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Evaluation of the cancer chemopreventive efficacy of silibinin in genetic mouse models of prostate and intestinal carcinogenesis: Relationship with silibinin levels

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ABSTRACT

Silibinin, a flavonolignan from milk thistle seeds, possesses cancer chemopreventive properties in rodent models of carcinogenesis. We tested the hypotheses that silibinin or silipide, silibinin formulated with phospholipids, delays tumour development in TRAMP or Apc^{Min} mice, genetic models of prostate or intestinal malignancies, respectively. Mice received silibinin or silipide with their diet (0.2% silibinin equivalents) from weaning. Intervention with silipide reduced the size of well differentiated TRAMP adenocarcinomas by 31%. Silipide and silibinin decreased the incidence of poorly differentiated carcinomas by 61% compared to mice on control diet. Silipide decreased plasma levels of insulin-like growth factor (IGF)-1 by 36%. Levels of circulating IGF binding protein (IGFBP)-3 in mice on silipide or silibinin were 3.9- or 5.9-fold, respectively, elevated over those in control TRAMP mice. In Apc^{Min} mice silibinin, but not silipide, had only a marginal adenoma number-reducing effect. The results cautiously support the advancement of silipide to the stage of clinical investigation in prostate cancer.

1. Introduction

The polyphenolic phytochemical silibinin, a flavonolignan (for structure see Fig. 1), is a major constituent of the seeds of milk thistle (*Silybum marianum* L.). Silibinin and silymarin, a standardised milk thistle extract of which silibinin is a major component, are widely consumed as dietary supplements, especially in the USA. Amongst claims as to health benefits related to milk thistle components is the suggestion that they possess anticarcinogenic properties. This claim is supported by evidence in rodents according to which silibinin and silymarin can interfere with experimental malignancies of the prostate, intestinal tract, skin and bladder.[1–8] The clinical evaluation of flavonoids such as silibinin has been hampered by their poor systemic availability associated with, at least in part, their propensity to undergo avid conjugative metabolism. In order to improve the bioavailability of silibinin, it has been formulated with phosphatidylcholine ('silipide', Indena SpA, Milan, Italy). Clinical evaluation of this formulation at single or repeated doses in healthy volunteers and cancer patients demonstrated its safety[9,10] and the superior bioavailability of silibinin released from silipide when compared to silymarin.[11]

Genetically induced rodent models of carcinogenesis can be exploited to generate information on the efficacy, pharmacodynamics and pharmacokinetics of novel putative

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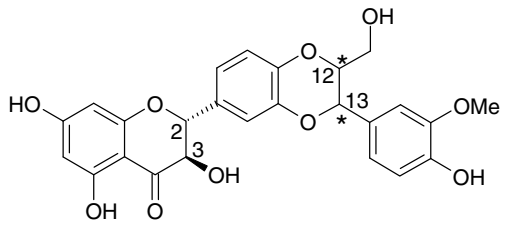

Fig. 1 – Structure of silibinin, a diastereoisomeric mixture (1:1) of the two forms 2*R*, 3*R*, 12*S*, 13*S* and 2*R*, 3*R*, 12*R* and 13*R*. Asterisks indicate optically active centres.

cancer chemoprevention agents, and such information is extremely valuable in the planning of clinical intervention studies. The 'transgenic adenocarcinoma of the mouse prostate' (TRAMP) is a model of prostate cancer which mimics progressive forms of the human disease. Expression of the SV40 early genes (T and t antigen) in TRAMP mice is driven by the prostate-specific promoter probasin, leading to cell transformation within the prostate.[12] All male TRAMP mice develop prostate cancer from approximately 18 weeks of age, and the disease progresses from prostatic intraepithelial neoplasia to histologic cancer and finally to carcinoma, which can metastasis to lymph nodes, lungs, liver and bone.[13] The *Apc*^{Min} mouse is a model of intestinal carcinogenesis genetically driven by a truncating *Apc* gene mutation.[14] It resembles the human heritable condition familial adenomatous polyposis coli (FAP). Tea polyphenols, genistein and curcumin are polyphenolic phytochemicals currently at varying stages of clinical evaluation, which have been found to impede carcinogenesis in these two models. The first two interventions interfered with carcinogenesis in TRAMP mice,[15,16] and curcumin slowed adenoma development in *Apc*^{Min} mice.[17,18]

Several mechanisms have been proposed to explain how silibinin may interfere with carcinogenesis. Amongst these mechanisms are impairment of receptor tyrosine kinase and erbB1 signalling, upregulation of cyclin-dependent kinase inhibitors causing attenuation of cancer cell growth and perturbation of cell cycle progression,[19,20] induction of cancer cell differentiation[21] and anti-angiogenesis.[22] Especially noteworthy is the finding that silibinin is able to modulate the insulin-like growth factor (IGF) system. IGFs are mediators of cell survival in that they can inhibit apoptosis and influence differentiation of many normal and malignant cell types.[23–25] The IGF system is regulated by IGF binding proteins (IGFBPs), especially IGFBP-3, which bind IGFs in the extra-cellular milieu with high affinity and specificity, thus reducing the bioavailability of IGFs. Epidemiological studies have linked increased serum concentrations of IGF-1, decreased concentrations of IGFBP-3, or both, with an increased risk of advanced prostate cancer,[26] although the validity of such an association has recently been questioned in a large case-control study.[27] Silibinin increased levels of IGFBP-3 in prostate cancer cells *in vitro*[28] and in prostate tumour-bearing rodents *in vivo*.[1] These results intimate that circulating IGF-1/IGFBP-3 levels may be suitable candidates for pharmacodynamic markers of efficacy in prostate cancer intervention studies with silibinin.

Two recent pilot studies of phytosomal silibinin formulations in patients with colorectal[29] or prostate cancer[10] define doses and schedules suitable for further clinical studies. Nevertheless many issues pertinent to the pharmacodynamics and pharmacokinetics of silibinin require optimisation prior to the further clinical evaluation of its potential value in cancer chemoprevention. In order to accrue preclinical information which might help define how best to evaluate silibinin or silipide in the clinic, we compared aspects of their pharmacology in TRAMP and *Apc*^{Min} mice. The work was specifically designed to test the hypotheses that silibinin and silipide delay prostate carcinogenesis and affect circulating levels of IGF-1/IGFBP-3 in TRAMP mice, and that they interfere with intestinal carcinogenesis in *Apc*^{Min} mice. Furthermore, we explored whether any differences in efficacy between silipide and silibinin may be explained in terms of plasma and tissue levels of silibinin.

2. Materials and methods

2.1. Animals

TRAMP mice on a C57BL/6J background and C57BL/6J Min/+ (Apc^{Min}) mice were bred in the Leicester University Biomedical Services facility using animals originally obtained from either the NCI Mouse Repository (NCI Frederick, TRAMP) or the Jackson Laboratory (Bar Harbor, ME, Apc^{Min}). Ear tissue was obtained from mice at approximately 10–14 days of age in order to assess the presence of the transgene using PCR as described previously[18] [The Jackson Laboratory website: www.jax.org].

2.2. Interventions

Silibinin (>98% pure as checked by HPLC analysis) was purchased from Sigma–Aldrich Comp. Ltd. (Gillingham, UK). 'Silipide' (IdB 1016), a phytosome product marketed for use as a hepatoprotectant (see www.indena.it/pdf/prodottiweb.pdf), was provided by Indena SpA (Milan, Italy). Silipide contains silibinin and soy phosphatidylcholine at a molar ratio of 1:1, in terms of percentage weight this equals approximately 40% silibinin and 60% phosphatidylcholine.

2.3. Animal experiments and dosing

Experiments were carried out under animal project license PPL 40/2496, granted to Leicester University by the UK Home Office. The experimental design was vetted by the Leicester University Local Ethical Committee for Animal Experimentation and met the standards required by the UK Co-ordinating Committee on Cancer Research guidelines.[30] At four weeks of age mice received standard AIN 93G diet (Dyets Inc., Bethlehem, PA, US) or AIN diet supplemented with silibinin or silipide (Indena SpA, Milan, Italy) (0.2% w/w in terms of silibinin) to the end of the animals' life. The dietary dose of silibinin used (0.2%, approximately 300 mg/kg per day) in mice equates to approximately 1.8 g per human per day, assuming a body surface area of 1.8 m^2 accompanying a body weight of 70 kg, when extrapolated on the basis of body surface area.[31] This dose is similar to high doses employed in clinical trials.[9,10]

Appearance and weight of the mice were checked on a weekly basis. Mice showing signs of distress, weight loss or very large tumours were killed as stipulated in the licence. In the analytical chemical experiments using C57BL/6J wild-type mice, mice received silibinin or silipide (0.2% in terms of silibinin) with their diet for 21 days, after which they were killed. Murine blood was obtained by cardiac exsanguination (halothane anaesthesia). Prostate and liver tissues were excised, plasma was obtained, and tissue and plasma samples were frozen (–80 °C) until analysis.

2.4. Assessment of tumour development

From 11 weeks of age TRAMP mice were palpated once or twice weekly for the presence of tumour. Animals were killed in week 28 (TRAMP) or 18 (Apc^{Min}). Murine tissues were excised, weighed and placed in buffered formalin for histopathology (see below). In the TRAMP mice, tumour tissue constituted 90% or more of total genitourinary (GU) tract mass (prostate, prostate tumour, seminal vesicles and empty bladder). Separation of prostate tumour from seminal vesicles was often difficult. Therefore in the results, GU tract weight values are given to reflect tumour development. The presence in some TRAMP mice of large poorly differentiated (pd) carcinomas confounded comparison of tumour size between groups. Therefore, the consequence of intervention in this model was assessed in two ways: by GU tract weight in the case of well differentiated (wd) adenocarcinomas, and by incidence in the case of pd tumours. Apc^{Min} mice were killed and their intestinal tract was removed and flushed with phosphate-buffered saline. Intestinal tissue was cut open longitudinally and examined under a magnifying lens. Multiplicity, location and size of adenomas,[18] and packed red cell volume (haematocrit)[32] were measured as described previously. In some TRAMP and Apc^{Min} mice blood was obtained by cardiac puncture under terminal halothane anaesthesia into heparinised tubes. PCR analysis of TRAMP tumour tissue obtained from mice on control diet, silibinin or silipide suggests that neither intervention interfered with the expression of the SV40 transgene (result not shown).

2.5. Histopathology

Maxillary gland, lungs, liver, kidneys, seminal vesicles, prostate and dorsal abdominal connective tissue of TRAMP or C57BL/6J wild-type mice and the intestinal tract from Apc^{Min} mice were fixed in formalin for a minimum of 2 weeks. All tissues were embedded in paraffin wax, and standard sections (5 μm thick) were cut and stained with haematoxylin and eosin for histopathological assessment. In the interpretation of the pathology of the TRAMP tumours criteria outlined in the Bar Habor classification were applied.[33]

2.6. Measurement of IGF-1 and IGFBP-3 concentrations

TRAMP mice received standard diet or diet fortified with silibinin or silipide (0.2% silibinin equivalents) for 30 weeks post weaning, after which they were exsanguinated under terminal halothane anaesthesia. Levels of IGF-1 and IGFBP-3 were determined in the plasma using the enzyme-linked immunosorbent assay (ELISA) kits 'Quantikine Mouse IGF-1' (catalogue number MG100) and 'Mouse IGFBP-3' (catalogue number DY775, both from R+D Systems, Abingdon, UK). The IGF-1 kit procedure contained an acid-ethanol extraction step to separate IGFs from their binding sites. The assays were validated and performed according to the vendor's instructions. Information on circulating IGFBP-3 levels in mice is sparse, and published values vary considerably between studies.[16,34] Therefore in a preparatory experiment we analysed IGFBP-3 levels in plasma from several mouse strains to determine typical levels and variability. Mean values varied between 1120 and 1450 ng/mL depending on strain, with intra-strain coefficients of variation of 25–35% ($n = 6$–10). The IGFBP-3 level observed in C57BL/6J mice in the experiment described here (920 ± 310 ng/mL) is compatible with these values. The molar ratio of IGF-1 to IGFBP-3 was calculated as (0.13 × IGF-1 concentration [ng/mL])/(0.036 × IGFBP-3 concentration [ng/mL]).[35]

2.7. Chemical analysis of silibinin

Liver and prostate tissues were thawed, weighed and homogenised in an equal part of KCl solution (0.15 M). Samples of plasma or tissue homogenate were mixed with three parts of ice-cold methanol. The mixture was centrifuged, the supernatant was decanted and dried under nitrogen, reconstituted in aqueous methanol (70%, containing 5% acetic acid) and analysed for silibinin by HPLC with UV detection, employing a gradient system with a two-component mobile phase. The details, characterisation and validation (for silibinin) of the method, which separates parent compound from its many conjugate metabolites, have been described before.[36] Silibinin is a mixture of two diastereoisomers, and their limits of quantitation were 3 and 5 ng/mL (6 and 11 pmol/mL). The results give values for the sum of both diastereoisomers. Silibinin was quantitated in the plasma, prostate and gastro-intestinal mucosa tissue from wild-type C57BL/6J, TRAMP and Apc^{Min} mice using this method.

2.8. Statistical evaluation

Evaluation of significance of differences to the appropriate controls was performed by either non-parametric Mann–Whitney *U*-test (to assess TRAMP adenocarcinoma weight) or Student's *t*-test for independent samples (to assess Apc^{Min} adenoma number and IGF-1/IGFBP-3 values).

3. Results

3.1. Effect of silibinin and silipide on mouse body weight

TRAMP or Apc^{Min} mice received unformulated silibinin or silipide at 0.2% (silibinin equivalents) in the diet for their lifetime. Intervention did not affect murine bodyweight (result not shown).

3.2. Effect of silibinin and silipide on prostate carcinogenesis

Neoplastic development was assessed in week 28, when tumours were small. Histopathological investigation revealed

that prostate tumour had replaced normal prostate tissue in all TRAMP mice (control and treated). Consistent with the original description of the TRAMP model,[13] two distinct histological types of malignant tumours were observed: wd adenocarcinomas in the prostatic epithelium and pd carcinomas. The wd tumours showed a cribriform glandular pattern and spread locally into adjoining seminal vesicles. Advanced wd tumours were accompanied by small lung metastases. The pd tumours were composed of large cells showing little or no glandular differentiation, and their size and weight were mostly an order of magnitude higher than those of the wd adenocarcinomas. They infiltrated local tissue including bladder as well as retroperitoneal lymph nodes, and rarely the pancreas. TRAMP mice presented also with atypical hyperplasia (prostatic intraepithelial neoplasia) and stromal hyperplasia in the epithelia of seminal vesicles comprising fronds of cells overlaying loose connective tissue stroma. Intervention with silipide reduced GU tract weight in mice with wd adenocarcinomas by 31% (Fig. 2A), whilst consumption of silibinin did not affect GU tract weight. The proportion

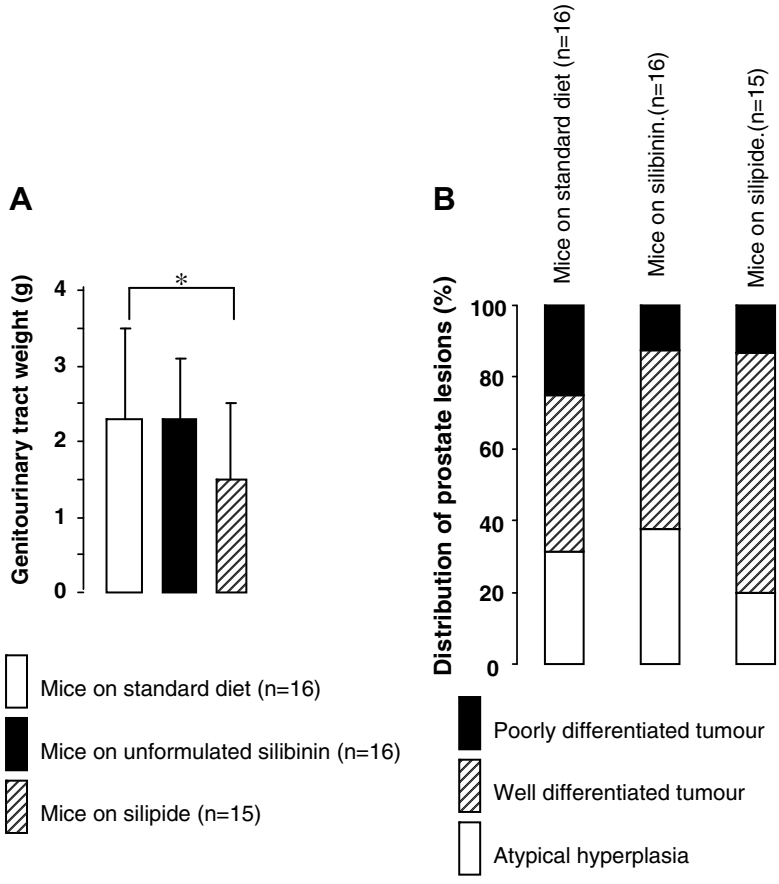

Fig. 2 – Prostate cancer development in TRAMP mice which received standard diet (open bars) or diet fortified with unformulated silibinin (closed bar) or silipide (hatched bar) at 0.2% (silibinin equivalents) for 24 weeks post-weaning. Tumour development is reflected by weight of genitourinary tract (prostate, prostate tumour, seminal vesicles and empty bladder) in mice bearing well differentiated prostate adenocarcinomas (A) and by percentage of mice per intervention group presenting with poorly differentiated prostate carcinomas, well differentiated carcinomas and/or atypical hyperplastic lesions (B). Asterisk indicates that the difference between mice on silipide and those on control diet was significant ($p < 0.005$, Mann–Whitney). Values in A are the means ± SD. For comparison, the genitourinary tract weight in wild-type C57BL/6J mice kept on standard diet was 0.5 ± 0.2 g ($n = 6$). For details of animal experiments and assessment of tumour development, see Section 2.

Table 1 – Incidence of malignancy-related pathology in TRAMP mice which received dietary silibinin or silipide(0.2% silibinin equivalents)

	Metastasis		Glandular/stromal hyperplasia in seminal vesicles	
	Lymph (%)	Lungs (%)	Mild/moderate (%)	Severe (%)
Wild-type C57BL/6J	0/6 (0)	0/6 (0)	0/6 (0)	0/6 (0)
TRAMP control	3/16 (19)	1/16 (6)	14/16 (88)	3/16 (19)
TRAMP on silibinin	0/16 (0)	3/16 (19)	15/16 (94)	2/16 (13)
TRAMP on silipide	1/15 (7)	1/15 (7)	14/15 (93)	2/15 (13)

of mice which presented with large pd carcinomas in either intervention group was 39% of that seen in the control group, and compared to mice on control diet, more mice in the silibinin group displayed atypical hyperplasia, whilst more mice on silipide had well differentiated tumours (Fig. 2B). The changes described in Fig. 2B were not statistically significant when analysed by the χ^2 test. Neither intervention interfered with the expression of the SV40 transgene (result not shown). Both interventions decreased metastatic deposits in lymph nodes, but failed to reduce metastases in the lungs and glandular and stromal hyperplasia in the epithelia of seminal vesicles (Table 1). None of the C56BL/6J wild-type mice presented with manifestations of metastasis or hyperplasia.

3.3. *Effect of silibinin and silipide on circulating levels IGF-1 and IGFBP-3*

IGF-1 and IGFBP-3 levels were determined in the plasma from TRAMP mice which received silibinin or silipide for 30 weeks post-weaning and, for comparison, also in the plasma of control C57BL/6J mice, the TRAMP background strain. Circulating IGF-1 levels in plasma from control TRAMP mice were 41% above those in their C57BL/6J wild-type counterparts. IGFBP-3 levels in TRAMP mice were reduced by 84% compared to their background strain, and the molar ratio of IGF-1/IGFBP-3 in TRAMP mice was 4.9-fold above that in C57BL/6J wild-type mice (Fig. 3). Both interventions returned circulating levels of IGF-1 (Fig. 3A) and of IGFBP-3 (Fig. 3B) and their ratio (Fig. 3C), at least partially, towards values observed in the background strain. Levels of IGF-1 in mice on silibinin or silipide were reduced by 11% and 36%, respectively, compared to control TRAMP mice, the latter difference being significant (Fig. 3A). Consumption of silibinin or silipide increased circulating IGFBP-3 levels significantly by factors of 5.9 and 3.9, respectively, in comparison with TRAMP mice on control diet (Fig. 3B). The IGF-1/IGFBP-3 ratio was decreased significantly by silibinin and silipide to 24% and 47%, respectively, of the corresponding value in TRAMP mice on standard diet (Fig. 3C). In a control experiment to examine any effect of intervention on IGFBP-3 in C57BL/6J wild-type mice, animals received a diet containing 0.2% silibinin or silipide for 21 days, and plasma IGFBP-3 levels were compared. In contrast to the scenario in TRAMP mice, neither intervention raised IGFBP-3 levels over those in mice on standard diet (results not shown), demonstrating that the modulation of this protein by silibinin or silipide can be observed only in mice with the malignant genotype.

3.4. *Effect of silibinin and silipide on intestinal carcinogenesis*

Intervention with silibinin or silipide reduced adenoma numbers in the small intestine by 18% or 30%, respectively (Fig. 4A), albeit the difference failed to reach levels of significance. Neither intervention affected adenoma numbers in the colon (Fig. 4B). At the late stage of adenoma development

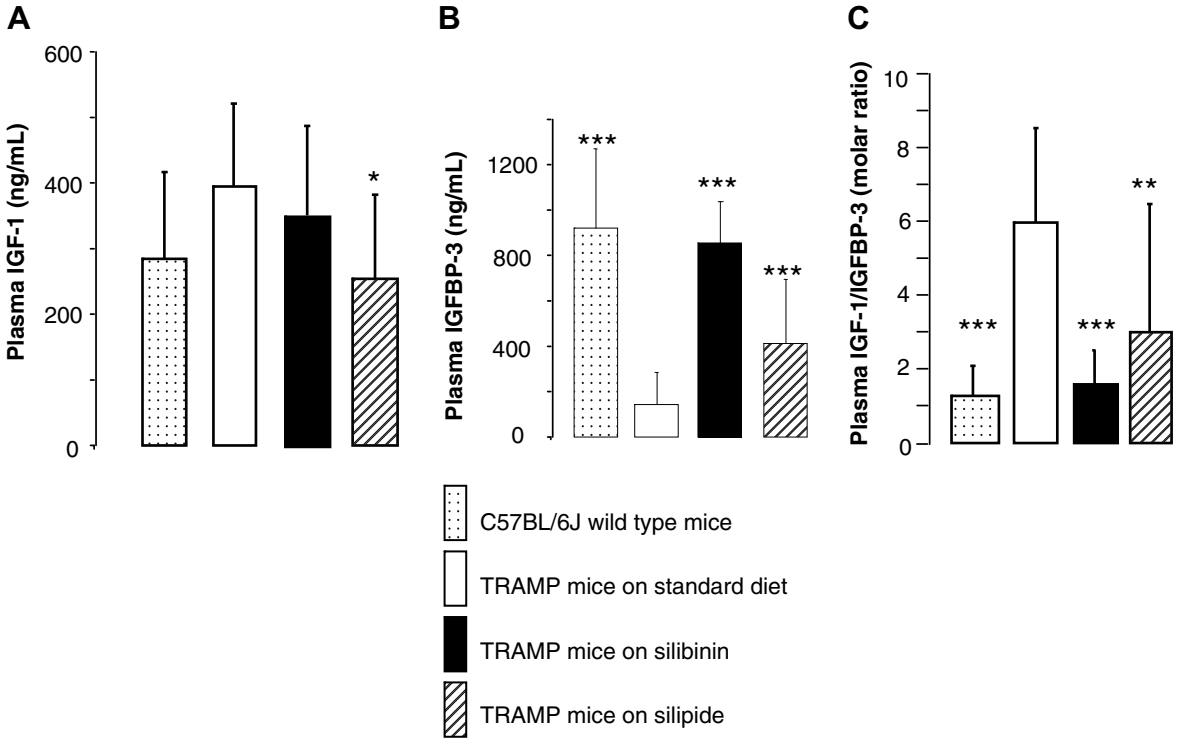

Fig. 3 – Plasma levels of IGF-1 (A), IGFBP-3 (B) and molar ratio of levels of IGF1 over IGFBP-3 (C) in TRAMP mice which received standard diet (open bars) or diet fortified with unformulated silibinin (closed bars) or silipide (hatched bars) at 0.2% (silibinin equivalents) for 30 weeks post weaning and, for comparison, in C57BL/6J wild-type mice (stippled bars). Values are the means ± SD of 13–16 mice. Asterisks indicates that the difference between TRAMP mice on silibinin or silipide and those on control diet was significant, $^{*}p < 0.02$, $^{**}p < 0.005$, $^{***}p < 0.001$. For details of animal experimentation and IGF-1/IGFBP-3 measurements, see Section 2.

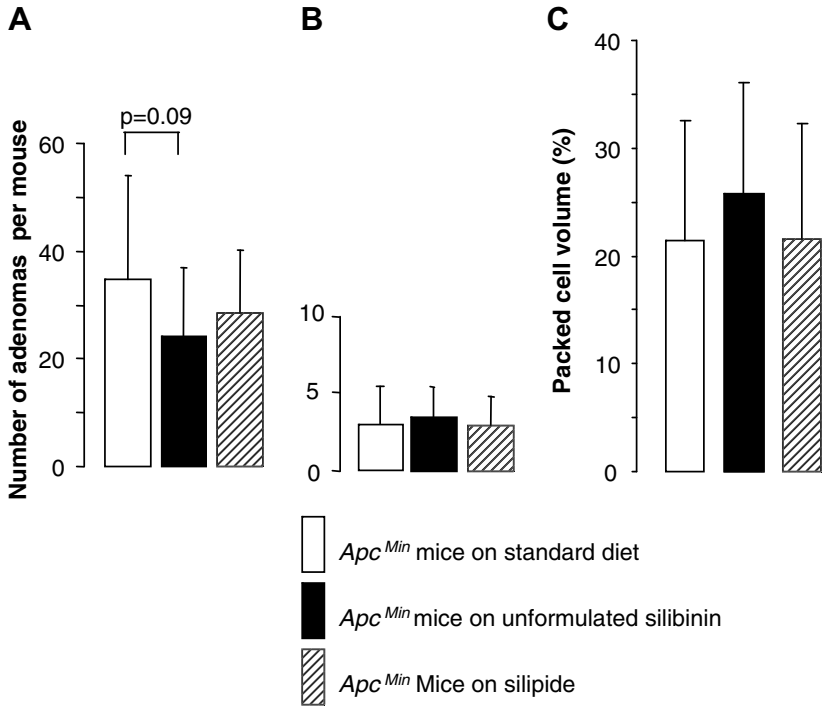

Fig. 4 – Adenoma numbers in the small intestinal tract (A) or colon (B) and packed cell volume (C) in Apc^{Min} mice which received standard diet (open bars) or diet fortified with unformulated silibinin (closed bar) or silipide (hatched bar) at 0.2% (silibinin equivalents). The results are the means ± SD of groups of 15–16; the *p* value suggests that the difference in small intestinal adenoma numbers between control and intervention with silibinin was outside significance levels. For details of animal experiments and assessment of adenoma development see Section 2.

Apc^{Min} mice suffer from intestinal bleeding, which causes a dramatic fall in haematocrit, and changes in haematocrit in this model reflect adenoma development. Intervention with silibinin raised the haematocrit, measured at the end of the experiment, by 21% (not significant), whilst the haematocrit in mice on silipide was unchanged compared to controls (Fig. 4C).

Histopathological analysis of the small intestine of Apc^{Min} mice showed focal proliferative lesions ranging from hyperplastic glands to larger areas of glandular hyperplasia and polypoid adenomas, without any significant differences in morphology between mice on control diet or on silipide or silibinin.

3.5. *Levels of silbinin in blood and tissues*

Silibinin was measured by HPLC analysis in plasma, prostate, liver and gastrointestinal mucosa from C57BL/6J wild-type mice, the background strain of the TRAMP and Apc^{Min} mice, which had received either silibinin or silipide (0.2% in terms of silibinin equivalents) in their diet for 21 days prior to analysis. Fig. 5 shows that levels of silibinin recovered from plasma, prostate or liver tissue of mice on unformulated silibinin were close to or below the limit of detection (6 and 11 pmol/mL or g, for both diastereoisomers). In contrast, silibinin levels in plasma, prostate or liver of mice on silipide were 0.5 μM, 24 and 7 nmol/g, respectively, thus easily within the measurable range. Silibinin levels in the intestinal mucosa of mice on either intervention were two orders of magnitude higher than those in prostate or liver. In mice on unformulated silibinin these levels were 1.9 μmol/g tissue, almost 2.5 times higher than those in mice on silipide. Silibinin levels were also quantitated in plasma, prostate and liver tissue from three TRAMP and in plasma and intestinal mucosa from three Apc^{Min} mice which had received silibinin/silipide for their lifetime, to ensure that the silibinin levels measured in the wild-type C57BL/6J mice had reached steady state after 21 days consumption of silibinin/silipide, and that they were representative of levels in tumour-bearing mice. Results obtained in this experiment were very similar to those described in Fig. 5.

4. Discussion

The results described above show for the first time that silipide, a phospholipid-containing formulation of silibinin, retards prostate carcinogenesis in the TRAMP mouse as reflected by the reduction in size of wd adenocarcinoma. Silipide also seemed to reduce the incidence of pd tumours, although the difference to control mice was not significant. Consistent with anticarcinogenic efficacy, silipide affected the murine IGF-1/IGFBP-3 system. Intervention with silipide decreased plasma levels of IGF-1, increased levels of IGFBP-3 and reduced the IGF-1/IGFBP-3 ratio to levels similar to those observed in wild-type mice. Intervention with unformulated silibinin, which furnished much lower agent concentrations in prostate tissue than silipide, reduced the incidence of pd carcinoma but failed to affect wd adenocarcinoma size. The apparently higher potency of silipide as compared to its

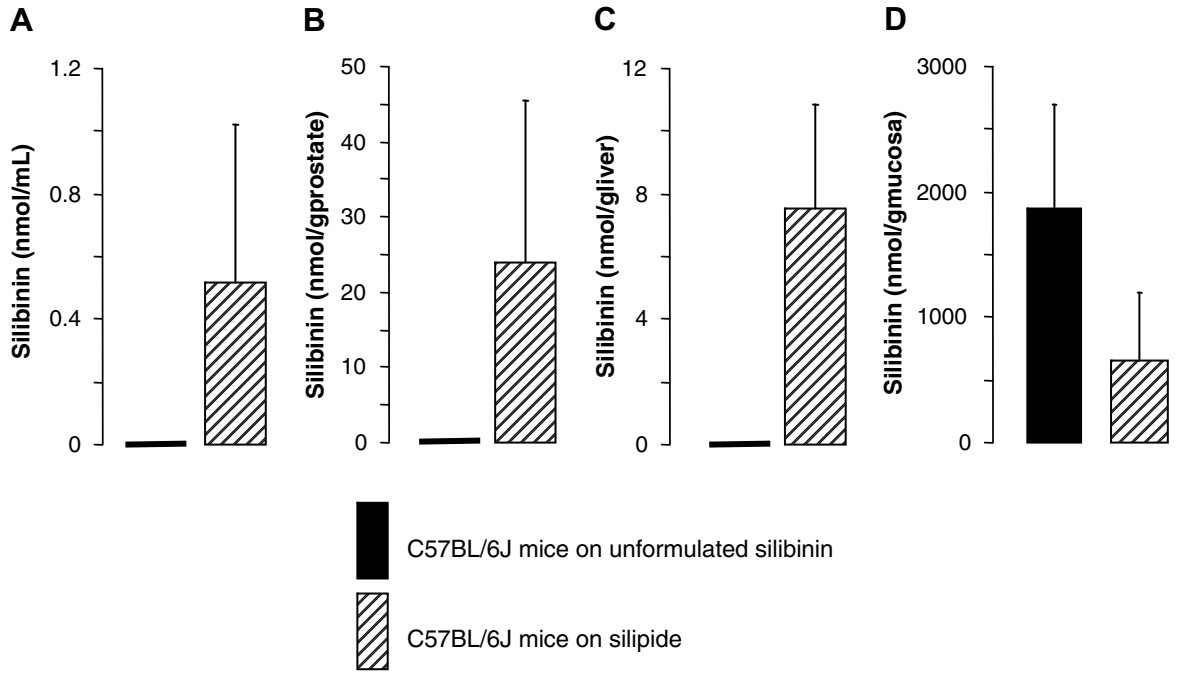

Fig. 5 – Levels of silibinin in the plasma (A), prostate (B), liver (C) and gastrointestinal mucosa (D) of C57BL/6J mice, the TRAMP and Apc^{Min} background strain, which received unformulated silibinin (closed bars) or silipide (crossed bars) at 0.2% (silibinin equivalents) with their diet for 21 days. Levels, which constitute the sum of both stereoisomers of silibinin, were analysed by HPLC. There was no silibinin in tissues of mice on control diet. Results are the means ± SD of 8 mice. For details of animal experiments and HPLC analysis, see Section 2.

unformulated counterpart can be explained by its pharmaceutical properties. The lipophilic silibinin–phospholipid complex, which constitutes silipide, is thought to improve silibinin absorption in the gastro-intestinal tract via the formation of a phospholipid monolayer on the mucosal surface, supporting the transition of silibinin from the hydrophilic gut content across lipophilic membranes into cells.[11] In spite of the poor systemic availability of unformulated silibinin in mice, its consumption affected the murine IGF system, in that it restored IGFBP-3 levels and the IGF-1/IGFBP-3 ratio to baseline wild-type values, albeit reducing IGF-1 levels only non-significantly. The prostate cancer-delaying efficacy and pharmacodynamic consequences observed for silibinin, especially as its phospholipid formulation, in TRAMP mice are consistent with the inhibition of prostate tumour development reported for silibinin in nude mice bearing the DU145 human tumour xenograft[1] and for silymarin in rats in which prostate adenocarcinoma were induced by an exposure to 3,2′-dimethyl-4-aminobiphenyl.[2] Unformulated silibinin at a dietary dose 2.5-fold higher than the one used here was very recently shown to ameliorate prostate tumour development in the TRAMP mouse modestly,[37] similar to the observations reported here. This activity was accompanied by a decrease in prostate tumour proliferative index and an increase in prostate tumour cell apoptosis. Although these authors found up-regulated IGFBP-3 levels in the tumour tissue of mice on silibinin as compared to controls, they failed to demonstrate changes in circulating levels of IGF-1/IGFBP-3, in contrast to the observations presented here.

Enhanced IGF-1 levels can contribute to the initiation and progression of prostate cancer by a variety of mechanisms, including induction of vascular endothelial growth factor (VEGF) and engagement of the angiogenic switch leading to prostatic neovascularisation.[38] Type I IGF receptors, via which IGFs mediate physiological effects, regulate matrix metalloproteinase (MMP)-2 synthesis,[39] and increased IGF signalling has been shown to enhance the expression of VEGF, urokinase plasminogen activator and MMPs, which in turn correlate with tumour angiogenesis and metastasis.[38–42] One way in which silibinin is thought to lower free IGF-1 levels is by up-regulating IGFBP-3.[1] *In vitro* data suggest that IGFBP-3 can affect cell proliferation and apoptosis also independent of IGF-1, in addition to its effects mediated via IGF-1 reduction. For example, IGFBP-3 compromised proliferation in breast cancer cells unresponsive to IGF-1[43] and in mouse fibroblasts lacking IGF-1 receptors.[44] All of these results are consistent with the notion that a decrease in IGF-1 and/or an elevation of IGFBP-3 may have contributed, at least in part, to the anticarcinogenic effects of silipide/silibinin in TRAMP mice.

There was a hint of efficacy of unformulated silibinin as a chemopreventive agent against gastrointestinal carcinogenesis in the Apc^{Min} mouse model, whilst silipide failed altogether to affect intestinal adenoma development. The tentative evidence of efficacy of silibinin complements the results of two preclinical studies of silymarin in carcinogen-induced rodent colorectal cancer models,[6,7] implying that milk thistle flavonolignans may delay gastrointestinal carcinogenesis.

The results of the quantitative chemical analysis of silibinin in blood and tissues shows that, when administered with the diet in mice, silipide is superior to unformulated silibinin in terms of systemic silibinin delivery. Differences in activity between the two interventions in the TRAMP and Apc^{Min} mice can be interpreted in the light of the observed discrepancies in silibinin levels. Blood and prostate levels were much higher after consumption of silipide than after unformulated silibinin, compatible with the relative enhanced ability of silipide as compared to unformulated silibinin to interfere with TRAMP wd adenocarcinoma development. The concentration of silibinin (24 nmol/g) recovered in this study from the prostate of mice, which received silipide, is within the concentration range of silibinin which reduced the growth of human–derived DU145 prostate cells in culture.[1] This fact intimates the possibility that mechanisms responsible for anticarcinogenesis in prostate cells in culture may also be engaged by silibinin in the TRAMP mouse prostate *in vivo*. Levels of silibinin in the gastrointestinal tract, where exposure does not depend on systemic delivery of agent, were higher after the consumption of unformulated silibinin than after silipide, consistent with the tentative potency difference between them in the Apc^{Min} mouse.

How may the findings presented above, together with those published previously, be exploited in the planning of the potential development of milk thistle preparations in humans? Obviously extrapolation to humans of the results obtained here in two genetic carcinogenesis models needs to be made with utmost caution. First and foremost, both interventions were equally well tolerated as reflected by the lack of adverse effects on murine body weight, reinforcing the good preclinical safety record of silibinin and silipide. The results in TRAMP mice described here and recently by others[37] suggest that the malignancy-delaying activity of silibinin in this model, whilst significant, is only modest. One needs to bear in mind that knowledge of how malignancy-delaying potency in the TRAMP mouse relates to efficacy in humans is lacking, so that we do not know if activity in the TRAMP mouse needs to be considerable to predict efficacy in humans, or if clinical effect can also be expected when TRAMP anticarcinogenesis is only marginal. Nevertheless as silibinin has shown convincing activity in another rodent model of prostate carcinogenesis,[1] the results shown here support the notion that it should be advanced to the stage of clinical evaluation, e.g. in patients under active surveillance. Circulating levels of IGF-1 and/or IGFBP-3 were shown here to respond sensitively to silipide in TRAMP mice, but this phenomenon may not be causally related to the observed anticarcinogenesis. Further research needs to establish whether IGF-1/IGFBP-3 might be useful as potential pharmacodynamic markers of clinical efficacy of silibinin. A recent phase I trial in hormone-refractory prostate cancer patients of a phytosomal silibinin formulation similar, but not identical, to silipide suggests that repeated administration of a daily dose equivalent to 4.3 g silibinin, given in three divided doses, is well tolerated and constitutes a suitable starting dose for future phase II trials.[29] Extrapolation of the results obtained in the Apc^{Min} mouse hints at the possibility that silibinin may be useful in the prevention of adenoma recurrence. In the light of the difference between unformulated silibinin and silipide in terms of intestinal levels achieved and putative efficacy, unformulated silibinin may well constitute the preferable pharmaceutical option as compared to silipide, to be employed in such intervention trials.

Conflict of interest statement

None declared.

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