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Short communication

Synthesis of platinum(II) and palladium(II) complexes with 9,9-dihexyl-4,5-diazafluorene and their *in vivo* antitumour activity against Hep3B xenografted mice

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ABSTRACT

Two complexes dichloro(9,9-dihexyl-4,5-diazafluorene)platinum(II) (Pt-DHF) and dichloro(9,9-dihexyl-4,5-diazafluorene)palladium(II) (Pd-DHF) were synthesized and their *in vivo* antitumour activity was investigated using an athymic nude mice model xenografted with human Hep3B carcinoma cells. Pt-DHF- and Pd-DHF-treated groups showed significant tumour growth inhibition (with about 9-fold and 3-fold tumour growth retardation) when compared with the vehicle control group. The liver toxicology effects on the animals of the two compounds were investigated. Pt-DHF and Pd-DHF-treated groups had a lower alanine transaminase and aspartate transaminase values than those of the vehicle treated group as the animals from the vehicle control group had very heavy hepatoma burden. We assume that both complexes could be further investigated as effective antitumour agents and it is worthwhile to study their underlying working mechanism.

1. Introduction

Metal complexes are important in the development of antitumour drugs because of the interaction between metal complexes with biomolecules in human body and the high stability of their final products under various conditions. Metal complexes have been employed in antitumour therapy since the discovery of the cytotoxicity of cisplatin (*cis*-Pt(NH_3)$_2$$Cl_2$) by Rosenberg and coworkers in the late 1960s [1,2]. Cisplatin was the first identified member of the platinum-based chemotherapeutic drugs. It has been applied clinically for more than three decades in oncology [2,3]. The introduction of cisplatin to the antitumour therapy has initiated the design and synthesis of metal complexes including platinum and palladium to improve the therapeutic activity of the

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antitumour drugs.

Pt(II) ion has a strong binding ability to sulfur. After taking the Pt(II)-based drug in the human body, there is a high potential for binding with sulfur-donor biomolecules, which can be found in peptides, proteins and enzymes. The interaction of Pt(II) complexes with S-containing biomolecules can lead to strong cytotoxicity [4,5]. The anti-tumour activity of Pt(II)-based drugs can be due to the interaction between the metal complex and genomic DNA [4,6]. Owing to the structural similarities and significant overlap of the coordination chemistry for palladium and platinum, these two metals are closely related [7]. Palladium related complexes have also been investigated intensively in the field of medicinal chemistry [8,9].

Utku et al. reported the *in vitro* anticancer activity of the synthesized benzimidazole-platinum(II) complexes on the human HeLa (ER−), MCF-7 (ER+) and MDA-MB 231 (ER−) cell lines. Pt(II) complex bearing oxalate leaving ligand possessed the most active anticancer activity, with about two or five-fold greater than those of the other benzimidazole-platinum complexes tested [10]. Kovala-Demertzi and co-workers studied the anticancer property of the palladium(II) complexes synthesized by the reaction of Pd(II) salt with 2-formylpyridine-4-*N*-ethyl-thiosemicarbazone, HFo4NEt. The complex [Pd(H_2Fo4NEt)(Fo4NEt)Cl_2] exhibited a better anticancer activity, with the IC_{50} values against MCF-7 and T-24 cancer cell lines being 8.42 and 5.88 μM, respectively, when compared with the complexes [Pd(Fo4Nethyl)Cl] (IC_{50} = 104.1 and 72.5 μM) and [Pd(Fo4Nethyl)$_2$] (IC_{50} = 14.52 and 7.59 μM) [11]. Motswainyana and co-workers examined the anticancer property of the synthesized palladium(II) and platinum(II) complexes: dichloro[(2-diphenylphosphino-benzylidene)-2-methylphenylen-amine]palladium(II), dichloro[2-diphenylphosphino-benzylidene)-2,6-dimethylphenylen-amine]palladium(II), dichloro-[(2-diphenylphosphino-benzylidene)-2-methylphenylen-amine]platinum(II) and dichloro-[2-diphenylphosphino-benzylidene)-2,6-dimethylphenylen-amine]platinum(II). Both palladium(II) complexes possessed a stronger cytotoxicity towards MCF-7 and HT-29 cancer cell lines (mean IC_{50} = 28.5–48 μM) when compared with the platinum(II) complexes (mean IC_{50} = 50–87 μM) [12]. This team further reported that the synthesized bis(imino-quinolyl) platinum(II) complex displayed a slightly stronger anticancer activity (mean IC_{50} = 55 and 41 μM against MCF-7 and HT-29 cancer cells, respectively) when compared with the bis(imino-quinolyl) palladium(II) complex (mean IC_{50} = 60 and 46 μM) [13]. Oliveira et al. investigated the anticancer activity of complexes containing palladium(II) and platinum(II): [Pd(NH_3)$_4$][Pd(opba)] and [Pt(H_2opba)]·H_2O, where opba = 1,2-phenylenebis(oxamate) against the chronic myelogenous leukemia cell line. The palladium(II) complex [Pd(NH_3)$_4$][Pd(opba)] showed a better growth inhibition against leukemia cells (mean IC_{50} = 19.9 μM) than the platinum(II) complex [Pt(H_2opba)]·H_2O (mean IC_{50} = 27.35 μM) [14].

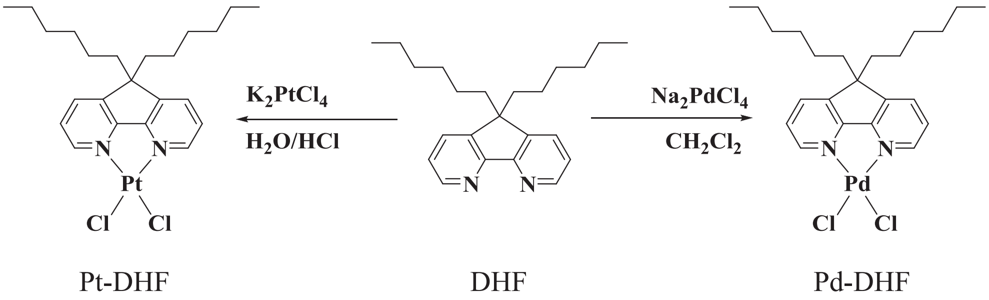
Barbara et al. reported the *in vitro* and *in vivo* biological properties of two bile acid-conjugated platinum(II) complexes: (NH_3)$_2$Pt(triacid) and (PPh_3)$_2$Pt(dehydrocholate)$_2$. (NH_3)$_2$Pt(triacid) showed a stronger growth inhibition on rat hepatoma cells (mean IC_{50} = 0.7 μM) after 48 h when compared with (PPh_3)$_2$Pt(dehydrocholate)$_2$ (mean IC_{50} = 3.8 μM). In a syngeneic and orthotopic rat hepatoma model, the (NH_3)$_2$Pt(triacid)-treated group displayed more than 6-fold tumour weight reduction at the dose of 80 mg/kg as compared to the control group and the (PPh_3)$_2$Pt(dehydrocholate)$_2$-treated group [15].

It appears that most of these studies have focused on *in vitro* anticancer analysis while *in vivo* antitumour studies including tumour size reduction evaluation have been infrequently reported. In our present study, two platinum(II) and palladium(II) complexes with 9,9-dihexyl-4,5-diazafluorene (DHF) derivatives were synthesized and their *in vivo* antitumour activities were investigated using an athymic nude mice model xenografted with human Hep3B carcinoma cells.

2. Results and discussion

2.1. Chemistry

The chemical structures and the synthetic protocols of the novel diazafluorene-based organic compounds are shown in Scheme 1. 9,9-Dihexyl-4,5-diazafluorene (DHF) was prepared using the method reported in the previous paper [16]. Platinum(II)-9,9-dihexyl-4,5-diazafluorene (Pt-DHF) complex was obtained from DHF by treatment with K_2PtCl_4 in water solution in the presence of a catalytic amount of conc. HCl in a high yield of 80% [17], while palladium-9,9-dihexyl-4,5-diazafluorene (Pd-DHF) congener was successfully synthesized using Na_2PdCl_4 in CH_2Cl_2 solution in 86% yield [18]. These air-stable compounds were isolated in high purity as golden or brown solids by column chromatography on silica gel eluting with CH_2Cl_2. These compounds were fully characterized by NMR (both ^{1}H and ^{13}C) spectroscopy (see Supporting Information) and fast atom bombardment mass spectrometry (FAB-MS). Both of them can afford good single crystals for X-ray diffraction analysis from their solid samples (Figs. 1 and 2). Based on our prior results with 4,5-diazafluoren-9-one as the coordinated ligands which showed very poor solubility in common solvents [18], we have purposely substituted the oxo group with long alkyl chains at the 9-position of fluorene in the present study to tune the solubility and hydrophobility of the metal complexes. The ligand DHF has been shown to possess a certain level of antitumour activity in athymic nude mice xenografted with human Hep3B carcinoma cells [16]. Since metal ions are promising candidates that have been successfully used for anticancer therapy [19], the potential antitumour potency was further investigated after the incorporation of metal ions (Pt and Pd) into the DHF (see Table 1).



Scheme 1. Synthetic profiles of Pt-DHF and Pd-DHF.

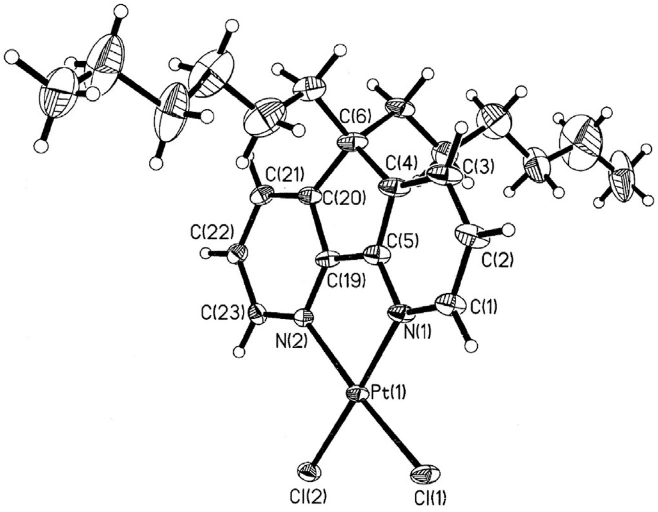


Fig. 1. Solid-state structure of Pt-DHF. Selected bond distances (Å) and angles (°): Pt(1)-Cl(1) 2.271(1); Pt(1)-Cl(2) 2.281(1); Pt(1)-N(1) 2.047(4); Pt(1)-N(2) 2.073(3); N(1)-Pt(1)-N(2) 83.8(1); Cl(1)-Pt(1)-Cl(2) 92.89(4).

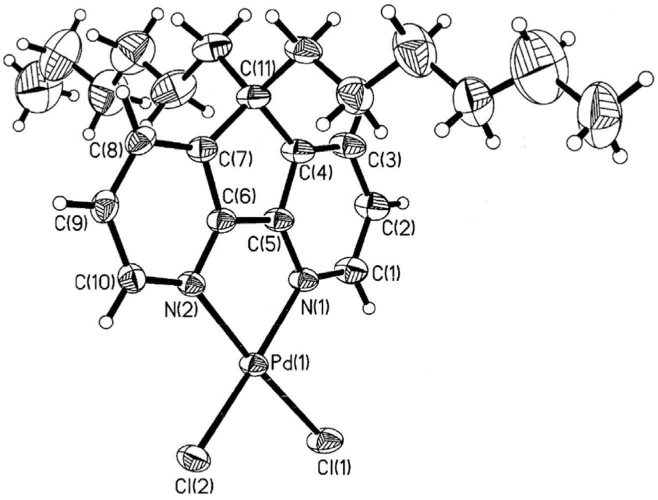


Fig. 2. Solid-state structure of Pd-DHF Selected bond distances (Å) and angles (°): Pd(1)-Cl(1) 2.2611(7); Pd(1)-Cl(2) 2.2707(7); Pd(1)-N(1) 2.069(2); Pd(1)-N(2) 2.093(2); N(1)-Pd(1)-N(2) 84.31(8); Cl(1)-Pd(1)-Cl(2) 93.18(3).

Table 1
Crystallographic data.

Compound	Pt-DHF	Pd-DHF
CCDC	1452122	1452123
Formula	$C_{23}H_{32}Cl_2N_2Pt$	$C_{23}H_{32}Cl_2N_2Pd$
Formula weight	602.5	513.81
Crystal system	Hexagonal	Hexagonal
space group	$P3_22_1$	$P3_22_1$
a/Å	12.3554(3)	12.452(1)
b/Å	12.3554(3)	12.452(1)
c/Å	26.5988(1)	26.767(4)
α/°	90	90
β/°	90	90
γ/°	120	120
V/Å^3	3516.5(2)	3594.2(7)
Z	6	6
Temperature/K	173(2)	293(2)
μ (Mo K_α)/mm^{-1}	6.224	1.008
D(calcd)/g cm^{-3}	1.707	1.424
Collected refl.	21334	21967
Unique refl.	5756	5916
R_{int}	0.036	0.0203
R_1[a] [$I > 2\sigma(I)$]	0.0262	0.0241
wR_2[b] [$I > 2\sigma(I)$]	0.0526	0.0611
R_1 [all data]	0.0321	0.0281
wR_2 [all data]	0.0543	0.0637
GOF	1.07	1.039
$\Delta\rho$/e Å^{-3}	0.725, −0.484	0.278, −0.291

[a] $R_1 = \Sigma(|F_o|-|F_c|)/\Sigma|F_o|$.
[b] $wR_2 = \{\Sigma[w(F_o^2-F_c^2)^2]/\Sigma[w(F_o^2)^2]\}^{1/2}$.

2.2. Preliminary animal experiments

Athymic nude mice xenografted with human Hep3B carcinoma cells were used as a model for this study. Mice with Hep3B cancer cells xenografted of average tumour volume from 200 mm^3 received intraperitioneal injection daily of either of buffer vehicle (saline for injection) or equal volume of Pt-DHF and Pd-DHF at 10 mg kg^{-1} for 9 consecutive days, respectively. The treatment stopping time (day 10) for tumour appearances of mice are shown in Fig. 3. As shown in Figs. 3 and 4, both Pt-DHF- and Pd-DHF-treated groups showed significant tumour growth inhibition (with about 9-fold and 3-fold tumour growth retardation, respectively) when compared with the vehicle control group at the end of the study. Both Pt-DHF and Pd-DHF revealed a stronger tumour growth inhibition than the ligand DHF itself (which was only about 2-fold tumour growth retardation [16] at the same dose of 10 mg kg^{-1} body weight). These results suggest the importance for the incorporation of Pt and Pd into the DHF as antitumour agents. Noticeably, extensively necrotic feature could be detected from the Pt-DHF-treated mice (Fig. 5B). For both the vehicle control group (Fig. 5A) and the Pd-DHF-treated group (Fig. 5C), tumour section displayed high cellular integrity.

In order to demonstrate whether the Pt-DHF and Pd-DHF at 10 mg kg^{-1} body weight has any possible toxicology effects on the animals under the current therapeutic protocol, hematoxylin and eosin (H and E) staining of liver sections (Fig. 5A–C) and plasma liver functional enzyme analysis including ALT and AST (Fig. 6) were investigated. Neither necrotic nor damaged tissue could be observed from the histological staining study of liver sections from sacrificed mice in all treated groups (Fig. 5D–F). Fig. 6 shows that both Pt-DHF and Pd-DHF-treated groups had a lower ALT and AST values than those of the vehicle treated group since the animals from the vehicle control group had very heavy hepatoma burden. Conclusively, no observable hepatic adverse effect could be identified when Pt-DHF or Pd-DHF at a concentration of 10 mg kg^{-1} body weight per day was administrated intraperitoneally in athymic nude mice.

3. Conclusions

We have demonstrated that the Pt-DHF and Pd-DHF complexes showed a much stronger *in vivo* antitumour activity than the DHF compound. The complexes-treated groups had a lower ALT and AST values than those of the vehicle treated group, suggesting that they exerted low liver toxicity under the therapeutic dosage (10 mg kg^{-1}). Our work here implies the importance of metal containing drugs for further antitumour regimen development. We assume that it is worthwhile to further study their underlying working mechanism and compare with those conventional metal containing antitumour regimens.

4. Experimental section

4.1. Chemistry

4.1.1. General methods

All of the manipulations were performed under a dry nitrogen

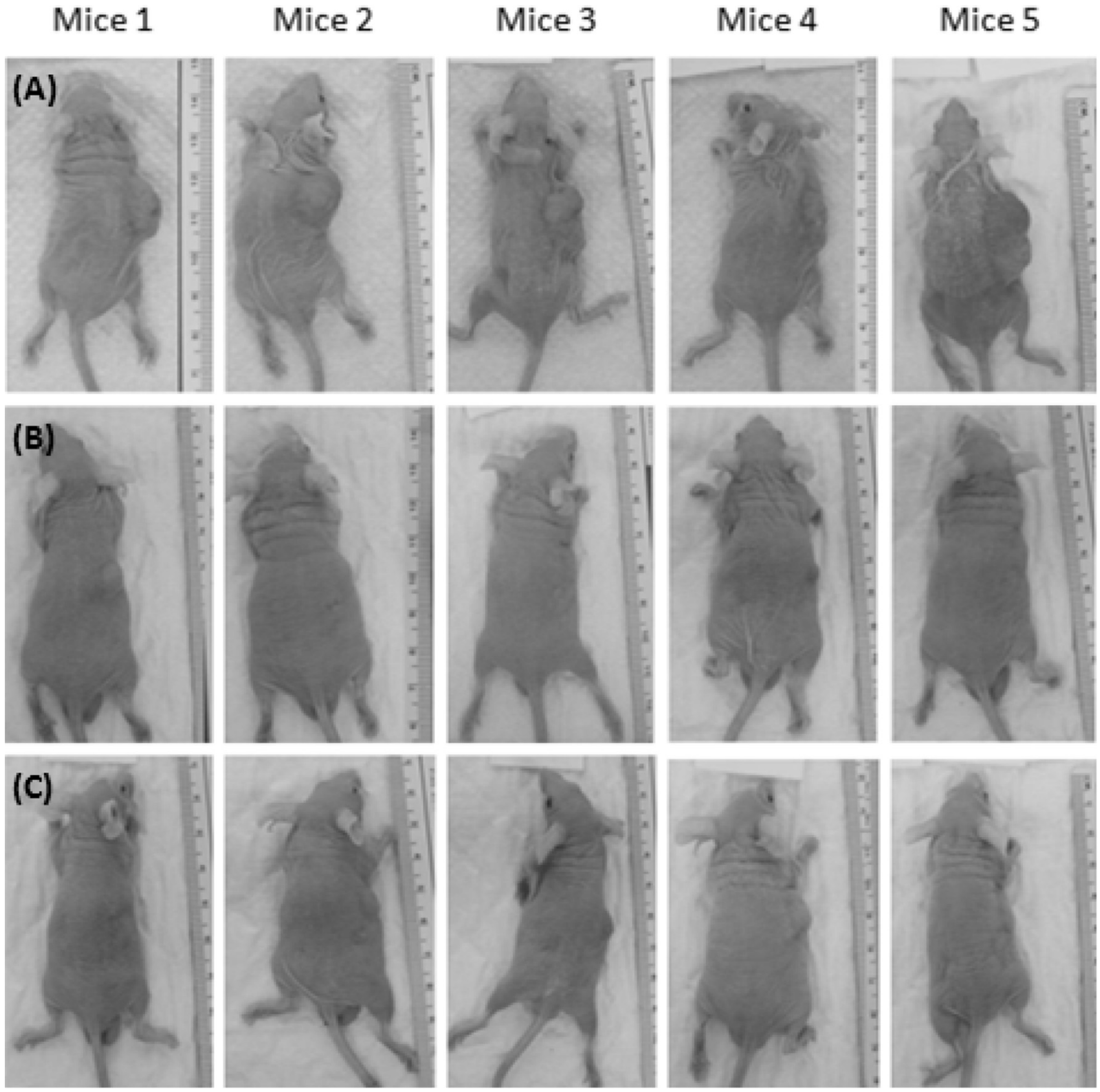


Fig. 3. Hep3B xenografted nude mice treated with (A) vehicle, (B) Pt-DHF and (C) Pd-DHF at 10 mg kg^{-1} body weight. Tumour appearances are shown on the treatment stopping time (day 10).

atmosphere by using Schlenk techniques. Solvents were dried by standard methods and distilled prior to use. All reagents and chemicals, unless otherwise stated, were purchased from commercial sources and used without further purification. Separation and purification of products were achieved by column chromatography on silica gel. The ligand precursor DHF was prepared according to the literature method [16].

4.1.2. *Physical measurements*

NMR spectra were measured in deuterated solvents as the lock and reference on a Bruker AV 400 instrument with ^{1}H and ^{13}C NMR chemical shifts quoted relative to tetramethylsilane standard. The positive-ion fast atom bombardment (FAB) mass spectra were obtained using Finnigan-MAT SSQ710 mass spectrometer. Crystals of our compounds suitable for X-ray diffraction studies were grown by slow evaporation of its solution in dichloromethane/hexane at room temperature and were mounted on a glass fibre. Geometric and intensity data were collected by using graphite-monochromated MoKα radiation ($\lambda = 0.71073$ Å) on a Bruker Axs SMART 1000 CCD diffractometer. The collected frames were processed with the software SAINT [20] and an absorption correction (SADABS) [21] was applied to the collected reflections. The structures of all compounds were solved by the Direct methods (SHELXTL™) [22] in conjunction with standard difference Fourier techniques and subsequently refined by full matrix least-squares analyses on F^2. All non-hydrogen atoms were assigned with anisotropic displacement parameters. Hydrogen atoms were generated in their idealized positions and allowed to ride on their respective parent carbon atoms.

4.1.3. *Synthesis of Pt-DHF*

A suspension of $K_2[PtCl_4]$ (27.2 mg, 0.066 mmol) in degassed water (20 mL), DHF (21.0 mg, 0.062 mmol), and 1 drop HCl was heated to boiling. Yellow precipitation was obtained, which was filtered off and washed with water. The yellow powder of pure Pt-DHF was obtained by column chromatography on silica gel eluting with CH_2Cl_2 (30.0 mg, 0.049 mmol, 80%). ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 8.87$ (m, 2H, Ar), 8.03 (m, 2H, Ar), 7.61–7.57 (m, 2H, Ar), 2.08–2.04 (m, 4H, C_6H_{13}), 1.18–1.12 (m, 12H, C_6H_{13}), 0.87–0.80 (m, 10H, C_6H_{13}); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 163.55$, 146.06, 143.18,

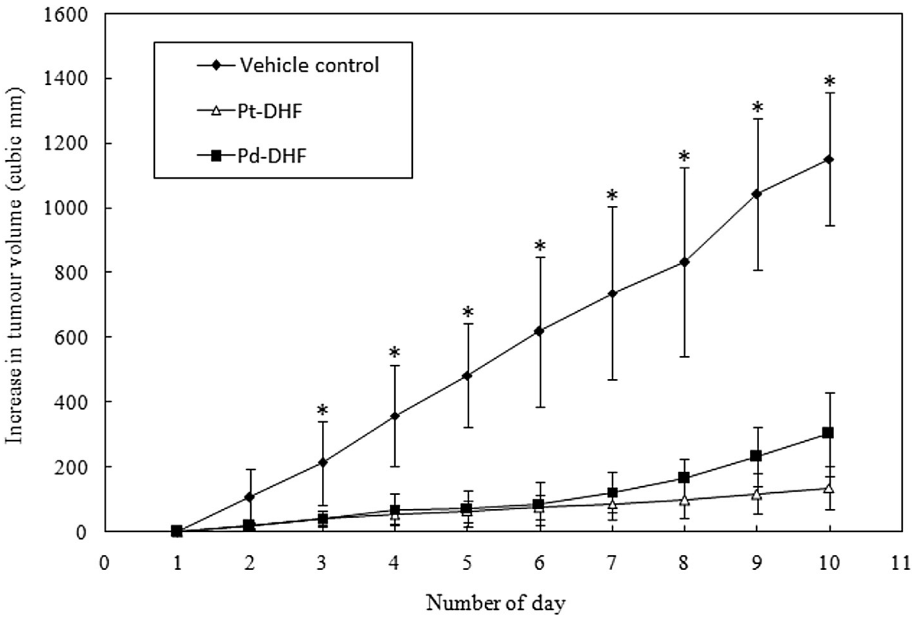


Fig. 4. Representative results showing the changes of tumour volume (mm^3) as a function of time for mice treated with vehicle, Pt-DHF and Pd-DHF. Intraperitoneal injection started for both groups when the mean tumour volume of mice reached ~200 mm^3 on day 0. A total of 15 mice were randomly divided into three groups. On day 10, after measuring individual tumour volume, all mice were sacrificed for plasma collection. Results represent the mean ± SD from 5 animals (each group); *$p < 0.05$ relative to untreated controls.

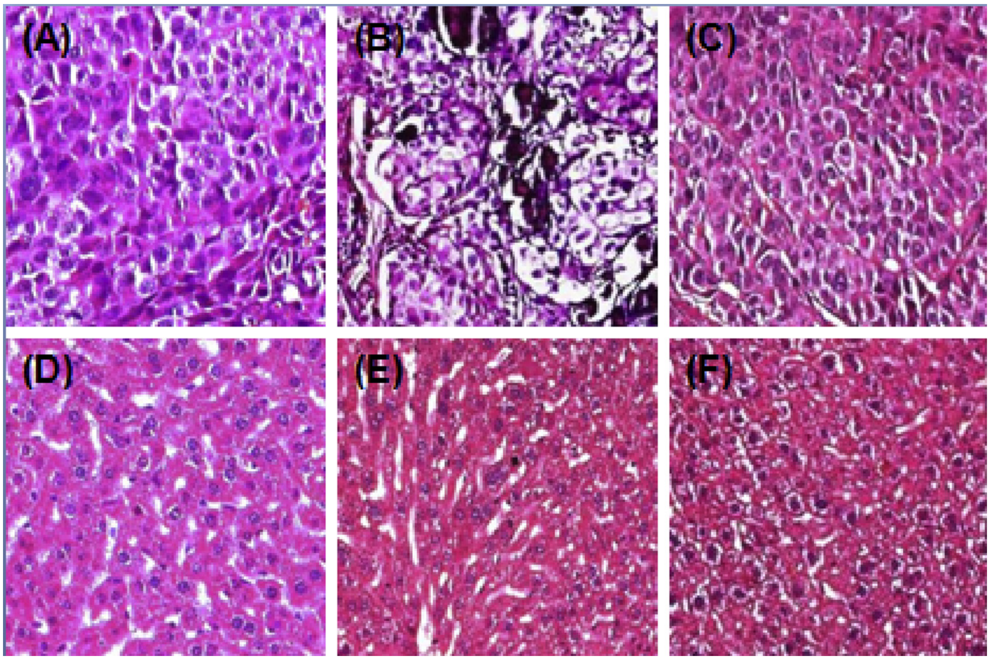


Fig. 5. Representative histological staining study of Hep3B tumour sections from sacrificed mice treated with (A) vehicle, (B) Pt-DHF and (C) Pd-DHF at 10 mg kg^{-1} body weight to detect any possible xenograft tumour necrosis; and liver sections from sacrificed mice treated with (D) vehicle, (E) Pt-DHF and (F) Pd-DHF at 10 mg kg^{-1} body weight to observe any possible liver toxicity.

134.44, 125.82 (Ar), 62.52 (quaternary C), 37.41, 31.20, 29.32, 24.82, 22.43, 13.92 (C_6H_{13}); FAB-MS: *m/z* 567.3 $[M-Cl]^+$; Anal. calcd for $C_{23}H_{32}Cl_2N_2Pt$ (%): C, 45.85; H, 5.35; N, 4.65. Found: C, 45.65; H, 5.40; N, 4.33.

4.1.4. Synthesis of Pd-DHF

A mixture of $PdCl_2$ (25.0 mg, 0.14 mmol) and NaCl (16.5 mg, 0.28 mmol) was stirred in MeOH (8 mL). The reaction mixture was warmed on a water bath at 40–50 °C until all the brown solid was dissolved to give a clear solution. The solution was evaporated to a volume of 1 mL and was then added to CH_2Cl_2 (3 mL). To this resulting solution mixture consisting of $Na_2[PdCl_4]$, DHF (47.4 mg, 0.14 mmol) in CH_2Cl_2 (3 mL) was added dropwise to give a brown suspension, which was then centrifuged to remove the liquid phase. The crude product was then purified by column chromatography on silica gel eluting with CH_2Cl_2 to give pure Pd-DHF (62.0 mg, 0.12 mmol, 86%) as a brown solid. ^1H NMR (400 MHz, $CDCl_3$): $\delta = 8.59$ (m, 2H, Ar), 8.02 (m, 2H, Ar), 7.59 (m, 2H, Ar),

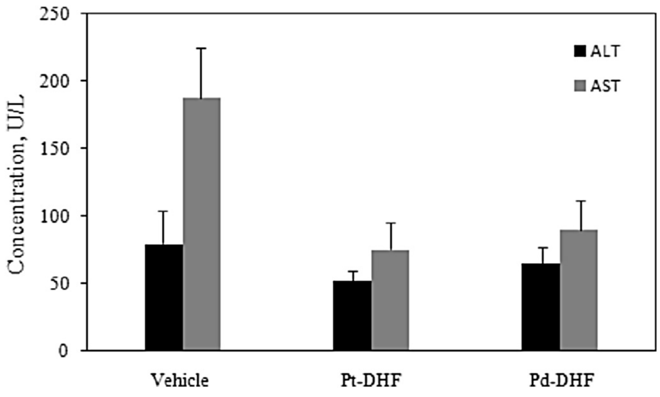


Fig. 6. Plasma liver enzyme assays for vehicle control, Pt-DHF- and Pd-DHF-treated Hep3B xenografted athymic nude mice. N = 5 for all vehicle control group, Pt-DHF- and Pd-DHF-treated groups (10 mg kg^{-1} body weight). Enzymatic levels were determined by the IDEXX laboratories machine using its veterinary biochemistry assay kits and expressed as units per litre. Results represent the mean ± SD.

2.10–2.05 (m, 4H, C_6H_{13}), 1.19–1.09 (m, 12H, C_6H_{13}), 0.89–0.79 (m, 10H, C_6H_{13}); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 162.18$, 147.15, 143.41, 135.01, 125.75 (Ar), 61.75 (quaternary C), 37.43, 31.32, 29.32, 24.73, 22.44, 13.95 (C_6H_{13}); FAB-MS: *m/z* 479.1 $[M-Cl]^+$; Anal. calcd for $C_{23}H_{32}Cl_2N_2Pd$ (%): C, 53.76; H, 6.28; N, 5.45. Found: C, 53.66; H, 5.99; N, 5.32.

4.2. Preliminary animal experiments

4.2.1. Cell culture

Human hepatoma Hep3B cells were removed from the sterile cell culture flasks with trypsin and neutralized with fetal bovine serum. After washing with phosphate buffered saline and centrifugation, cells were re-suspended in complete cell culture medium [16,23–25].

4.2.2. Preliminary in vivo athymic nude mice experiment

Eight weeks old athymic nude mice, weighing approximately 15–20 g, were purchased from the animal unit of The Chinese University of Hong Kong and maintained in a sterile facility, in accordance with the guidelines from the institute and Department of Health, Hong Kong SAR, on animal care, with the required consistent temperature and relative humidity. Mice were housed under normal regular ambient light condition (a 12 h light and 12 h dark cycle) for the whole experimental period. All the procedures were approved by the Animal Research Ethics Committee. Fifteen athymic nude mice were injected subcutaneously with the Hep3B cells. They were housed under a sterile condition. Tumour size was measured by the electronic calliper daily. When tumour size reached about 200 mm^3 whereas the tumour volume was calculated by the formula (length × width × width)/2, they were randomly divided into three groups. Pt-DHF and Pd-DHF at 10 mg kg^{-1} body weight per day were administered intraperitoneally for a continuous period of 9 days starting from day 1. Each group consisted of five mice. Body weight of each animal was also recorded. On day 10, mice were sacrificed and H and E staining of autopsy analysis including xenografted Hep3B tumour from all of the animals were investigated for any possible significant necrotic effects. Whole blood was also collected and plasma liver enzymes including alanine aminotransferase (ALT) and asparate aminotransferase (AST) were measured by the Vet biochemistry assay kit for the IDEXX laboratories machine to determine the hepatoma burden from the mice [16,25].

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ejmech.2016.08.033.

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