate**

Results of acute toxicity found that LD$_{50}$ for captopril and lovastatin according to procedure of Dixon were 4294.8 and 5896.4 mg/kg BW respectively which reduced after their interaction to 3144.4+4344.4 mg/kg BW (Table 1).

Isobolographic analysis (Figure 1) revealed that LD$_{50}$ levels of captopril and lovastatin are intersected after the coadministration of both (to the right of the line that joined values of LD$_{50}$ of each of the above drugs solely

| Groups          | Initial dose | Last dose | Doses Difference | K value | Results after 24 h$^*$ | LD$_{50}$$^{**}$ |
|-----------------|--------------|-----------|------------------|---------|------------------------|-----------------|
| captopril       | 3600         | 4000      | 400              | 0.737   | OOXOXO                 | 4294.8          |
| lovastatin      | 4400         | 5600      | 400              | 0.741   | OOOOOXOXO              | 5896.4          |
| captopril+lovastatin | 4000+5200 | 2800+4000 | 400+400          | -0.861  | XXOXXO                 | 3144.4+4344.4 |

$^*$O=Survival animal, X=Dead animal. $^\dagger$LD$_{50}$= X$+K$, where: X=final dose; k (constant)=0.860, d= differences between doses (Dixon, 1988). $^\ddagger$All doses are in mg/kg BW

**Table 1.** LD$_{50}$ of captopril, lovastatin with their interaction of the acute toxicity study$^1$

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By applying Tallarida equation, the result was:

$$\text{(a/A) + (b/B) = } (3144.4/4294.8) + (4344.4/5896.4) = 1.4$$

This result indicated that there was an antagonistic effect of toxicity after the captopril and lovastatin combination of the acute administration.

**Acute toxicity study of P-gp Inducer and Substrate**

Acute toxicity showed that LD$_{50}$ for spironolactone and lovastatin according to Dixon procedure were 1174 and 5896.4 mg/kg BW, respectively which were reduced after their interaction to 526 + 3703.6 mg/kg BW (Table 2).

Isobolographic analysis: (Figure 2) showed that the intersected lines of LD$_{50}$ of spironolactone and lovastatin after combined administration was near the line of those joined values of LD$_{50}$ of only 2 drugs.

**Chronic Administration LD$_{50}$ of P-gp Inhibitor and Substrate**

Chronic toxicity studies explained that LD$_{50}$ for captopril and lovastatin after the trial end (90 days) according to method of Dixon were 2462.8 and 5200 mg/kg BW respectively that decreased after their combined administration to 861.6 + 2861.6 mg/kg BW (Table 3).

Isobolographic analysis (Figure 3) revealed that the lines of LD$_{50}$ levels of captopril and lovastatin intersected after their coadministration together was to the left of the line that joined values of LD$_{50}$ of each both drugs.

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**Table 2.** LD$_{50}$ of spironolactone, lovastatin and their interaction of the acute toxicity study$^1$

| Groups                  | Initial dose | Last dose | Doses Difference | K value | Results after 24 h$^*$ | LD$_{50}$ $^\text{**}$ |
|-------------------------|--------------|-----------|------------------|---------|------------------------|------------------------|
| spironolactone          | 900          | 1100      | 100              | 0.741   | OOOXOXO               | 1174                   |
| lovastatin              | 4400         | 5600      | 400              | 0.741   | OOOXOXO               | 5896.4                 |
| spironolactone +lovastatin | 900 +5200  | 600 +4000 | 400 +400        | 0.741   | XXXXOXOX              | 526 +3703.6            |

$^0$O=Survival animal, X=Dead animal. $^1$LD$_{50}$=X$_f$+K$_d$, where: X$_f$=final dose; K (constant) =0.860, d= differences between doses (Dixon, 1980). $^1$All doses are in mg/kg BW.

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**Table 3.** LD$_{50}$ estimation for captopril, lovastatin and their interaction in study of chronic toxicity

| Groups                  | Initial dose | Last dose | Doses Difference | K value | Results after 24 h$^*$ | LD$_{50}$ $^\text{**}$ |
|-------------------------|--------------|-----------|------------------|---------|------------------------|------------------------|
| captopril               | 3200         | 2400      | 400              | -0.157  | XOOXX                  | 4294.8                 |
| lovastatin              | 5000         | 4600      | 400              | 1.5     | OXXX                   | 5896.4                 |
| captopril +lovastatin   | 2000 +4000   | 800 +2800 | 400 +400        | -0.154  | XXXXXX                 | 3144.4 +4344.4         |

$^0$O=Survival animal, X=Dead animal. $^1$LD$_{50}$=X$_f$+K$_d$, where: X$_f$=final dose; K (constant) =0.860, d= differences between doses (Dixon, 1980). $^1$All doses are in mg/kg BW.
The result of chronic isobolographic interaction between the two drugs captopril and lovastatin had synergistic effect.

**Chronic Administration LD\textsubscript{50} of P-gp Inducer and Substrate**

Chronic toxicity studies exhibited that LD\textsubscript{50} for spironolactone and lovastatin after the end of study (90 days) according to Dixon method were 850 and 5200 mg/kg BW, respectively, that decreased after their coadministration to 762.8+3851 mg/kg BW (Table 4).

Isobolographic analysis (Figure 4) exhibited the lines of LD\textsubscript{50} of spironolactone and lovastatin intersected after their coadministration together was to the right of the line that joined values of LD\textsubscript{50} of each two drugs.

![Figure 4](image)

**Figure 4.** Isobolographic for chronic toxicity interaction between spironolactone and lovastatin

By applying Tallarida equation, the result was:

$$\frac{(a/A) + (b/B)}{(2681.6/5200) + (3851.6/2462.8)} = 0.8$$

**Table 4.** Determination of LD\textsubscript{50} for spironolactone, lovastatin and their interaction in study

| Groups                        | Initial dose | Last dose | Doses Difference | K value | Results after 24 h* | LD\textsubscript{50}** |
|-------------------------------|--------------|-----------|------------------|---------|---------------------|------------------------|
| spironolactone                | 800          | 700       | 100              | 1.5     | OXXOXX              | 850                    |
| lovastatin                    | 5000         | 4600      | 400              | 1.5     | OXXOXX              | 5200                   |
| spironolactone+lovastatin     | 900+4400     | 800+4000  | 100+400          | 0.372   | XXOXX               | 762.8+3851             |

*O=Survival animal, X=Dead animal. **LD\textsubscript{50} = X\textsubscript{f} + K\textsubscript{d}, where: X\textsubscript{f}=final dose; K\textsubscript{d}(constant)=0.860, d= differences between doses (Dixon, 1980). All doses are in mg/kg BW

**Chronicity index (CI)**

Results of chronicity index are presented in Table 5. Index of chronicity was measured consistently with LD\textsubscript{50} after chronic and acute administration of different treatments by employment the following equation to determine the possibility of accumulation after chronic administration.

| P-gp inhibitor and substrate | Administered | CI   |
|-----------------------------|--------------|------|
| captopril                   | alone        | 1.70 |
| lovastatin                  | alone        | 1.13 |
| captopril                   | combined     | 3.60 |
| lovastatin                  | combined     | 1.50 |

| P-gp inducer and substrate  | Administered | CI   |
|-----------------------------|--------------|------|
| spironolactone              | alone        | 1.50 |
| lovastatin                  | alone        | 1.13 |
| spironolactone              | combined     | 0.70 |

**DISCUSSION**

Interaction of such used drugs in the study were possible since both captopril and spironolactone used in the therapy of high blood pressure while lovastatin usually used to overcome high lipid and cholesterol that is caused by the high blood pressure. Study of acute toxicity is
important to compare between the drugs for understanding
types of interaction according to isobolographic study and
then chronicity index that possibly explain the
accumulation or decreasing of drugs in the body tissues.
Chronic study was used to know the effects of these drugs
during long periods of treatment.

The present study was designed and performed for the
first time in Iraq to study the interaction between P-
glycoprotein inhibitor (captopril), P-glycoprotein inducer
(spironolactone) and its substrate (lovastatin) and to
investigate its toxicological effect consequence of using
therapeutic doses for all drugs by performing acute and
chronic studies with isobolographic interaction studies and
chronicity index. P-gp influences the pharmacokinetics of
its substrate drugs due to its poly specific binding nature
and its expression in many physical barriers and
pharmacokinetics related organs (i.e., the gastro-intestinal
(GI) tract, blood-brain-barrier (BBB), kidney, liver,
endothelium and placenta) that function to limit the cellular
uptake, distribution, excretion and toxicity of many
substances and xenobiotics (19).

The results of isobolographic analysis showed that the
sort of interaction between P-gp inhibitor (captopril) and
lovastatin in groups of alone and combined administration
were antagonistic after acute administration while it was
synergistic after chronic administration. For P-gp inducer
spironolactone and lovastatin, it showed additive after
acute administration and antagonistic after chronic
administration. Chronicity index results showed that both
captopril and lovastatin were accumulated after giving
alone and were more after their combined administration
while the chronicity index for P-gp inducer
(spironolactone) and lovastatin showed less total
concentration in the body burden after their combined
administration than giving alone.

These results explained the sort of interaction between
P-gp inhibitor and inducer with their common substrate
lovastatin (20). Lin, 2003 showed that P-gp could be viewed
as a unique defensive barrier network against the entry of
xenobiotics into the body. This efflux carrier decreased the
bioavailability of administered drugs by preventing their
sufficient accumulation intracellularly, so the efficacy of
drugs had to be lowered. It also altered the
pharmacokinetics and pharmacodynamics of its substrates.

So it played an important role in first-pass elimination
of orally administered drugs to limit their bioavailability by
effluxing drugs from the lumen-facing epithelia of the small
intestine and colon, and from the bile-facing canaliculi
of the liver. It eliminated substrates from the systemic
circulation at the urine-facing side of the brush border
membrane of proximal tubules in the kidney, and again
through biliary excretion. It restricted the permeability of
drugs into ‘sanctuary’ organs from the apical or serosal side
of BBB (e.g., blood–brain, blood–cerebral spinal fluid,
blood–placenta, blood–testis barriers) (21). These results
agreed with (22) who explained the drug-drug interaction
between inhibitors of P-glycoprotein and its substrates
leading to modification in pharmacokinetics and thus
increased in bioavailability and organ uptake leading to
more adverse drug reactions and toxicities. While
interaction between P-gp inducer and its substrate led to a
reduction in plasma drug levels and consequently
reduction in efficacy of drug. Our results were in agreement
with (23) Glaeser, 2011 who pointed the induction or
inhibition of P-glycoprotein might cause drug–drug
interactions. Results of coadministration of P-gp inhibitor
or inducer with their common substrate were
accompanying with (24) Lund et al., 2017 who explained
the administration of combined drugs that inhibited or
induced P-gp might increase or decrease body substrate
concentration, respectively, the systemic exposure of P-gp
substrates. As mentioned by Zhou, 2008(25) altered P-gp
activity due to induction and/or inhibition can cause drug-
drug interactions with modification drug pharmacokinetics
and response.

It seems from the result of chronicity index of both
giving alone and combined administration of P-gp inhibitor
and substrate that captopril possibly acted as both inhibitor
and substrate since it showed more accumulation after
chronic administration (3.6) for captopril but (1.5) for
lovastatin. This explained by the increase in intestinal
absorption and decrease in biliary and renal excretion due
to the inhibition of P-gp transmembrane function by
captopril in contrast P-gp inducer (spironolactone) caused
reduction in body burden concentration similar to that of
its substrate (lovastatin) after their combined
administration to 0.7 and 0.9 times due to the increase in P-
gp kinetic effects.

It can be concluded that P-gp inhibitor (captopril) may
cause accumulation of itself and substrate (lovastatin),
while P-gp inducer (spironolactone) possibly cause
reduction in the body burden of itself as well as lovastatin
due to their effects on the kinetics of the body and this may
affect on efficacy and safety of drugs.

So care must be taken to the therapeutic dose of
substrate, where it must be decreased or increased after its
chronic coadministration with P-gp inhibitor or inducer.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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