INORGANIC CHEMISTRY







FRONTIERS

REVIEW

12. 897

View Article Online
View Journal | View Issue



Cite this: Inorg. Chem. Front., 2025, Pav



Pavel Štarha 🗓

Platinum-based anticancer drugs have been highly effective at treating various cancers. While they have shown significant promise, their potential limitations have motivated researchers to explore other noble metal-based compounds, including iridium (Ir) complexes. Among these, half-sandwich Ir(III) cyclopentadienyl (Ir–Cp^x) complexes have emerged as promising new anticancer compounds. This relatively new area of bioinorganic chemistry has made significant progress since its inception in 2007, although no representative has yet entered clinical trials. Recent studies over the past 5–10 years have significantly advanced our understanding of the stability, speciation, intracellular localization, target organelles and molecular targets involved in the mechanisms of action (MoAs) of these compounds. This comprehensive review provides the reader with an overview of anticancer Ir–Cp^x complexes and diverse chemical, biochemical and biological methods used for their research and development. Structure–activity relationships (SARs) and mechanisms of action (MoAs) are discussed with respect to anticancer activity and in comparison with their structurally similar ruthenium(III), rhodium(III) and osmium(III) analogues. Considerable attention is paid to *in vivo* anticancer activity and related aspects, such as drug delivery strategies, multi-component drugs or photodynamic therapy.

Received 30th September 2024, Accepted 11th December 2024 DOI: 10.1039/d4qi02472a

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Introduction

Iridium (Ir) is a d-block noble metal, belonging to group 9 and period 6 of the periodic table and having atomic number 77. Ir is considered to be one of the rarest elements on Earth and is known for being highly inert and non-corrosive. Iridium, as one of the platinum (Pt) metals, typically occurs together with platinum and the other platinum metals in the same deposits (alloys, sulfides). It is used in various alloys (e.g., for hardening, corrosion resistance and heat resistance) or catalysts (methanol carbonylation in the Cativa process using the $[Ir(CO)_2I_2]^-$ complex). Iridiumbased catalysts have been widely used in various processes, such as C–H bond activation or asymmetric hydrogenation. $^{3-5}$

In the periodic table, Ir is positioned next to Pt, the complexes of which (*e.g.*, cisplatin, carboplatin or oxaliplatin) have been used for the treatment of various types of cancer for more than forty years.^{6,7} Even Rosenberg's initial study on cisplatin identified several non-platinum compounds as having similar biological effects to those of cisplatin. Among them, the ruthenium(III) complex [RuCl(NH₃)₄(OH)]Cl seems to be the first non-platinum complex reported to have anticancer activity. Later, Ru became a prominent d-block metal in the fields of bioinorganic and bioorganometallic chemistry,^{8,9} because several complexes have entered clinical trials as new anticancer metallodrugs.^{10–12}

Department of Inorganic Chemistry, Faculty of Science, Palacky University Olomouc, 17. listopadu 12, 77146 Olomouc, Czech Republic. E-mail: pavel.starha@upol.cz; Tel: +420 585 634 348

Following early studies on bioactive Ru complexes and the relative success of this type of compound, complexes of osmium, 13 rhodium 14 and iridium 15 were introduced into the field of bioinorganic chemistry a couple of years later. Nowadays, Ru, Os, Rh and Ir complexes^{9,16,17} are accepted as prospective candidates for the research and development of new metallodrugs (Fig. 1).18 Regarding iridium, the first complexes bioanalysed in the 1970 and 80s were (NH₄)₂[Ir^{IV}Cl₆] $(1)^{15}$ and $[Ir^{I}(\eta^{4}\text{-cod})(acac)](2)^{14,19}$ (Fig. 1); cod = cycloocta-1,5diene, Hacac = pentane-2,4-dione. Especially Ir(1) complexes have been investigated in depth, because their metal centre is isoelectronic with Pt(II), which is involved in conventional Pt anticancer drugs. Later, other Ir oxidation states and structural types were introduced, such as octahedral polypyridyl (e.g., fac-[IrCl₃(dmso)(phen)] (3))²⁰ or cyclometalated (e.g., [Ir(biq) (ppy)₂] (4))²¹ Ir(III) complexes or pseudo-octahedral half-sandwich Ir(III) cyclopentadienyl complexes (e.g., [Ir(η⁵-Cp*)Cl (dppz)]CF₃SO₃ (5)),²² as new anticancer agents (Fig. 1); dmso = dimethyl sulfoxide, phen = 1,10-phenanthroline, biq = 2,2'biquinoline, Hppy = 2-phenylpyridine, HCp* = 1,2,3,4,5-pentamethylcyclopenta-1,3-diene, dppz = dipyrido[3,2-a:2',3'-c]phenazine. Other types of Ir complexes have also been reported as having anticancer properties in vitro. 23,24 Although anticancer complexes have been the subject of extensive research, significantly fewer compounds have been studied for their antimicrobial or other biological properties.²⁵

In contrast to Pt-based drugs, non-platinum half-sandwich metallodrugs of Ru, Os, Rh and Ir do not primarily target DNA and kill the cancer cells through a different mechanism of

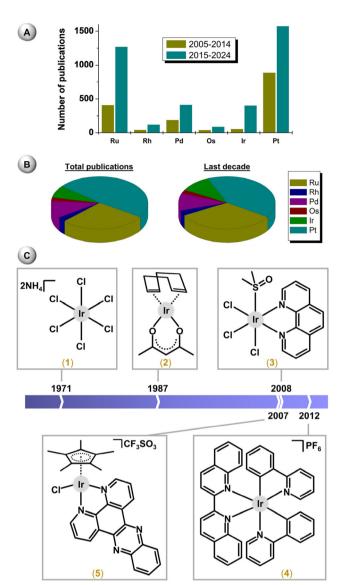


Fig. 1 (A) Absolute and (B) relative number of scientific publications dealing with anticancer complexes of platinum metals. (C) Chronology of the pioneering works on iridium anticancer compounds 1-5.

action (MoA). 8,18,26 Together with the different structures and differences in chemistry between classical Pt drugs and nonplatinum half-sandwich complexes, this gives much potential for the latter to be a new type of biologically active compound. In this review, the history of anticancer Ir(III) cyclopentadienyl (Ir-Cp^x) complexes is briefly recapitulated, and the design strategies, current knowledge regarding the structure-activity relationships (SARs) and mechanisms of action (MoAs) and challenges in the field are discussed. It is worth noting that some reviews of biologically active Ir complexes can be found in the literature, but these have either been published quite a few years ago^{16,27,28} or focus on a specific part of the topic, specifically anticancer apoptosis inducers, 29 complexes with C-donor ligands, 30 multi-targeted complexes 26 and multinuclear complexes.31

2. General properties

Structural types

The first antiproliferative activity studies on Ir-Cp^x complexes were reported by Sheldrick and co-workers in 2007.²² Among the four investigated complexes, [Ir(η⁵-Cp*)Cl(en)]CF₃SO₃ and $[Ir(\eta^5-Cp^*)Cl(phen)]CF_3SO_3$ were inactive $(IC_{50} > 100 \mu M)$ against MCF-7 breast carcinoma cells, 32,33 but co-studied analogues 5 (Fig. 1)³⁴ and $[Ir(\eta^5-Cp^*)(dppn)(tmtu)](CF_3SO_3)_2$ (6; Fig. 2), 22 with more extended chelating ligands, revealed acute cytotoxicity in the MCF-7 breast and HT-29 colon cancer cell lines used; en = ethylene-1,2-diamine, dppn = benzo[i]dipyrido [3,2-a:2',3'-c]phenazine, tmtu = 1,1,3,3-tetramethylthiourea. Earlier, these complexes were studied in depth for their ability to interact with DNA and its models (see section 5.4). 34-36

These pioneering Ir-Cpx complexes represent one of two basic structural types. In general, their pseudo-octahedral geometry consists of η⁵-coordinated arenyl (i.e., substituted cyclopentadienyl, Cp^x) anions occupying three of the six positions, and three other coordination sites occupied either by three monodentate ligands or by a bidentate (chelating) ligand combined with a monodentate one (Fig. 3).

This categorization can be applied to both mononuclear and multinuclear complexes. Complexes containing three monodentate ligands usually belong to the family of dichlorido complexes of the general formula $[Ir(\eta^5-Cp^x)Cl_2(L)]^{0/+}$, with two chlorido ligands and a third monodentate ligand (L) coordinated through various donor atoms (section 3.1). The second type is dominantly represented by chlorido complexes of the general formula $[Ir(\eta^5-Cp^x)Cl(L^{\perp}L)]^{0/+}$, where L^L symbolizes a bidentate-coordinated (i.e., chelating) ligand (section 3.2). Only a few structurally different bioactive Ir-Cp^x complexes have been reported to date (section 3.4).

Synthesis

For both structural types of the most studied (di)chlorido Ir(III) complexes (Fig. 3), dinuclear $[Ir(\mu-Cl)(\eta^5-Cp^x)Cl]_2$ compounds represent key intermediates, which are easily prepared from IrCl₃·xH₂O either conventionally^{37,38} or by microwave-assisted syntheses^{39,40} (Scheme 1). A cyclopentadienyl ring is most

Fig. 2 Structural formulas of the complexes [Ir(n⁵-Cp*)(dppn)(tmtu)] (CF₃SO₃)₂ (6), 1,10-phenanthroline (phen) and dipyrido[3,2-a:2',3'-c]phenazine (dppz).

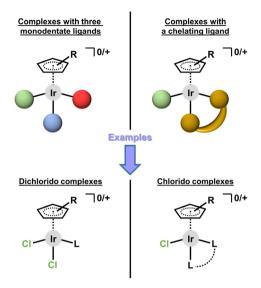


Fig. 3 Two basic structural types of half-sandwich iridium(III) cyclopentadienyl complexes (Ir-Cpx).

Scheme 1 Synthesis of the most used dinuclear intermediate, [Ir(μ-Cl) (η⁵-Cp^x)Cl]₂, for the synthesis of half-sandwich Ir(III) cyclopentadienyl complexes.

widely represented by Cp*, 22 followed by its arenyl derivatives with a more extended Cpx ring, such as (2,3,4,5-tetramethylcyclopenta-2,4-dien-1-yl)benzene (HCp^{ph}) or 4-(2,3,4,5-tetra-(HCp^{bph}).⁴¹ methylcyclopenta-2,4-dien-1-yl)biphenyl Alternatively to the abovementioned direct syntheses of [Ir(μ-Cl)(η^5 -Cp^x)Cl]₂, IrCl₃·xH₂O can be transformed into the [Ir^I(μ -Cl)(η^4 -cod)]₂ intermediate, which subsequently reacts with an appropriate Cp^x derivative.⁴²

Dimers $[Ir(\mu-Cl)(\eta^5-Cp^x)Cl]_2$ are usually allowed to react with a stoichiometric amount or an excess of appropriate organic compound (pro-ligand), providing the $[Ir(\eta^5\text{-}Cp^x)Cl_2(L)]^{0/\text{+}}$ and $[Ir(\eta^5-Cp^x)Cl(L^L)]^{0/+}$ compounds. In the case of organic compounds coordinated as an electroneutral bidentate ligand, it is the chloride salt of an ionic complex, $[Ir(\eta^5-Cp^x)Cl(L^L)]Cl$, which is formed by this synthesis, and which typically undergoes further reaction to replace the chloride anion in the outer coordination sphere, 22 for example, with hexafluorophosphate, 41 to get compounds of the general formula $[Ir(\eta^5 Cp^{x}$)Cl(L^L)]PF₆.

Chlorido complexes $[Ir(\eta^5-Cp^x)Cl(L^L)]^{0/+}$ are frequently used as an intermediate for the synthesis of congeners bearing different monodentate ligands (see section 3.4).36 To exemplify, halogenido, 43 py-44 or pta-containing 45 complexes can be mentioned in this context; py = pyridine, pta = 1,3,5-triaza-7phosphaadamantane. In most cases, complexes bearing a monodentate ligand different from the chlorido one (e.g., Br, I, py or pta) are prepared by dehalogenation using a silver(1) salt (e.g., nitrate or triflate), followed by the addition of an excess of appropriate pro-ligand (salt, organic compound etc.). 36,43-45 Halogenido (bromido and iodido) complexes can also be prepared from appropriate $[Ir(\mu-Br)(\eta^5-Cp^x)Br]_2$ or $[Ir(\mu-I)(\eta^5-Cp^x)I]_2$ dimers,46 which can be prepared from their chlorido analogues.47,48

Regarding [Ir(μ-Cl)(η⁵-Cp*)Cl]₂, it proved to be more cytotoxic in several human cancer cell lines (e.g., $IC_{50} = 4.2 \mu M$ in A2780 ovarian carcinoma cells) than similar arene (for Ru and Os) and Cp* (for Rh) dimers used for the preparation of anticancer half-sandwich complexes of the abovementioned platinum metals.49

Structural classification and in vitro antiproliferative activity

The structural type of the half-sandwich Ir-Cpx complex is accepted and proves to be a suitable one for the development of new anticancer compounds. It is noteworthy that this structural type, while pharmacologically promising, cannot be considered as having general toxicity, because numerous representatives are reported to be inactive in various cancer cells. 34,50-52

In this section, Ir-Cp^x complexes, which have been studied for their in vitro antiproliferative activity, are comprehensively overviewed and discussed with respect to their composition, specifically the type of ligand (monodentate vs. chelating), the donor set of ligands used or the nuclearity of complexes.

3.1. Mononuclear complexes with three monodentate ligands

Among the first complexes of this type reported in 2010, only [Ir(η⁵-Cp*)Cl₂(mpta⁺)]CF₃SO₃ (7; Fig. 4A), containing a P-donor ligand, 1-methyl-1,3,5-triaza-7-phosphaadamantane (mpta), showed some antiproliferative activity (IC₅₀ = 349 μ M) against A2780 cells, which was comparable with the Ru reference drug $[Ru(\eta^6\text{-pcym})Cl_2(pta)]$ (RAPTA-C; $IC_{50} = 353 \mu M$); pcym = 1-methyl-4-(1-methylethyl)benzene. 53 Other complexes, [Ir(η^5 - Cp^*) $Cl_2(pta)$], $[Ir(\eta^5-Cp^*)Cl(pta)_2]PF_6$ and $[Ir(\eta^5-Cp^*)Cl(mpta^+)$ (pta)](CF₃SO₃)(PF₆), were essentially inactive (IC₅₀ > 500 μ M). The last two compounds represent a different structural type with only one chlorido ligand and two monodentate ligands. Additional studies proved a different ability to inhibit the cysteine (Cys) protease cathepsin B with $IC_{50} = 2.5 \mu M$ for RAPTA-C, 6.5 μ M for the Os analogue $[Os(\eta^6-pcym)Cl_2(pta)]$ and >300 μ M for both $[Ir(\eta^5-Cp^*)Cl_2(pta)]$ and $[Rh(\eta^5-Cp^*)]$ $Cl_2(pta)$].

Dichlorido complexes with diphenylphosphano-functionalized methyl-phenyl sulfides, sulfoxides, and sulfones were in

Fig. 4 Structural formulas of (A) ionic complex [Ir(n⁵-Cp*)Cl₂(mpta⁺)] CF_3SO_3 (7), (B) electroneutral complex $[Ir(\eta^5-Cp^*)Cl_2(phs^1)]$ (8) and P-donor ligands phs², tcep, psf and poh involved in analogues 9-12, respectively, and (C) complex 13 with monodentate N-donor ligand from (B).

most cases less potent than cisplatin for the panel of cell lines. ⁵⁴ Only the $[Ir(\eta^5-Cp^*)Cl_2(phs^1)]$ (8) complex exceeded cisplatin against 8505C (IC₅₀ = 3.5 μ M, RA = 1.4) and SW480 (IC₅₀ = 2.3 μ M, RA = 1.4) cells; phs¹ = diphenyl[(phenylsulfinyl) methyl]phosphane, 8505C = thyroid carcinoma, SW480 = colon carcinoma, RA = relative activity calculated as IC₅₀(reference drug)/IC₅₀(complex). While apoptosis and autophagy were detected in 8505C cells, the lower level of ROS/RNS was found in 8505C cells treated with 8 compared with nontreated cells. The same research team developed a series of analogues involving similar ligands with a longer alkyl chain (propyl).⁵⁵ Among them, the $[Ir(\eta^5-Cp^*)Cl_2(phs^2)]$ (9) complex exceeded the cytotoxic efficacy of cisplatin (IC₅₀ = 0.2- $0.6 \mu M$, RA = 4.0-25.0); phs² = diphenyl[3-(phenylsulfanyl)propyl]phosphane (Fig. 4B). Apoptosis was identified in 8505C cells as the cell death mechanism. The $[Ir(\eta^5-Cp^*)Cl_2(tcep)]$ (10) complex was more active (IC₅₀ = 7.8 μ M) towards MDA-MB-231 triplenegative breast cancer cells than its Rh analogue (IC50 = 67 μ M) and cisplatin (IC₅₀ = 61 μ M); tcep = tris(2-carboxyethyl) phosphane (Fig. 4B).56

Another series of dichlorido complexes were derived from various phosphane ligands. ^{57–62} The $[Ir(\eta^5-Cp^*)Cl_2(pcfx)]$ (11; Fig. 4B) complex exceeded (IC₅₀ = 11.8 μ M) the antiproliferative activity of cisplatin (IC₅₀ > 100 μM) against DU-145 human prostate carcinoma,57 a cell line that was also highly sensitive to various congeners of 11;^{58,59} pcfx = phosphane bearing fluoroquinolone ciprofloxacin. Complex 11 was highly selective towards cancer cells over HEK-293 normal ones. Additionally, these phosphane-derived complexes were effective against various multicellular (3D) tumour spheroids (see section 5.9). Other complexes, which contained (diphenylphosphanyl) methanol (poh for 12; Fig. 4B) or its 4,4-bismethoxy derivative, showed only moderate (e.g., $IC_{50} = 22.5 \mu M$ in A549 lung cancer cells for 12) or even no cytotoxic activity. 59,61,62

A series of complexes with triphenylamine-modified pyridines used as a monodentate N-donor ligand were designed to act as luminescent compounds for the intracellular tracking studies. 63 Hit complex 13 (Fig. 4C) showed moderate antiproliferative activity (e.g., $IC_{50} = 26.7 \mu M$ in A549 cells) and high fluorescence (quantum yield of 15.2%) allowing advanced incell and in vivo biological studies.

Numerous complexes of this type bearing monodentate N-, 64-66 S-67,68 or C-donor 69-72 ligands showed no significant cytotoxicity. Similarly, an advanced metal-peptide conjugate coordinating numerous {Ir(η⁵-Cp*)Cl₂} moieties through benzimidazolium groups of a peptide was not effective against the human cancer cell lines used (nor were Ru/pcym, Rh/Cp* and Os/pcvm analogues).⁷³

3.2. Mononuclear complexes with a chelating ligand

This section is devoted to mononuclear Ir-Cp^x complexes with a bidentate-coordinated chelating ligand of a different donor set, which is used here for the classification of these compounds.

3.2.1. Complexes with an N,N-donor ligand. This structural type is discussed above, as introduced for the first representatives of Ir-Cp^x complexes (5, 6) developed in the field.^{22,34-36} The research of Sheldrick and co-workers, dealing with bidentate (chelating) N,N-donor ligands (e.g., phen or dppz; Fig. 2), was soon followed by other research groups using either N,Ndonor ligands (section 3.2.1) or ligands offering a different donor set (section 3.2.2-3.2.7).

In 2010, Therrien and co-workers reported an inactive Ir complex with 2-(1,3-thiazol-2-yl)pyridine. 74 The next year, Sadler et al. reported the anticancer activity and basic mechanistic studies of previously reported Cp* complexes with en, bpy, phen and pico ligands^{32,33,75} and their Cp^{ph} and Cp^{bph} congeners; bpy = 2,2'-bipyridine, Hpic = pyridine-2-carboxylic (2-picolinic) acid.⁴¹ The $[Ir(\eta^5-Cp^{bph})Cl(phen)]PF_6$ (14; $IC_{50} =$ 0.7 μ M) and $[Ir(\eta^5-Cp^{bph})(bpy)Cl]PF_6$ (15; $IC_{50} = 0.6 \mu$ M) complexes reached even higher activity than cisplatin (IC50 = 1.2 μM) (Fig. 5). The antiproliferative activity against A2780

Fig. 5 The general structural formula of complexes 14 and 15.

cells increased with the size of the Cp^x ligand (section 4.2). Interestingly, the hydrolysis rate, lipophilicity and cellular accumulation also proved to be Cpx-size dependent and correlated with antiproliferative activity. Other properties (e.g., interactions with DNA or intracellular distribution) were investigated for [Ir(n⁵-Cp^x)Cl(phen)]PF₆ and these are discussed in more detail below. 76,77 Despite its moderate antiproliferative activity in A2780 cells, 41 the [Ir(n5-Cpph)(bpy)Cl]PF6 complex was later reported to be inactive against A549 and HeLa cells.⁷⁸

Following this cutting-edge work, 41 various phen and bpy derivatives have been used for the synthesis of analogous Ir-Cp^x complexes.⁷⁹ Regarding bpy complexes, [Ir(η⁵-Cp^{bph})(bpy¹) Cl]PF₆ (16; IC₅₀ = 7.3 μ M; RA = 2.0) containing 4,4'-dinitro-2,2'bipyridine (bpy¹; Fig. 6) was ca. 2-fold more cytotoxic than 15 (IC₅₀ = 14.3 μ M) in A549 cells and exceeded the potency of other co-studied Ir-Cp^{bph} complexes containing bpy derivatives with electron-donating groups -NH2 (17; Fig. 6), -OH or -OCH₃ (IC₅₀ = 14.9-35.2 μ M). This suggests a positive effect of the substitution of the chelating ligand (bpy in this work) by the electron-withdrawing groups on the resulting antiproliferative activity. Another improvement to the antiproliferative activity was reached by the substitution of the bpy ring for one triphenylamine substituent (18; Fig. 6), which was not the case for similar complexes bearing two of these substituents on both pyridines of bpy (19; Fig. 6).81,82

Ir complexes involving bpy derivatives bearing the antimalarial drug artemisinin were, with respect to the bound organic drug, studied especially for their antimicrobial activity (section 7.1).83 Their antiproliferative activity was examined against human cancer cell lines, where the best performing complex, $[Ir(\eta^5-Cp^{bph})(bpy^2)Cl]PF_6$ (20), exceeded cisplatin; bpy² = 4-methyl-4'-carboxy-2,2'-bipyridine dihydroartemisinin ester (Fig. 6). A similar synthetic strategy for the biofunctionalization of Ir-bpy-based cyclopentadienyl complexes was also reported elsewhere (section 6.2).84

Complexes with bpy-based ligands derived from rhodamine were shown to target lysosomes of the treated cancer cells.85 The use of a bpy derivative bearing a biologically relevant sulfonamide substituent led to an Ir compound that was inactive in cancer cells.86 A set of substituents used for bpy derivatization indicated that the resulting biological activity was connected to lipophilicity, because derivatization with more lipophilic substituents (phenyl and especially nonyl in 21; Fig. 6) led to markedly higher antiproliferative activity than in the case of poorly effective or even inactive complexes bearing

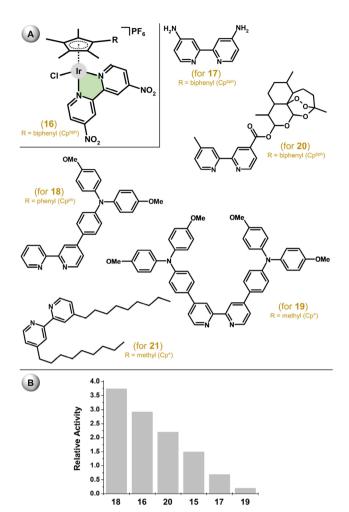


Fig. 6 (A) The structural formula of complex 16 and bpy-based ligands of analogues 17-21, and (B) comparison of the in vitro antiproliferative activity of 15-20 against the A549 lung carcinoma cell line (given as relative activity). Complex 15 (see Fig. 5) is given for comparative purposes. Complex 21 was not tested in A549 cells.

more polar substituents (e.g., amine or methylene alcohol) on the bpy moiety.87 Remarkably, the nonyl substituted complex, $[Ir(\eta^5-Cp^*)(bpy^3)Cl]PF_6$ (21; Fig. 6), was ca. 40-fold more effective (IC₅₀ = 2.0 μ M) against the HT-29 colon cancer cells than cisplatin; $bpy^3 = 4,4'$ -dinonyl-2,2'-bipyridine.

For the complexes with phen-based ligands, a series of compounds were derived from previously studied $[Ir(\eta^5-Cp^*)Cl$ (phen)]⁺. 33,41,88 This compound (PF₆ salt) was reported to be inactive in A2780 cells (IC50 > 100 µM),41 but later it showed decent cytotoxicity in the same cells ($IC_{50} = 29.0 \mu M$).⁸⁸ More importantly, its potency was improved by phen derivatization $(IC_{50} = 0.2 \mu M \text{ for } [Ir(\eta^5-Cp^*)Cl(bphen)]PF_6)$ as well as by using different Cp^x rings (e.g., IC₅₀ = 0.02 μ M for [Ir(η^5 -Cp^{bph})Cl (bphen)]PF₆ (22; Fig. 7); bphen = bathophenanthroline). In addition to nanomolar in vitro potency, 22 also showed high anticancer (and antiangiogenic) activity in vivo (section 5.9).

A series of Ru, Rh and Ir complexes were developed with various bithiazole ligands.⁸⁹ Their antiproliferative activity was

Fig. 7 Structural formulas of ligands L^L of $[Ir(\eta^5-Cp^x)Cl(L^L)]^+$ complexes 22-27, where $Cp^x = Cp^*$ or Cp^{bph} .

studied towards two MDA-MB-231 and T47D breast carcinoma cells, where Ir complex 23 containing 2,2'-diphenyl-4,4'-bithiazole (Fig. 7) was the most potent one. Ir complexes with benzhydrazone derivatives (e.g., 24; Fig. 7) were comparably effective against HCT116^{+/+} (p53 wild type) and HCT116^{-/-} (p53 null) cell lines and even more cytotoxic than cisplatin towards HCT116^{-/-} cells, although their activity was lower when compared with free benzhydrazones. 90 An organic intercalator, acridine, was used for the synthesis of the ligand N-(6chloro-2-methoxyacridin-9-yl)-N'-[pyridin-2-ylmethylidene] ethane-1,2-diamine (Lacr) and its Ir, Ru, Rh and Os complexes, as well as for complexes containing a similar N,O-ligand (see section 3.2.2).⁹¹ The $[Ir(\eta^5-Cp^*)Cl(L^{acr})]BPh_4$ (25; Fig. 7) complex was more cytotoxic but less selective than cisplatin. A similar design - a bioactive substituent (mesalazine in this work) linked to a heterocycle through the Schiff bond - was applied for a series of Ir complexes, such as [Ir(n5-Cp*)Cl (L^{mes})]Cl (26; Fig. 7).⁹² Although the antiproliferative activity of 26 was in the low micromolar range (e.g., $IC_{50} = 3.5 \mu M$ in HepG2 cells), it was less effective than some co-studied Ru complexes.

Other complexes followed the pioneering complexes of Sheldrick and co-workers, because they contained dppz derivatives (including dppn)93 or similar imidazo[4,5-f][1,10]phenanthroline derivatives. 94,95 Although these complexes interacted with DNA (similarly to 5, 6), they also disrupted mitochondria despite their cytoplasmic localization. A very recently reported complex, [Ir(η⁵-Cp^{bph})Cl(ndi)]PF₆ (27; Fig. 7), also contained a phen-based ligand (ndi), this time modified by naphthalene diimide, which was used to improve the photochemical behaviour of 27 to treat hypoxic tumours. 96 In this regard, 27 was studied in vitro for its photocytotoxicity under normoxic and hypoxic conditions and in vivo after laser activation in tumours

Although a large series of Ir-Cp* complexes with various Cand N-glycosyl azoles (1,2,3-triazole, 1,3,4-oxadiazole and 1,2,4oxadiazole were used) were prepared, only complex 28 (Fig. 8)

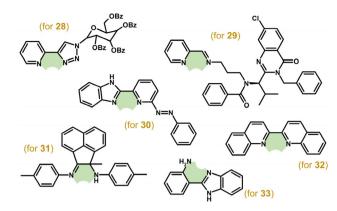


Fig. 8 Structural formulas of ligands L^L of $[Ir(\eta^5-Cp^*)Cl(L^L)]^+$ complexes 28-33; Bz = benzyl.

was effective against some of the human cancer cell lines used (e.g., $IC_{50} = 1.6 \mu M$ in A2780 cells). 97 Other highly cytotoxic complexes containing imino-pyridyl bases, 98-101 imino-quinolines/naphthyridines, 102 diimines, 103 rhodamine- or naphthalimide-modified bpy-based ligands, 104,105 lonidamine-based amides, 106 a kinesin spindle protein (KSP) inhibitor ispinesibderived ligand, 107-109 1,3,4-thiadiazoles 110 or aza derivatives of 2-(pyridin-2-yl)-1*H*-benzimidazole¹¹¹ were prepared studied for their antiproliferative activity. Among them, for example, ispinesib-derived complex 29 (Fig. 8) showed submicromolar activity in various human cancer cell lines (e.g., $IC_{50} = 0.27 \mu M$ in A549 cells). Complex 30 (Fig. 8) was, as the first example of such studies, investigated in mixtures of relevant intracellular small biomolecules (NADH, GSH, ascorbic acid; section 6.1.1).¹¹¹

Very recently, Guo, Liu and co-workers demonstrated that the type of very similar N,N-donor ligand (pyridyl-imine vs. pyridyl-amido) could affect the resulting cytotoxicity. 112 Specifically, complexes containing widely used pyridyl-imine ligands exhibited moderate cytotoxicity (IC₅₀ = 23.2-29.8 μM in A549 cells), while the 16-electron pyridyl-amido complex was inactive (IC₅₀ > 100 μ M). The same research group reported an interesting coordination mode for a series of Ir compounds, represented by Cp* complex 31, containing hybrid sp²-N/sp³-N donor (i.e., imine-amine) chelating ligands (Fig. 8). 113 These compounds were found to be cytotoxic, which contrasted with structurally similar analogues with a diimine-type chelating ligand. 103

The $[Ir(\eta^5-Cp^*)(biq)Cl]PF_6$ (32; Fig. 8) complex was studied, together with its Ru analogue, for its photochemical and photobiological properties (section 6.3).114 An interesting series of complexes involving various N,N- (e.g., 2-(1H-benzimidazol-2-yl)aniline in 33; Fig. 8), C,N- and N,O-donor ligands was developed, but complexes with N,N-donor ligands exhibited the lowest antiproliferative activity (section 4.3). 115

Numerous other Ir chlorido complexes containing a chelating N,N-donor ligand showed little to no cytotoxicity (usually significantly less than the reference drug used). 64,65,116-142 Also of interest, a non-cytotoxic complex, $[Ir(\eta^5-Cp^*)(bpy)Cl]Cl$, later

proved to be a selective chemosensitizer for cancer cells treated with platinum-based drugs (section 6.4). 143

3.2.2. Complexes with an N,O-donor ligand. Probably the first Ir-Cp^x complex, $[Ir(\eta^5-Cp^*)Cl(qui)]$ (34; Fig. 9), involving an N,O-donor chelating ligand was derived from a well-known pharmacological moiety, quinolin-8-ol (Hqui). 144 34 was effective against human melanoma and glioblastoma cell lines $(e.g., ID_{50} = 0.8 \mu M \text{ in SK-Mel cells})$. In the same year, the [Ir $(\eta^5-\text{Cp*})\text{Cl(nqo)}$ (35; Fig. 9) complex was developed and proved to have much stronger activity against the cancer cells used (e.g., $IC_{50} = 2.2 \mu M$ in HeLa cells) than cisplatin ($IC_{50} =$ 25.0 μ M), but only low selectivity towards cancer cells (IC₅₀ = 5.0 µM against HUVEC human umbilical-vein endothelial cells); Hnqo = 1-nitrosonaphthalen-2-ol (1,2-naphthoquinone-1-oxime). 145 This pioneering investigation proposed a different MoA for 35 in comparison with that of cisplatin. Recently, 34 was followed by a series of Ir-Cpx complexes containing 2-[2-(4-nitrophenyl)ethenyl]quinolin-8-ol. 146 Although the best-performing Ir complex 36 (Fig. 9) exceeded the potency of cisplatin (e.g., $IC_{50} = 5.6 \mu M$ in HeLa cells), it has not been studied in detail because it was outperformed by the co-studied Ru congener.

The $[Ir(\eta^5-Cp^{bph})Cl(pic)]$ (37; Fig. 9) complex showed moderate antiproliferative activity against A2780 cells (IC₅₀ = 16.3 µM), which was markedly lower than that for cisplatin (IC50 = 1.2 μ M) and analogues with phen and bpy (section 4.3). Later, 37 (IC₅₀ = 31.3 μ M in A549 cells) was derivatized on pic by various substituents (e.g., halogeno, carboxy or hydroxy), leading in most cases to improved antiproliferative activity, as exemplified by $[Ir(\eta^5-Cp^{bph})Cl(pic^1)]$ (38; Fig. 9) with $IC_{50} = 4.4 \mu M$ in A549 cells; $Hpic^1 = 5$ -(trifluoromethyl)pyridine-2-carboxylic acid. 147

McGowan and co-workers developed a series of complexes with different donor atoms (i.e., N,N-, N,O- and O,O-ligands; section 4.3), including the $[Ir(\eta^5-Cp^*)Cl(fpb)]$ (39; Fig. 9) complex with 1-(3-fluorophenyl)-3-(phenylamino)but-2-en-1one (Hfpb). This complex was less effective (e.g., IC_{50} =

(34)(37) (for 41)

Fig. 9 Structural formulas of N,O-donor ligands (HL) of representative $[Ir(\eta^5-Cp^x)Cl(L)]$ complexes 34–42, where $Cp^x = Cp^*$ or Cp^{bph} .

5.1 μ M in HT-29 cells) than cisplatin (IC₅₀ = 2.4 μ M). Its derivatization by reducing the ligand size (-N-H instead of -Nphenyl) and changing the donor set (N,O-donor fpb vs. O,Odonor 1-(3-fluorophenyl)-3-hydroxybut-2-en-1-oate) did not lead to improved antiproliferative activity. 148 In contrast, using a different position and/or substituent than 3-fluoro of 39¹¹⁶ led, in some cases, to higher potency compared with cisplatin. For example, the $[Ir(n^5-Cp^*)Cl(dcpb)]$ (40; Fig. 9) complex with 1-(2,4-dichlorophenyl)-3-(phenylamino)but-2-en-1-one (Hdcpb) showed much higher antiproliferative activity (IC₅₀ = 2.8 μ M) than cisplatin (IC₅₀ = 8.1 μ M) in HCT116 p53^{-/-} cells; this was connected to significant selectivity towards the cancer cells mentioned over the ARPE-19 normal retinal epithelial cells used ($IC_{50} > 100 \mu M$).

Complexes with various benzohydrazones bearing the fluorenyl substituent (e.g., 41; Fig. 9) showed moderate cytotoxicity in HeLa cells. 150 Acridine was used for the derivatization of 2-[(imino)methyl]phenol within complex 42 (Fig. 9).91 This complex, analogous to co-studied ionic 25 with an N,N-ligand, was highly potent towards the HL60 cancer cells used but not selective towards the cancer cells mentioned over FG0 normal skin fibroblasts. Similar complexes derived from different 2-[(imino)methyl]phenol-based ligands, 151 as well as complexes containing 2-[(alkyl/aryl-substituted imino)methyl]phenols or pyridylphosphinates^{46,121,152,153} were markedly less effective or even inactive towards human cancer cell lines.

3.2.3. Complexes with a C,N-donor ligand. As the abovementioned complexes demonstrate, even seemingly very small structural changes can result in effective switching on/off of a biological effect. This was also demonstrated in pioneering work from 2011, in which replacing N,N-chelating bpy in the inactive [Ir(η⁵-Cp*)(bpy)Cl]⁺ complex (Fig. 3)⁴¹ with the C,Nchelating deprotonated 2-phenylpyridine (ppy) switched on the antiproliferative activity for the electroneutral $[Ir(\eta^5-Cp^*)Cl]$ (ppy)] complex (43; Fig. 10) against A2780 cells (IC_{50} = 10.8 μM). 154 This success triggered follow-up research on compounds involving ppy-derived C,N-ligands. It was demonstrated that the position and type of substituent on the ppy pyridine and phenyl rings critically influenced the outcome of

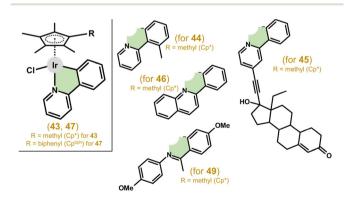


Fig. 10 Structural formulas of complex 43, containing deprotonated 2-phenylpyridine (ppy), and its analogues (44-47, 49) involving different ionic C,N-donor ligands.

such structural modification, as even positional isomers exhibited different antiproliferative effects, with $[Ir(\eta^5-Cp^*)Cl$ (mppy)] (44; Fig. 10) as the best performing within the studied group of analogues (IC₅₀ = 1.2 μ M in A2780 cells, *i.e.*, 10× more active than 43); Hmppy = 2-(2-methylphenyl)pyridine. 155 Ruiz et al. modified 43 by introducing a lipophilic steroidal ppy conjugate with a levonorgestrel group, 17-α-[2-phenylpyridyl-4ethynyl]-19-nortestosterone (Hppy^{LEV}), involved in complex 45 (Fig. 10) that was twice as active (IC₅₀ = $5.4 \mu M$) as the non-steroidal parent molecule 43 in A2780 cells, while being equally active in cisplatin-resistant A2780Cis cells. 156 Another innovative derivatization of ppy involves a steroidal backbone based on androsterone. 157 The prepared steroidal complexes showed potent activity in, e.g., the RT112 human bladder carcinoma cell line and its cisplatin-resistant variant with very low resistance factors (RF = 0.5-1.2), while retaining promising selectivity with respect to somatic fibroblasts.

Complexes with 2-(p-tolyl)pyridine, 2-phenylquinoline (for complex 46; Fig. 10), and 2-(2,4-difluorophenyl)pyridine showed promising potency in A2780 cells with IC50 values from 2.5 to 6.5 µM, and exceeded the potency of 43. 158 Another improvement to the antiproliferative activity of 43 was reached by a Cp^x ring extension, as exemplified by the $[Ir(\eta^5-Cp^{bph})Cl$ (ppy)] complex (47) in section 4.2. Other analogues of 43 were reported in which ppy was derived from substitution with rhodamine dyes with the aim of preparing a prospective theranostic agent. 159 The complexes had good fluorescent properties; however, they exhibited only moderate antiproliferative activity and no selectivity to cancer cells compared with normal cells. Furthermore, triphenylamine, carbazole and their derivatives, as efficient fluorescent materials, were also introduced as substituents for ppy, resulting in complexes with higher activity than that of cisplatin in A549, HeLa and HepG2 cell lines. 160,161 These complexes also showed the ability to prevent the migration of cancer cells, as revealed in a study on prospective antimetastatic agents (section 6.4). Unfortunately, no selectivity with respect to healthy cells was found. Other complexes derived from the ppy ligand are discussed below (section 3.4), as they contain a different monodentate ligand (e.g., pyridine) than the chlorido one, and therefore, represent another structural type. 44,162,165

Following the success of ppy-based complexes, other organic scaffolds have been investigated as C,N-chelating ligands for Ir-Cpx complexes. Ru(II), Rh(III) and Ir(III) complexes involving various 2-phenylbenzimidazoles were prepared. 166 All complexes showed significant anticancer activity on all tested cell lines in low micromolar ranges. The Ir complex $[Ir(\eta^5-Cp^*)(bzim^1)Cl]$ (48; section 7.3) was the most potent one of all the tested congeners, with, e.g., $IC_{50} = 1.0 \mu M$ in HT-29 cells; Hbzim¹ = methyl 1-butyl-2-phenyl-1*H*-benzimidazole-5-carboxylate. Notably, all the tested complexes were also significantly active in A2780Cis cells (RF = 0.6-1.1; 9.7 for cisplatin). Based on these positive results, further derivatization of the 2-phenylbenzimidazole core was performed on the phenyl ring (e.g., CH₃, F, CF₃, NO₂ or phenyl), ¹⁶⁷ to extend the SAR study. The highest efficiency towards a panel of cancer cell lines was observed for a complex with a phenyl ring as the substituent (i.e., 2-(biphenyl-4-yl)-1H-benzimidazole derivative) with the best results achieved on both A2780 and A2780Cis cell lines with $IC_{50} \approx 1.2 \mu M$.

Schiff bases represent other C,N-donor ligands used in Ir-Cp^x cyclometalated complexes. Complexes with substituted benzylidene(4-tert-butylphenyl)amines were comparably or slightly less active than cisplatin against A549 cells (IC₅₀ \approx 20 μM). 168 Complexes (e.g., 49 in Fig. 10) with ketimine Schiff bases based on aniline and acetophenone/2-acetonaphthone derivatives were found to be significantly active in K562 cells (IC₅₀ = 0.3-4.8 μ M), all outperforming cisplatin (IC₅₀ = 5.9 μM). 169 SAR analysis revealed that electron-donating groups in the para-position of the aromatic rings favourably contributed to the activity of the complexes, while electronwithdrawing groups decreased the activity.

Other works employed various N-heterocyclic carbenes (NHC) as C,N-chelating ligands. The study of complexes involving imidazole-based imine-NHC presented compounds with promising anticancer activity. 170,171 For these compounds, enlarging the substituents on the aniline and imidazole rings, as well as on the Cpx arenyl ligand, leads to higher anticancer efficiency. On the other hand, low selectivity compared to healthy cells was found for this class of complexes, with the best results found for $[Ir(\eta^5-Cp^{bph})Cl(nhc^n)]PF_6$, where $nhc^n = a$ 1-(phenylimino)methylimidazol-2-ylidene core substituted with methyl, phenyl or isopropyl (for 50 in Fig. 11) groups, with ca. 25 times higher activity than cisplatin in the A549 cell line (IC₅₀ = 0.9 vs. 21.3 μ M) and a selectivity index $(IC_{50}(BEAS-2B)/IC_{50}(A549))$ of ca. 5.4 (SI = 2.0 for cisplatin).¹⁷¹ In the follow-up study with benzimidazole-appended imidazole-based carbenes, the complexes showed no improvement over the abovementioned ones.172

Triazolyl-functionalized NHCs based on (benz)imidazole were also used as ligands in Ir(III), Rh(III), Ru(II) and Os(II) complexes.¹⁷³ The complexes were inactive in HCT116, NCI-H460, SiHa and SW480 cells except for the Ir(III) ones, achieving moderate activity with the lowest $IC_{50} = 10 \mu M$ in NCI-H460 cells for 51 (Fig. 11). The same research team achieved a significant improvement in antiproliferative activity by introducing a ferrocene moiety into the C,N-carbene ligand structure (e.g., 52

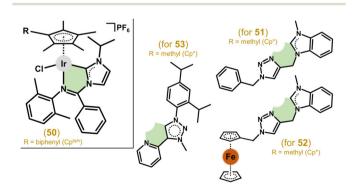


Fig. 11 Structural formulas of complexes N-heterocyclic carbenes (NHC) as C,N-chelating ligands.

in Fig. 11). 174 Another class of carbenes as C,N-donor ligands includes pyridyl functionalized mesoionic carbenes of the 1,2,3-triazol-5-ylidene type. Some complexes (e.g., 53 in Fig. 11) reached low micromolar IC₅₀ values (e.g., 2.0 µM in HeLa cells) while being non-toxic in normal primary keratinocytes. 175

Complex 54 (Fig. 12) with 1-benzyl-4-phenyl-1H-1,2,3-triazole showed potent efficacy in A549 cells ($IC_{50} = 4.7 \mu M$), which was comparable to auranofin, while being moderately active in other tested cancer cell lines (e.g., HeLa). 176 1-Phenyloxazoline derivatives (Hphox) were also investigated as ligands, for example, in complex 55 (Fig. 12) with low-micromolar potency in HeLa cells. 177 As a continuation of this study, complexes bearing either a fluorescent and lipophilic BODIPY entity (56)178 or a bioorthogonal azido probe (57)179 were reported by the same research group (Fig. 12). 56 was less active in HeLa cells ($IC_{50} = 8.6 \mu M$) than its predecessors (55) and showed low selectivity to cancer cells. 178

Another study reporting complexes of this type was in the field of photodynamic therapy (PDT), because even chlorido complexes but especially their analogues bearing a monodentate heterocyclic N-donor ligand (e.g., imidazole) exhibited higher antiproliferative activity when irradiated than in the dark (see section 6.3). The authors used π -expansive ligands, such as 4,9,16-triazadibenzo [a,c] naphthacene (pbpn; Fig. 12), in a highly phototoxic complex $[Ir(\eta^5-Cp^*)Cl(pbpn)]$ (58).

Bidentate 7-azaindole derivatives with N1-phenyl/thiophen-2-yl substituents (e.g., 59; Fig. 12) also coordinate in the C,Nfashion in Ir(III) complexes, which were either inactive or moderately active in A2780 and A2780Cis cells. 181

3.2.4. Complexes with an N,X-donor ligand (X = S or P)

3.2.4.1. N,S-Donor ligands. Inspired by Ru half-sandwich complexes with thiosemicarbazone (TSC)-based N,S-chelating ligands, Ir(III), Rh(III) and Ru(II) complexes involving pyrenylderived TSC were reported in 2015. 182 Iridium complexes (e.g., 60 in Fig. 13) showed low antiproliferative activity in cancer cells (e.g., A549 or MCF-7 cell lines), while achieving some selectivity, as IC50 values were up to 6.2-times higher in normal HEK-293 cells.

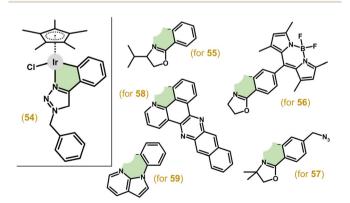


Fig. 12 Structural formulas of complex 54 and C,N-donor ligands involved in its analogues 55-59.

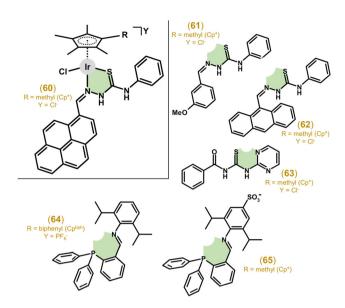


Fig. 13 Structural formulas of complex 60, N,S-donor ligands involved in analogues 61-63 and N,P-donor ligands involved in complexes 64

Other work, focusing on substituted benzaldehyde-N4-phenylthiosemicarbazones as ligands, describes complex 61 (Fig. 13) with promising antiproliferative activity (e.g., $IC_{50} =$ 3.6 μM vs. 15.0 μM for cisplatin in HeLa cells) and significantly improved selectivity for cancer cells (SI of up to 26). 183 In a follow-up study, Su et al. developed TSC complexes for dual chemo- and photodynamic therapy by introducing a photosensitizer moiety (e.g., 9-anthraldehyde for 62; Fig. 13) into the TSC ligand (see section 6.3 for more details). 184

Thiourea was used as a basic scaffold for N,S-coordinating ligands. Ir-Cp* cationic complexes with N-phenyl-N'-pyridyl/ pyrimidyl thiourea showed rather low anticancer activity, significantly lower than cisplatin in, e.g., the HCT116 cell line. 185 When benzoyl(2-pyrimidyl/4-picolyl)thiourea ligands were used instead, a notable improvement in activity and selectivity were observed, with the best results of $IC_{50} = 1.4 \mu M$ (2.8 μM for cisplatin) in HCT116 cells and SI ≈ 13 obtained for 63 (Fig. 13).⁶⁷ The introduction of N,S-ligands based on (benz) imidalole-2-thione appended with 1-benzyl-1,2,3-triazole led to Ir-Cp* complexes without relevant antiproliferative activity. 186 The complex involving N,S-coordinated N-(4-fluorophenyl)pyridine-2-carbothioamide showed a low antiproliferative effect, generally lower than that of its Ru/Os(II) and Rh(III) analogues.187

3.2.4.2. N,P-Donor ligands. Liu and co-workers systematically studied organometallic complexes with various P,X-donor ligands (X = P, O or N), including triphenylphosphane-imine based N,P-ligands. 188 Most of the complexes (e.g., 64 in Fig. 13) showed good anticancer activity towards A549 cells $(IC_{50} = 4.7 \mu M)$, higher than the clinical drug cisplatin $(IC_{50} =$ 21.3 µM). Similar complexes involving N,P-donor phosphaneimines, this time prepared as zwitterionic compounds, exhibited moderate potency (e.g., $IC_{50} = 14.7 \mu M$ in A549 cells for 65;

Fig. 13)¹⁸⁹ and exceeded inactive analogues containing N,Ndonor pyridyl-imines. 101 These investigations suggested the positive effect of phosphorus on cytotoxicity.

3.2.5. Complexes with an O,X-donor ligand (X = O, S, Se, P, C)

3.2.5.1. O,O-Donor ligands. As already mentioned, in 2012 McGowan and co-workers presented a series of complexes involving ligands with different donor atoms (i.e., N,N-, N,Oand O,O-ligands). Therein, the first anticancer Ir-Cp^x complex involving an O,O-donor ligand (66; Fig. 14) was reported with deprotonated 2-hydroxy-1,4-napthoquinone. However, 66 was less active than cisplatin (IC₅₀ = 20 μ M ν s. 2.4 μ M) in HT-29 cells.116

Similarly, using the O,O-donor benzovlacetone derivative did not result in an active compound (67; Fig. 14), compared to more effective complexes with N,O-donor analogues (section 4.3). 148 Unfortunately, even using an extended diketonato ligand with intrinsic biological activity, i.e., curcumin and its derivatives, complexes (e.g., 68 in Fig. 14) with a moderate effect and no selectivity in A2780 and A2780Cis cells were obtained. 45 The following study, which evaluated the influence of various substitutions on curcumin, resulted in complexes again with a low anticancer effect in HepG2 and HeLa cancer cells, yet in comparison with normal cells, some selectivity was observed. 190 Another study also chose anticancer active chelating O,O-ligands, specifically, a naturally occurring β -diketone dibenzovlmethane and its derivatives, including synthetic avobenzone used in cosmetics. 191,192 Similarly to previous works, the results also did not identify the complexes (e.g., 69 in Fig. 14) as being effective with significantly lower activity in A2780 and A2780Cis cell lines than cisplatin and the starting β-diketones.

3.2.5.2. O,S- and O,Se-donor ligands. In an effort to increase the stability of anticancer organometallic complexes, Keppler and colleagues used thiomaltol as an O,S-chelating ligand and prepared the complexes and analogous 1-methylimidazole derivatives (section 3.4). The Ir-Cp* complexes (e.g., 70 in Fig. 15) studied were found to be less active in A549 and CH1/ PA-1 cells than cisplatin, but were significantly more active towards SW480 cells (IC₅₀ = 0.7 μ M vs. 3.5 μ M for cisplatin).

Follow-up studies introduced thiopyridone and derivatives as O,S-chelating ligands. 194,195 These compounds (e.g., 71 in Fig. 15) showed increased stability in an aqueous solution and

Fig. 14 Structural formulas of complex 66 and O,O-donor ligands involved in analogues 67-69.

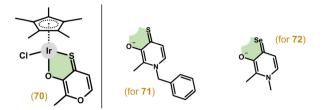


Fig. 15 Structural formulas of complex 70 and O,X-donor ligands involved in complexes 71 (X = S) and 72 (X = Se).

higher antiproliferative activity (e.g., $IC_{50} = 0.5 \mu M$ in SW480 cells for 71) compared to their pyridone and thiomaltol parental compounds. This group then explored the effect of sulphur substitution with selenium when using selenopyridones as O,Se-donor ligands. 196 However, some complexes showed remarkable air sensitivity and the stable compounds (e.g., 72 in Fig. 15) were significantly less active than their thiopyridone analogues.

3.2.5.3. O,P-Donor ligands. Liu and collaborators explored Ir-Cp*/Cp^{ph}/bph complexes with O.P-donor phosphane phosphonic amide ligands, specifically [2-(dicyclohexylphospanyl) phenyl](phenyl)-phosphinic diisopropyl-amide. All the studied complexes (e.g., 73 in Fig. 16) were significantly effective against HeLa and A549 cells; however, no selectivity was found.197

The follow-up work studied structurally similar complexes involving phosphane sulfonato O,P-ligands. 198 The electroneutral complexes (e.g., 74 in Fig. 16) were investigated as prospective theranostics for their rich fluorescence properties and generally favourable anticancer activity against HeLa and A549 cell lines, which was in some cases significantly better than that of cisplatin. Selectivity to cancer cells over normal cells was also identified (the best SI was equal to ca. 3.3).

3.2.5.4. C,O-Donor ligands. The IC₅₀ values of the complexes (e.g., 75 in Fig. 16), involving C,O-coordinated deprotonated 1-(2-hydroxyphenyl)-1H-benzimidazolium-based NHCs, towards A549 and HeLa cells ranged from 2.5 to 20.7 µM and 2.2 to 6.7 μ M, respectively (cisplatin IC₅₀ = 21.3 and 7.5 μ M). ¹⁹⁹ The activity of the complexes increased with a higher number

Fig. 16 Structural formulas of complex 73 and ligands involved in similar complexes 74 (with an O.P-donor ligand) and 75 and 76 (with C. O-donor ligands). Electroneutral complexes 74-76 do not contain any counter-anion (Y).

of phenyl groups in the complex molecule. Unfortunately, no selectivity to cancer cells over normal ones was found. Effective complexes, such as complex **76** (Fig. 16), were derived from imidazolium-based NHCs and studied for their anticancer activity even at the *in vivo* level (section 5.9).²⁰⁰

3.2.6. Complexes with a P,X-donor ligand (X = P or S). Together with the above-discussed highly-cytotoxic electroneutral dichlorido complexes with monodentate P-coordinated sulfides, sulfoxides, and sulfones (phsⁿ; section 3.1), their ionic monochlorido [Ir(η^5 -Cp*)Cl(phsⁿ)]PF₆ analogues (*e.g.*, 77 in Fig. 17) with the same ligands coordinated as chelating P,S-donor ligands, were also investigated.^{54,55} A different coordination mode (*i.e.*, P- ν s. P,S-donor) did not significantly impact the antiproliferative activity.

A follow-up study further investigated P,P-donor ligands involving two diphenylphosphano units with differing spacers between the P atoms. 201 The best anticancer activity was found for Ir-Cp^{bph} complex 78 (Fig. 17) with the simplest studied spacer, *i.e.*, ethylene, with IC_{50} = 2.3 μM in A549 cells (21.3 μM for cisplatin). This group continued their systematic research and next they reported on luminescent Ir-Cp*/Cpbph complexes with 1,2-bis(diphenylphosphano)benzene and 1,8-bis (diphenylphosphano)naphthalene as P,P-ligands.202 The complexes displayed higher activity than cisplatin towards A549 and HeLa cancer cells, with the most potent complex, 79 (Fig. 17), being up to ca. 40 times more active than cisplatin against A549 cells. Their self-luminescence helped uncover their MoA linked to lysosomal damage. Other complexes (e.g., 80) involving P,P-coordinating 2,20-bis(diphenylphosphano)-1,10-binaphthyl (Fig. 17) were studied and proved to be significantly more active than cisplatin in A549 and HeLa cells.²⁰³ Surprisingly, unlike in works involving complexes with N,Nand C,N-chelating ligands, an increase in activity was not observed for Ir-Cp^{bph} compared to its Ir-Cp* analogue. Also, no selectivity over healthy cells was found.

3.2.7. Complexes with a C,X-donor ligand (X = B or C). The first work that introduced differently substituted 1,1'-methylenebis(1*H*-imidazol-3-ium)-based NHCs coordinated in a bidentate C,C-fashion was reported in 2017.²⁰⁴ The anticancer activity could be tuned by varying the NHC and Cp^x ligands, in

Fig. 17 Structural formulas of complex 77 and P,P-donor ligands involved in complexes 78–80.

the order of ph- > butyl- > ethyl- > methyl-substituted NHCs and $Cp^{bph} > Cp^{ph} > Cp^*$. Complex **81** (Fig. 18) with a phenyl substituent on imidazole and a biphenyl substituent on the cyclopentadienyl ring was 3-times more potent than cisplatin against HeLa cells. Their intrinsic luminescence allowed their MoA to be studied in greater detail. 205

Another group of C,C-ligands included 1-benzyl-3-methylimidazolium-based NHCs. 206 All the studied Ir(III) complexes (e.g., 82 in Fig. 18) showed significantly higher antiproliferative activity (IC $_{50}$ values from 3.9 to 11.8 μM against A549 cells) than cisplatin (IC $_{50}$ = 21.3 μM). The abovementioned (section 3.1) dichlorido complexes involving C-coordinated imidazolium-based NHCs were co-studied with a chelated complex involving a mixed C,C-/C,B-coordination, which resulted in activity comparable to cisplatin in A2780 cells and better in A2780Cis cells for the complex involving the decaboranyl-imidazolium derivative as a B,C-donor NHC ligand. 71

3.3. Multinuclear complexes

Multinuclear Ir cyclopentadienyl complexes containing two or more Ir atoms (homometallic complexes; section 3.3.1) or combining Ir with different metals (heterometallic complexes; section 3.3.2) have been described. Clearly, both designs offer an increase in the resulting biological activity of such multinuclear complexes through multiplication of (multiple metal centres in the molecule) or combining (different metal centres acting through different MoAs) biological effects.

3.3.1. Homometallic complexes. Multinuclear Ir cyclopentadienyl complexes, belonging to families of symmetrical 192,207-211 or unsymmetrical 135 dinuclear complexes, complexes of higher nuclearity 121,152,153,209,212-216 thiolato and chalcogenato complexes, 217-219 and metallacages, 220-224 have recently been comprehensively reviewed. That is why only some examples of these compounds are discussed in this review together with complexes reported in the literature in the last few months.

The first multinuclear Ir–Cp^x complexes, which were studied for their cytotoxic activity, were derived from complexes **5** and **6** (Figs. 1 and 2)²² by the replacement of their monodentate ligands (*i.e.*, Cl for **5** and tmtu for **6**) by an appropriate N-donor bridging ligand (L = pyrazine (pyz) or 4,4'-bipyridine (bpy⁴)).²⁰⁷ Complexes, such as $[Ir_2(\mu\text{-dpeb})(\eta^5-Cp^*)_2(dppz)_2](CF_3SO_3)_4$ (**83**; Fig. 19), were highly cytotoxic against MCF-7 and HT-29 cell lines (IC₅₀ = 0.1–3.8 μ M).²⁰⁸ Improved antiproliferative activity was reached by analogues

Fig. 18 Structural formulas of complexes 81 and 82.

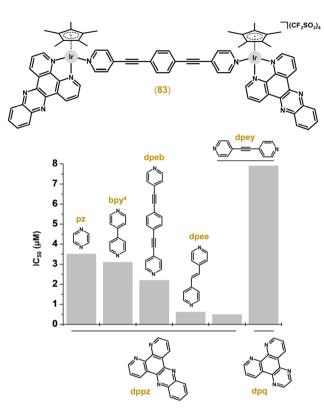


Fig. 19 The structural formulas of the representative dinuclear complex $[Ir_2(\mu-dpeb)(\eta^5-Cp^*)_2(dppz)_2](CF_3SO_3)_4$ (83; top) and its polypyridyl analogues, given with a comparison of their in vitro antiproliferative activity against MCF-7 breast carcinoma cells.

containing larger dipyridinyl bridging ligands, specifically 4-[(*E*)-2-(4-pyridinyl)ethenyl]pyridine (dpee), 4-(2-pyridin-4ylethynyl)pyridine (dpey) or 1,4-di(2-pyridin-4-ylethynyl) benzene (dpeb). Nevertheless, the type of polypyridyl chelating N,N-ligand seems to be more important for the resulting antiproliferative activity than a bridging ligand (Fig. 19). Interestingly, the bridging ligand used determined the type of nuclease activity, because dpee- and dpey-based complexes cleaved DNA in the dark, which was observed for the dpeb complex only when irradiated.

Hanif, Hartinger and co-workers prepared dinuclear Ir compounds containing various bitopical bispyridinone bridging ligands differing in the length of linkers between the two pyridinone units.²¹⁰ The linker length correlated with the lipophilicity and cytotoxic activity of the complexes, making [Ir₂(μ-bpd)(η⁵-Cp*)₂Cl₂ (84; Fig. 20) with bis(3-hydroxy-2-methyl-4-pyridinon-1-yl)dodecane (Hbpd) the most potent complex with sub-micromolar activity (IC₅₀ = 0.2-0.9 μM) against HCT116, NCI-H460, SiHa and SW480 cell lines, markedly outperforming both the reference drugs used (mononuclear Ru complex IT-139, cisplatin). Importantly, 84 was less haemolytic towards red blood cells than its Rh analogue and cisplatin, with a negligible effect on vascular vessel formation in zebrafish embryos.

The $[Ir_2(\mu\text{-bphp})(\eta^5\text{-Cp*})_2Cl_2](PF_6)_2$ (85; Fig. 20) complex was derived from the tetradentate N-donor ligand N,N'-(biphe-

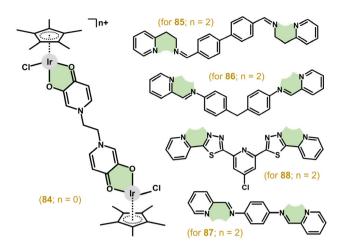


Fig. 20 Structural formulas of dinuclear complex 84 and N-donor ligands involved in its analogues 85-88.

nyl-4,4'-diyldimethylidyne)bis-2-(pyridin-2-yl)ethanamine (bphp).²¹¹ This compound was highly cytotoxic, especially towards A2780 (IC₅₀ = 3.1 μ M) and MCF-7 (IC₅₀ = 6.0 μ M) cell lines, where it showed even higher activity than the Pt-based drugs. 85 was highly selective towards cancer cells (e.g., the abovementioned A2780 and MCF-7 cells) over normal ones, studied in MRC-5 fibroblasts (IC₅₀ = 32.3 μ M) and the primary culture of human hepatocytes (IC₅₀ = 61.3 μ M). Recently, this work was followed by less cytotoxic analogues containing similar tetradentate N-donor ligands, this time derived from 4,4'-methylenedianiline (for 86 in Fig. 20)^{225,226} and benzene-1,4-diamine (for **87** in Fig. 20). ²²⁶

The $[Ir_2(\mu\text{-bphp})(\eta^5\text{-Cp*})_2Cl_2](PF_6)_2$ (85; Fig. 20) complex was derived from the tetradentate N-donor ligand N,N'-(biphenyl-4,4'-diyldimethylidyne)bis-2-(pyridin-2-yl)ethanamine (bphp).211 This compound was highly cytotoxic, especially towards A2780 (IC₅₀ = 3.1 μ M) and MCF-7 (IC₅₀ = 6.0 μ M) cell lines, where it showed even higher activity than the Pt-based drugs. 85 was highly selective towards cancer cells (e.g., the abovementioned A2780 and MCF-7 cells) over normal ones, studied in MRC-5 fibroblasts (IC₅₀ = 32.3 μ M) and primary culture of human hepatocytes (IC50 = 61.3 µM). Recently, this work was followed by less cytotoxic analogues containing similar tetradentate N-donor ligands, this time derived from 4,4'-methylenedianiline (for 86 in Fig. 20)225,226 and benzene-1,4-diamine (for **87** in Fig. 20). ²²⁶

Very recently, dinuclear complex 88 (Fig. 20) with a thiadiazole-based bitopic tetradentate N-donor ligand, showed lowmicromolar antiproliferative activity in various human cancer cells (e.g., $GI_{50} = 1.7 \mu M$ in MV4-11 cells). Importantly, this highly effective complex outperformed its mononuclear analogue. The MoA and some related processes (e.g., interaction with mixtures of small biomolecules) were studied in detail for 88 (see sections 4.5, 5.5 and 6.1.1).

The trinuclear complex derived from a quinolyl-benzimidazole-based polydentate ligand was inactive in MCF-7 and MDA-MB-231 cancer cells.²²⁸ Highly cytotoxic octanuclear complexes $[Ir_8(\mu\text{-dend}^1)(\eta^5\text{-}Cp^*)_8Cl_8]$ and $[Ir_8(\mu\text{-dend}^2)(\eta^5\text{-}Cp^*)_8Cl_8]$ (89; Fig. 21) were developed from N,O-donor salicylaldimine (Hdend¹) and N,N-donor 2-iminopyridyl (dend²) substituted poly(propyleneimine)diaminobutane-based dendrimers. The best-performing complex 89 was more cytotoxic (IC $_{50}=0.8~\mu\text{M}$) than cisplatin (IC $_{50}=1.5~\mu\text{M}$) in A2780 cells, and retained high selectivity with IC $_{50}=28.6~\mu\text{M}$ in normal HEK-293 cells.

Generally, metallacages contain two (tetranuclear metallar ectangles), three (hexanuclear metallaprisms) or four (octanuclear metallacubes) conjugated dinuclear units (clips). All three types have been reported for Ir–Cp^x complexes, which in most cases showed high activity but low selectivity. Higher and pharmacologically prospective selectivity towards cancer cells over normal ones was reached by tetranuclear complexes involving 3-undecyl-2,5-dihydroxy-1,4-benzoquinone (embelin, Hemb; Fig. 22). For example, [Ir₄(μ -emb)₂(μ -dpee)₂(η ⁵-Cp*)₄[CF₃SO₃)₄ (90; Fig. 21) exhibited markedly lower IC₅₀ values in cancer cells (*e.g.*, 0.6 μ M in HeLa cells) compared with HEK-293 cells (70.8 μ M).

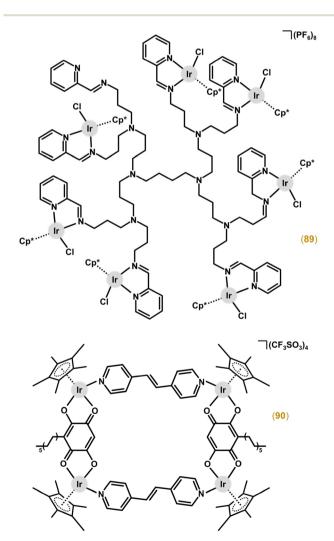


Fig. 21 Structural formulas of complexes 89 and 90

Fig. 22 Structural formulas of complexes 91 and 92.

Thiolato and chalcogenato complexes showed nanomolar activity in human cancer and normal cells, implying their low selectivity, which excluded them from advanced pharmacological studies. ^{217–219} Similar dinuclear Ir complexes were prepared by two different research groups, with a sulfur atom being involved in the chelate ring and bridging both metal centres at the same time. ^{230–232} Complexes with pyrrole-2-thioamide ligands showed only low activity towards A549 cancer cells at a concentration of 100 μM. ²³⁰ Their analogues with triphenylamine-modified TSC (*e.g.*, **91**; Fig. 22) ²³¹ or ferrocene-modified TSC²³² were effective against A549 and HeLa cancer cells, with low selectivity towards these cells over the BEAS-2B normal cells used. Complex **91** is discussed in more detail below (including *in vivo* anticancer activity).

The electroneutral $[Ir_2(\mu\text{-mpa})_2(\eta^5\text{-Cp*})_2\text{Cl}_2]$ (92; Fig. 22) complex involves 2-mercapto-*N*-phenylacetamide (Hmpa), which has a different coordination mode (an S-donor bridging ligand) than its Ru analogue $[Ru_2(\mu\text{-mpa})_2(\eta^6\text{-pcym})_2]$ with mpa coordinated as an N,S-chelating ligand bridging the two metal centres through the sulfur atom of mpa. ²³³ Both complexes exhibited comparable reductions of cancer cell viability expressed in mg mL⁻¹, implying a higher cytotoxicity of the Ir complex 92 (with respect to its higher M_w).

3.3.2. Heterometallic complexes. Similarly to the above-discussed multinuclear homometallic Ir–Cp^x complexes, their heterometallic counterparts have recently been comprehensively reviewed.³¹ The first combination of an Ir cyclopentadienyl motif with another metal was reported by Sheldrick and co-workers, who studied the DNA interaction of heterometallic conjugates of $\{Ir(\eta^5-Cp^*)(dppz)\}$ with various $Pt(\pi)$ species (*e.g.*,

trans-{Pt(NH₃)₂(DMF)}) bridged by methionine-based peptides (see section 5.4 for more details). 234,235

Other heterometallic Ir-Cp^x complexes represent a family of ferrocene (Fc)-appended compounds. 153,174,215,236-240 Since Fc is involved in a well-known antimicrobial active agent, ferroquine, such compounds were often studied for their antimicrobial activity. Along with antimicrobial activity, these Fcappended heterometallic complexes were also studied for their anticancer activity. Liu and co-workers suggested a positive effect from the introduction a ferrocene substituent into the structure of Ir-Cpx complexes, 78,239 because, for example, the heterometallic $[Ir(\eta^5-Cp^*)Cl(ppy^{Fc})]$ (93) complex exceeded the potency of its mononuclear analogue 43 (Fig. 23A).²³⁹ Interestingly, a Cp^x ring extension did not provide higher antiproliferative activity for the ferrocene-containing compounds (e.g., 93), which was in contrast with congeners involving unsubstituted ppy. Other strategies by the same research group to introduce the Fc entity into the structure of various Ir cyclopentadienyl complexes (see complexes 94 and 95 in Fig. 23B) did not lead to an improvement of the antiproliferative activity. 241,242

A different design was applied for heterometallic Ir-Pt²⁴³ and Ir-Ru²⁴⁴ complexes (Fig. 24). Ir-Pt complex 96 was not

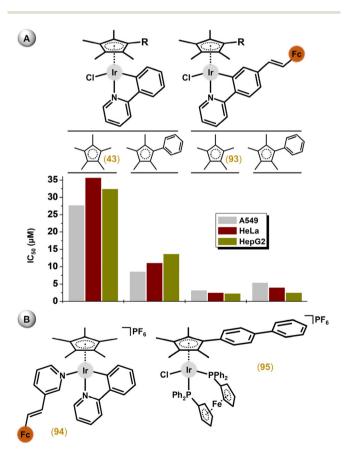


Fig. 23 (A) Structural formulas and in vitro antiproliferative activity of [Ir $(\eta^5-Cp^x)Cl(ppy^n)$] complexes 43 and 93, containing various Cp^x derivatives (Cp* or Cp^{ph}) in combination with ppy or its ferrocene (Fc)-substituted derivative (ppy^{Fc}). (B) Structural formulas of ferrocene-containing complexes 94 and 95.

Fig. 24 Structural formulas of heterometallic complexes 96-98.

effective against MDA-MB-231 cells, which indicated its lower potency compared with the co-studied mononuclear Pt complex and dinuclear heterometallic Ru-Pt and Cu-Pt analogues. The Ir-Ru complex $[Ir(\eta^5-Cp^*)Cl(\mu-bpm)Ru(\eta^6-pcym)]$ Cl](PF₆)₂ (97), containing tetradentate 2,2'-bipyrimidine (bpm; Fig. 24), was studied, together with Ir2 and Ru2 analogues, in MDA-MB-468 (breast carcinoma) and Caco-2 (colon carcinoma) cells. Although 97 was less effective (IC₅₀ = 1.9 μ M) against MDA-MB-468 cells than Ir_2 ($IC_{50} = 1.8 \mu M$) and Ru_2 ($IC_{50} =$ 0.9 µM) analogues, this heterometallic compound exceeded (IC₅₀ = 6.2 μ M) both homometallic analogues (IC₅₀ = 32.4 and 46.0 μM for Ir₂ and Ru₂, respectively) in Caco-2 cells. Also of interest, 97 was more effective towards Caco-2 cells than both mononuclear parts, i.e., $[Ir(\eta^5-Cp^*)(bpm)Cl]PF_6$ ($IC_{50} =$ 50.4 μ M) and $[Ru(\eta^6-pcym)(bpm)Cl]PF_6$ ($IC_{50} = 49.6 \mu$ M) (not studied in MDA-MB-468 cells).

The same research group also developed a new type of heterometallic complex, [Ir(η⁵-Cp*)Cl(μ-bpm)ReCl(CO)₃]Cl (98; Fig. 24), using the conjugation of the Ir(III)-Cp* and Re(I)-tricarbonyl motif through the same bridging bpm ligand.245 This complex showed approximately 5-fold higher antiproliferative activity against MDA-MB-468 cells (IC₅₀ = 24.1 μ M) than its Re₂ homometallic and Ru-Re heterometallic analogues. 98 was highly selective towards MDA-MB-468 cells in comparison with non-cancerous HaCaT ones ($IC_{50} = 234.8 \mu M$).

The combination of Ir and Cu was obtained with phosphanes (P-coordinated to Ir) derived from fluoroquinolones (O,O-coordinated to Cu). 246 These complexes, such as the bestperforming complex, [Ir(η⁵-Cp*)Cl₂(μ-pcfx)Cu(phen)(H₂O)]NO₃ (99; Fig. 25 and Fig. 4), were significantly more effective than cisplatin in various human cancer cell lines, whereas they were almost ineffective in non-cancerous HEK-293T cells. Especially the anticancer potency of 99 in DU145 cells is noteworthy not only because of the extremely low IC50 value in the low-picomolar range (IC₅₀ = $1.3 \times 10^{-6} \mu M$; 24 h exposure time), but also because of the unusual recovery of treated cells (IC₅₀ =

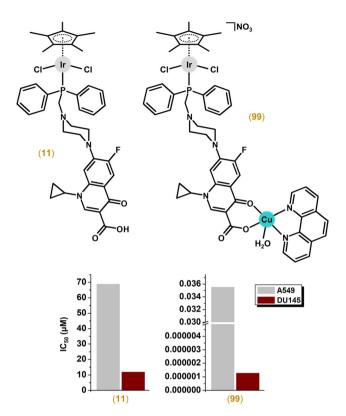


Fig. 25 Structural formulas and in vitro antiproliferative activity of mononuclear complex [Ir(n⁵-Cp*)Cl₂(pcfx)]NO₃ (11) and its heterometallic analogue $[Ir(\eta^5-Cp^*)Cl_2(\mu-pcfx)Cu(phen)(H_2O)]NO_3$ (99).

125.7 µM; 24 h exposure + 48 h recovery time in a drug-free environment). Similar results were obtained for 99 and analogues in, e.g., MCF-7 cells, while the opposite effect was observed in A549 cells ($IC_{50} = 35.5$ nM for 24 h exposure time, and $IC_{50} = 0.4$ nM for 24 h exposure + 48 h recovery time). 99 was also loaded into liposomes (section 6.4). Importantly for future studies in the field of heterometallic anticancer Ir-Cp^x complexes, 99 exhibited markedly higher antiproliferative activity in cancer cells (Fig. 25) than its mononuclear analogues (11 and congeners; Fig. 4). 57,246

3.3. Other structural types

Many researchers have tried to replace the chlorido ligand of widely studied chlorido Ir-Cpx complexes by a different monodentate ligand to improve biological activity. Obviously, when an electroneutral monodentate ligand is used to replace the chlorido ligand, the charge of the complex changes. The first investigation of this phenomenon involved $[Ir(\eta^5-Cp^*)(dppz)]$ (py)](CF₃SO₃)₂ (**100**; Fig. 26).²⁰⁷

Contrasting results were reported for an electroneutral chlorido ppy complex and its ionic analogue with pyridine, [Ir $(\eta^5-Cp^{bph})(ppy)(py)]PF_6$ (101; Fig. 27).⁴⁴ In particular, 101 showed higher ($GI_{50} = 0.2 \mu M$) activity in the NCI-60 human cancer cell screen and improved selectivity compared with the chlorido complex ($GI_{50} = 0.7 \mu M$). Regarding similar Cp^{ph} complexes, $[Ir(\eta^5-Cp^{ph})(ppy)(py^{NMe2})]PF_6$ (102; $py^{NMe2} = N,N-di-$

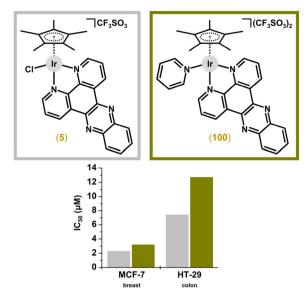


Fig. 26 Structural formulas and in vitro antiproliferative activity of [Ir $(\eta^5-Cp^*)(dppz)X]^{n+}$ complexes 5 and 100 containing various monodentate ligands.

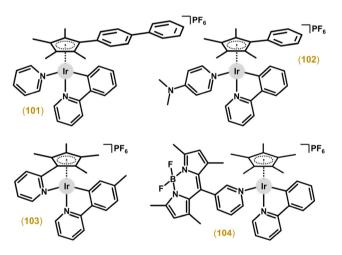


Fig. 27 Structural formulas of complexes 101-104.

methylpyridin-4-amine) also outperformed cisplatin in the NCI-60 screening (Fig. 27; section 4.4). 162

Other groups used pyridine for the introduction of other functionalities to Ir-Cpx complexes. However, mono- and trinuclear complexes with 4-ferrocenylpyridine were less effective than analogues with unsubstituted pyridine. 153 On the other hand, a similar complex with 3-pyridyl-BODIPY (104; Fig. 27) was more active than the chlorido complex in a small panel of human cancer cell lines (e.g., $IC_{50} = 0.6 \mu M \nu s.$ 14.0 μM in A2780 cells). 163 Thanks to the fluorescent BODIPY substituent, this complex was also used for live cell imaging.

A different introduction of pyridine to Ir was reported by Pizarro and co-workers. 138,164,165 Specifically, they used 2-[(2,3,4,5-tetramethylcyclopenta-2,4-dien-1-yl)methyl]pyridine

(HCp^{mpy}) as the η⁵-bound arenyl ligand, the pendant pyridine of which coordinated to the central atom of the complexes. 164 The activity differed significantly according to the chelating C, N- or N,N-donor ligands used. $[Ir(\eta^5-Cp^{mpy})(ppy^1)]PF_6$ (103; ppy¹ = 2-(4-methylphenyl)pyridine) exhibited nanomolar activity towards the MCF-7 cell line (IC₅₀ = $0.05 \mu M$) with promising selectivity towards this cancer cell line over the MRC-5 normal cells used (SI = 91.8).

A similar approach was reported for thiomaltol- and thiopyridone-based complexes with the chlorido ligand being replaced by 1-methyl-1H-imidazole (e.g., complex 105 in Fig. 28). 193,195 Motivated by the clinically-studied Ru complex RAPTA-C, several Ir-Cpx complexes were prepared with pta as a monodentate P-donor ligand. 45,191,247 These pta complexes were in most cases of low-to-moderate antiproliferative activity. The representative Ir-pta complex $[Ir(\eta^5-Cp^*)(dpp)(pta)]CF_3SO_3$ (106; Fig. 28) was not stable under the mimicked extracellular conditions (100 mM NaCl solution), where it released its chelating dpp ligand and degraded to $[Ir(\eta^5-Cp^*)Cl_2(pta)]$; Hdpp = 1,3-diphenylpropane-1,3-dione. 191

In some cases, the chlorido ligand was replaced by a different halogenido ligand. 43,46,248 For example, a pair of pyridylphosphinate complexes (e.g., 107 in Fig. 28) differs markedly in their potency against the H460 cell line (IC₅₀ > 200 μM for the chlorido complex and $IC_{50} = 52 \mu M$ for its iodido analogue).46 A similar approach was used for a series of hydrogensulfido Ir-Cp^x complexes, including the highly cytotoxic [Ir(η^5 - $Cp^{bph})(bpy)(SH)PF_6 complex (108 in Fig. 28).^{249}$

Another design used bioactive carboxylato ligands (e.g., histone deacetylase (HDAC) inhibitor 4-phenylbutyrate, pb) to replace the chlorido ligand, providing multi-component (multi-targeted) complexes releasing two bioactive species (i.e., organic and Ir-based) under conditions that mimicked physiological conditions (section 6.2). 43,250 Another pair of complexes was derived from N,O-coordinated lidocaine and two different monodentate N-donor (bi)phenylcyanamide-based ligands.²⁵¹ These complexes were reported as one of only a few representa-

SO₃CF (108)

Fig. 28 Structural formulas of complexes 105-108.

tives of Ir cyclopentadienyl complexes studied for possible applications in PDT (section 6.3).

The $[Ir(\eta^5-Cp^*)(pyth-\kappa N,\kappa S)(pyth-\kappa S)]$ (109; Fig. 29) complex, with pyrimidine-2-thiol (Hpyth) coordinated as N,S-chelating (four-membered rings) and monodentate S-donor ligands, was markedly less cytotoxic than cisplatin and its Rh congener. 252 No relevant antiproliferative activity was detected either for a dinuclear Ir complex with {Ir(n⁵-Cp*)Cl} and {Ir(n⁵-Cp*)Cl₂} moieties bridged by a tridentate-coordinated azo ligand (2 + 1 fashion) bearing pyrazine and pyridine terminal substituents (110; Fig. 29). The Ir(i) complex $[Ir(\eta^5-Cp^*)(\eta^4-L)]$, where L stands for p-benzoquinone (IC₅₀ = 93.0 μ M in A2780 cells) and its dithio (IC₅₀ = 154.0 μ M) and diseleno (IC₅₀ = 5.0 μ M; 111; Fig. 29) derivatives represent a unique design combining two hapto-coordinated ligands; $IC_{50} = 3.0 \mu M$ for cisplatin.²⁵³

Liu et al. obtained stable five-coordinated (16-electron) complexes via a solvent-involved rearrangement reaction with α-keto-β-diimine ligands (e.g., 112 in Fig. 29) 254,255 or similar compounds derived from amine-imine ligands (e.g., 113 in Fig. 29). 256 Among them, complexes involving isopropyl-substituted amino-imines structurally differed in the substitution on the Cp^x ring (Me, Cy, ph, bph, Me-ph, F-ph; see section 4.2).²⁵⁴ These complexes (e.g., 112), in most cases, exceeded the activity of cisplatin towards cancer cells; however, no selectivity over normal cells was found.

Other work on electron deficient five-coordinated complexes involves S,S-coordinated 1,2-dicarba-closododecarborane-1,2-dithiolato and benzene-1,2-dithiolato ligands. Unlike some Ru(II) or Os(II) congeners, Ir(III) complexes (e.g., 114 in Fig. 29) were found to be inactive. 257 Lord and co-workers replaced the η⁵-Cp* arenyl ligand with an η⁴-cod arene within the structure of the electroneutral chlorido complex, $[Ir(\eta^4-cod)]$

Fig. 29 Structural formulas of complexes 109-115.

Cl(nhc¹)] (115; Fig. 29); nhc¹ = decaborane-appended NHC ligand.⁷¹ Although 115 was less effective against cisplatin-sensitive cancer cell lines (e.g., $IC_{50} = 2.2 \mu M$ in A2780 cells) than cisplatin ($IC_{50} = 1.3 \mu M$), it exceeded the structurally similar cyclopentadienyl complex, $[Ir(\eta^5-Cp^*)Cl_2(nhc^1)]$ ($IC_{50} = 6.4 \mu M$).

4. Structure—activity relationships

The anticancer Ir-Cpx complexes reviewed herein have often been studied with their Rh analogues and with structurally similar Ru and Os arene complexes, allowing the discussion of the central atom effect on antiproliferative activity (section 4.1). Furthermore, the $[Ir(\eta^5-Cp^x)(L^{\perp}X)]^{0/+}$ type anticancer Ir-Cpx compounds are discussed as they are more prominent than analogues containing three monodentate ligands (see section 2.1 and Fig. 3). Regarding $[Ir(\eta^5-Cp^x)(L^L)X]^{0/+}$ complexes, they consist of three ligands, namely, an n⁵-coordinated Cpx ring, a bidentate (chelating) L^L ligand and a monodentate X ligand. Obviously, various SARs can be derived for the anticancer Ir-Cpx complexes reviewed with respect to their ligands. Thus, in this section, the effect of the composition of all three ligands on the resulting biological effect is also analysed (sections 4.2-4.4). Additionally, the effects of nuclearity (i.e., the number of central atoms in multinuclear complexes) and counter-anions in ionic complexes are also discussed (sections 4.5 and 4.6).

4.1. Central atom effect

In one of the pioneering studies, Sheldrick and co-workers reported two pairs of analogous Ir and Ru complexes, which enabled a discussion of the central atom effect on biological activity.22 In fact, although there were significant differences in the IC50 values obtained, the trend did not direct future research. Specifically, Ir complex 5 was less potent ($IC_{50} = 2.3$ and 7.4 μM) than its Ru analogue [Ru(η⁶-hmb)Cl(dppz)]CF₃SO₃ (IC₅₀ = 2.1 and 2.5 μ M) in MCF-7 and HT-29 cells, respectively (Fig. 30), but another co-studied Ir compound, 6 (IC₅₀ = 0.2and 0.4 µM), exceeded its Ru congener, which showed IC₅₀ values of 2.1 and 1.4 µM in the same cancer cells.

Regarding the following works with Ru and Ir analogues being studied for their anticancer effect, some Ir compounds exceeded the potency of their Ru congeners. 46,59,60,111,114,146,157,192,197,245 In other cases, Ir complexes were comparably 46,59,60,111,114,192,197,256 or even less potent 53,59,64,92,104,110,116,142,148,157,167,201,203,241,244 than their Ru analogues (Fig. 30). The careful reader will have noticed that some papers belong to more than one category, which makes subsequent evaluation very difficult. The same then applies to the following discussion.

A similar conclusion can be drawn for the comparison of Ir-Cpx complexes and their direct Rh analogues. Specifically, several Ir complexes outperformed the anticancer activity of their Rh analogues, 43,64,67,83,89,112,141,145,184,190,191 while other cases, Ir complexes exhibited only comparable 45,46,67,83,144,190,191,252 even lower

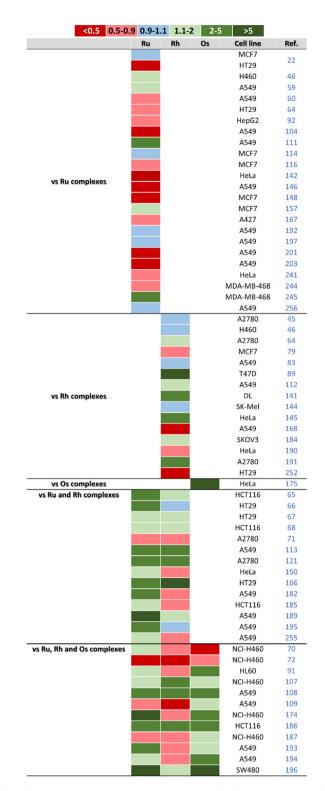


Fig. 30 A comparison of the relative activity (RA) of Ir complexes with their Ru, Rh and/or Os analogues. RA = $IC_{50}(Ru/Rh/Os complex)/IC_{50}(Ir$ complex). The best-performing Ir complexes and the data from lung cancer cells (where possible) were chosen for these comparisons.

potency^{43,45,67,79,83,86,144,168,184,190,191,252} than Rh compounds derived from the same ligands (Fig. 30). Only one paper was dedicated to Ir-Cp* and Os-pcym complexes. 175 For both pairs

of analogues derived from these metals, the Ir complex was more effective than its Os congener (Fig. 30).

Many papers have reported complexes derived from three (Ru/Rh/Ir or Ru/Os/Ir) of the four metals of interests. For these complexes, it can be concluded that Ir and Rh compounds are more effective than Ru ones (Fig. 30). This is because an equal number of papers reported the Ir^{65,67,68,113,121,166,185,189,195} or Rh^{65,66,71,121,150,182,185,255} complexes as the best-performing ones. Significantly fewer papers discuss Ru compounds as being more potent than structurally similar Ir and Rh compounds. ^{66,68} In some cases, Ir complexes exhibited the same biological effect as their Ru^{68,166} or Rh^{65–67,121,185,195} analogues, thus outperforming complexes of the third metal (*i.e.*, Rh or Ru, respectively). Several Ir compounds have shown the lowest potency. ^{71,121,150,182} The equal potency of the Ru, Rh and Ir complexes is exceptional in the literature. ¹⁸⁵

Regarding the second group of complexes derived from three different metals (Ru/Os/Ir in this case), 10 μM trinuclear Ir complex was comparably active to an equimolar dose of its Ru and Os analogues derived from the hexadentate quinolyl-benzimidazole-based ligand (IC $_{50}$ were not reported for Ir complex). The second paper reported on complexes containing various dithiolato ligands, but Ir complexes were inactive (IC $_{50} > 100~\mu M$), and thus, less effective than their Ru and Os analogues. 257

The last group of compounds is represented by co-studied complexes of all four metal (*i.e.*, Ru/Rh/Os/Ir). As in the case of the above-discussed Ru/Rh/Ir complexes, it was Ir^{70,107,108,176,186,193,194,196} and Rh^{70,91,107,174,193,194} complexes that were most often reported as the most active ones from Ru/Rh/Os/Ir analogues (Fig. 30). Other papers reported appropriate Ir complexes as having lower anticancer activity than Ru,¹⁷⁶ Ru and Rh,^{91,109,187} Ru and Os,¹⁰⁷ and Rh and Os^{70,193} analogues. Several Ir complexes were outperformed by all three Ru, Rh and Os analogues.^{70,72,107,140,187}

The effect of the central atom type is discussed elsewhere 31 for multinuclear complexes. $^{121,152,153,209-224}$ Recently, a series of dinuclear Ru, Rh, Os and Ir complexes with two different bis(1-(pyridin-2-yl))(methanimine)-based bridging ligands was reported. 226 One Ir complex and its Ru and Os complexes were inactive (IC $_{50} > 100~\mu\text{M}$) and outperformed by the Rh complex. The second Ir complex was moderately effective against the human cancer cell lines used, where it exceeded the potency of the Ru and Os analogues. Regarding its comparison with a similar Rh complex, it is ambiguous again, because the potency of the Ir complex is higher than (HCT116 cells), comparable to (SiHa cells) or lower than (SW480 cells) its Rh analogue.

4.2. Effect of a cyclopentadienyl ring

In pioneering work in 2011, Sadler and co-workers reported the dependence of antiproliferative activity (and other properties) on the ${\rm Cp}^{\rm x}$ ring size (Fig. 31). In particular, inactive ${\rm Cp}^{*}$ complexes were turned into active compounds when their ${\rm Cp}^{*}$ ring was replaced by a more extended one, namely, 2,3,4,5-tetramethyl-1-phenylcyclopenta-2,4-dienyl (${\rm Cp}^{\rm ph}$) or 1-

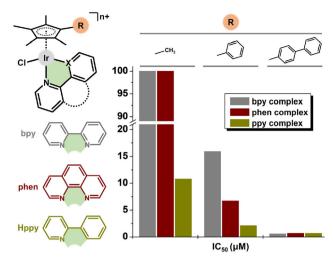


Fig. 31 The dependence of the *in vitro* antiproliferative activity of $[Ir(\eta^5-Cp^x)Cl(L^{\Lambda})]^{n+}$ complexes in A2780 ovarian carcinoma cells on the cyclopentadienyl ring size; $Cp^x = Cp^x$, Cp^{ph} or Cp^{bph} , $L^{\Lambda}L = 2,2'$ -bipyridine (bpy; n = 1), 1,10-phenanthroline (phen; n = 1) or deprotonated 2-phenylpyridine (ppy; n = 0).

(biphenyl-4-yl)-2,3,4,5-tetramethylcyclopenta-2,4-dienyl (Cp^{bph}). This was observed especially for phen and bpy complexes, the Cp^{bph} complexes (14 and 15, Fig. 5) of which reached even sub-micromolar activity (Fig. 31). Cp^{bph} complexes bearing en or pico were markedly less effective, but their Cp^{bph} complexes still exceeded the potency of their Cp* analogues. The activity enhancement with increasing phenyl substitution on Cp^x was confirmed by the same group for a series of electroneutral [Ir(η^5 -Cp^x)Cl(ppy)] complexes (Fig. 31). 154,158

In numerous subsequent studies, a Cp^x ring extension was successfully applied for the enhancement of the antiproliferative activity of parent Cp* complexes. On the other hand, this dependence should not be accepted as being straightforward, because in numerous cases it was Cp* complexes that outperformed their Cp^{ph} and Cp^{bph} analogues. This is briefly summarized in Fig. 32.

Similarly to the majority of Ir–Cp^{ph} and Ir–Cp^{bph} complexes, ppy-based Ir–Cp^x complexes involving the benzyl substituted Cp^x ring exceeded the antiproliferative activity their Cp* analogues. ¹⁶⁵ For a similar en-derived complex, the benzyl substituent of the Cp^x ring did not induce any relevant antiproliferative activity of the previously mentioned inactive complex (IC₅₀ > 500 μ M; MCF-7 cells). ¹³⁸ Also of interest, it was reported that the effect of Cp^x ring extension on the resulting antiproliferative activity could be different for chlorido complexes (positive effect) and their iodido counterparts (negligible or even negative effects). ²⁴⁸

Although not studied for the final mononuclear complexes, substitution of the Cp^x ring with a long-chain alcohol was found to be beneficial in terms of the antiproliferative activity of dinuclear $[Ir(\mu\text{-Cl})(\eta^5\text{-Cp}^x)Cl]_2$ intermediates (see section 2.2), with $IC_{50} = 92.0 \ \mu\text{M}$ (Cp^* complex), 30.0 μ M (5-hydroxy-

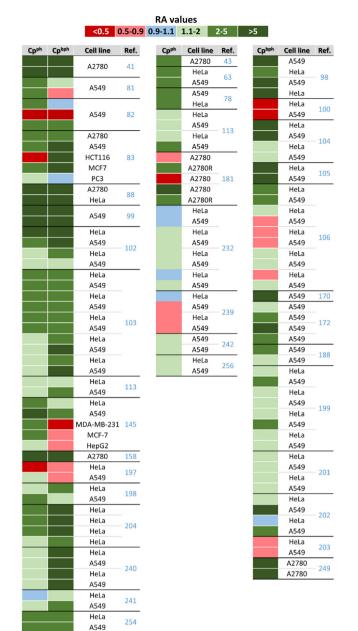


Fig. 32 A comparison of the relative activity (RA) of Cp^{ph} and Cp^{bph} complexes versus their Cp* analogue. RA = $IC_{50}(Cp* complex)/IC_{50}(Cp* complex)$ complex); $Cp^x = Cp^{ph}$ and Cp^{bph} .

pentyl derivative) and 10.2 µM (14-hydroxytetradecyl derivative) in the HT-29 cell line.⁶⁴

Within their extended research on anticancer Ir-Cp^x complexes, Liu and co-workers paid attention to different Cpx substituents, 189,254,258 than the notoriously used Cp^{ph} and Cp^{bph} ones. In particular, various Cp^x rings were used within complexes derived from phosphane-imines, 189 amino-imines (in five-coordinated $16e^-$ complexes) 254 and iminopyridines (in zwitterionic complexes). 101,258 The data implied a positive effect of fluorine substitution on the Cpx ligand for the antiproliferative activity of such compounds (Fig. 33). Similar

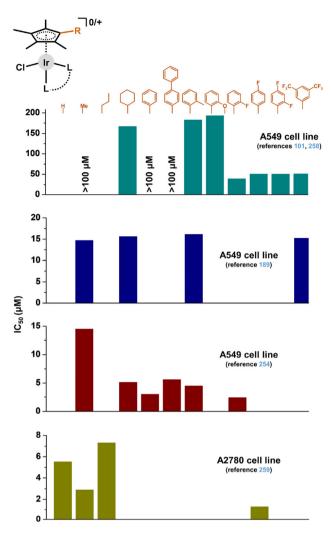


Fig. 33 A comparison of the in vitro antiproliferative activity (IC₅₀ values $[\mu M]$) of complexes containing different cyclopentadienyl derivatives. Dark cyan – zwitterionic iminopyridine complexes; 101,258 dark blue - complexes with phosphane-imines; and dark red - five-coordinated 16e- complexes with amino-imines; dark yellow - electroneutral [Ir $(\eta^5-Cp^x)Cl(ppy)]$ complex.²⁵⁹

research was reported for electroneutral $[Ir(\eta^5-Cp^x)Cl(ppy)]$ complexes involving various Cpx ring substituents.259 Their activity for a panel of cancer cells followed the order (of Cp^x substituents) of 4-fluorophenyl > hydrogen > methyl > propyl, which again claimed that the fluoro-substituted Cpx ligand was beneficial for the resulting antiproliferative activity.

4.3. Effects of a chelating ligand

4.3.1. Donor set effect. In several works, complexes with a different donor set of coordinated chelating ligands have been prepared. The [Ir(η^5 -Cp^{bph})Cl(pic)] (37; Fig. 9) complex involving N,O-coordinated pic was less potent than its congeners with the N,N-donor ligands phen and bpy (14, 15; Fig. 34).⁴¹ Despite the lower antiproliferative activity, 37 had higher affinity towards the model nucleobases 9-ethylguanine (EtG) and 9-ethyladenine. Although this result was encouraging for

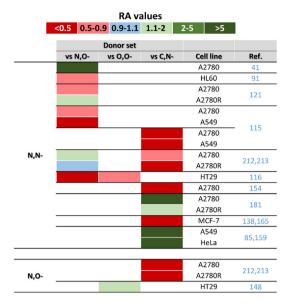


Fig. 34 A comparison of the relative activity (RA) of complexes involving differently coordinated ligands. For the N,N- column: $RA = IC_{50}$ (complex with different donor set)/IC50 (complex with an N,N-donor set); for the N,O- column: $RA = IC_{50}$ (complex with different donor set)/ IC₅₀ (complex with an N,O-donor set).

future investigations with N,N-donor ligands instead of N,Oones, most of the published results showed that complexes with an N,N-donor set were less anticancer effective than analogues with N,O-coordinated ligands (Fig. 34). 91,115,116,121

Even in the case of the donor set effect, the resulting antiproliferative activity was cell-dependent, because an ionic complex containing the N,N-coordinated electroneutral N-[pyridin-2-ylmethylidene]aniline was less effective in A2780 cells but more potent in A2780Cis cells, in comparison with its electroneutral analogue involving deprotonated N,O-coordinated 2-[(Z)-(phenylimino)methyl]phenol (Fig. 34). 121

Other studies report complexes with C,N-donor ligands, along with the N.N- and/or N.O-ones discussed above. Within a pair of isoelectronic complexes, it was the electroneutral complex 43 (with C,N-coordinated ppy) that showed a higher antiproliferative effect than its ionic bpy-based analogue (N,Ndonor set). 41,154 In a similar manner, untypical doubly chelated Ir-Cp^{mpy} complexes containing various C,N-donor ligands (e.g., ppy¹ in 103; Fig. 27) were several orders of magnitude more cytotoxic in various human cancer cells than congeners with N,N-donor ligands (Fig. 34). 138,164,165 For Ir-Cp* complexes with various benzimidazole derivatives, compounds with C,N-donor ligands were more effective than analogues involving N,O- and especially N,N-donor ligands (Fig. 34). 115 Similarly, the complex with the C,N-coordinated naphthaldimine outperformed its analogues with similar ligands derived from pyridine (N,N-donor set) or phenol (N,O-donor set) (Fig. 34). 212,213

A different trend was observed for other pairs of complexes involving similar chelating C,N- and N,N-donor ligands. For complexes containing bidentate 7-azaindole derivatives with

N1-phenyl (C,N-ligand in 59; Fig. 12) or N1-pyridin-2-yl (N,Nligand; section 6.4) substituents, it was electroneutral complex 59 that showed a lower activity ($IC_{50} > 50 \mu M$ in A2780 cells) than its more potent analogue with the N,N-donor ligand (IC₅₀ = 3.1 μM).¹⁸¹ Similarly, the ppy-based complexes (C,N-donor set) were outperformed by their bpy analogues (N,N-donor set) bearing the rhodamine substituent for theranostic applications.85,159

McGowan and co-workers presented a series of complexes involving ligands with N,N-, N,O- and O,O-donor atoms. 116 Despite the ligands used being of a different chemical type (see 39 in Fig. 9 and 66 in Fig. 14), it can be concluded that the most active was the complex with an N,O-donor ligand (i.e., 39), while the complexes with N,N-donor ligands showed the lowest biological activity (Fig. 34). Later, the same research group used a similar N,O-donor ligand (3-amino-1-phenylbut-2-en-1-one) and its direct hydroxo analogue, which coordinated as an O,O-donor ligand. This strategy allowed a relevant comparison of both complexes, which exhibited more or less similar biological effects (IC₅₀ = 83 and 93 μ M in HT-29 cells, respectively). Both complexes were significantly less potent than the co-studied complex 39 (IC₅₀ = 5.1 μ M). Finally, complex 72 with a unique O,Se-donor set (Fig. 15) was less active than its analogue involving analogous O,S-donor ligands (thiopyridone). 194,196

4.3.2. Chelate-ring size. In the context of the effect of different donor sets of ligands used for the preparation of anticancer Ir-Cpx complexes, the effect of chelate ring size for several representatives containing ligands with the same donor set but forming chelate rings of different sizes can also be discussed. In the case of the abovementioned complexes with various benzimidazole derivatives, two types of N,Ndonor ligands were used - one with pyridine (forming a fivemembered chelate ring) and the second one with aniline (forming a six-membered chelate ring). 115 This variation led to different antiproliferative activities, showing that the anilinederived complex with a six-membered chelate ring was more effective than its pyridine-based analogue with a smaller chelate.

Within the pair of dinuclear complexes involving the bridging 4,4-substituted biphenyl, complex 85, the ligand of which formed two six-membered chelate rings (Fig. 20), was more cytotoxic (IC₅₀ in low-micromolar range) than its analogue containing a slightly different ligand forming five-membered chelate rings (IC₅₀ > 30 μ M).²¹¹

4.4. Effect of a monodentate ligand

Sheldrick et al. reported $[Ir(\eta^5-Cp^*)(dppz)(py)](CF_3SO_3)_2$ (100)²⁰⁷ as being less cytotoxic in MCF-7 and HT-29 cells than its chlorido analogue 5 (Fig. 26).22 This concept was revisited by Sadler and co-workers, and the significantly effective chlorido complex 47158 was a stepping stone for this cutting-edge research. 44 The derived ionic complex 101 (Fig. 27), involving monodentate pyridine instead of the chlorido ligand, aquates slowly yet is more active towards a wide range of cancer cells (e.g., $IC_{50} = 0.1 \mu M$ in A2780 cells) compared with initial hydro-

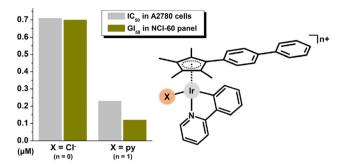


Fig. 35 A comparison of the *in vitro* antiproliferative activity of $[lr(\eta^5 Cp^{bph})(ppy)(X)]^{n+}$ complexes containing different monodentate ligands (X = Cl and n = 0 for 47; X = py and n = 1 for 101).

lytically unstable electroneutral chlorido complex 47 (Fig. 35). The mechanistic aspects of this highly promising complex (101) were investigated in detail relating them to redox balance in the cell.

A subsequent study showed that the introduction of an electron-donating group (e.g., NMe₂) on the monodentate pyridine ring of similar Ir-Cp^{ph} compounds generally increased the antiproliferative activity while electron-withdrawing groups decreased it, with 102 (Fig. 27) being the most effective in the series (with $IC_{50} = 0.2 \mu M$ in MCF-7 cells, ca. 36 times more active than cisplatin). 162 For these complexes (101, 102), a benefit of replacing the chlorido ligand with a monodentate pyridine or its derivatives was unambiguously proved by the advanced NCI-60 screening. 44,162 A similar observation was reported for mono- and trinuclear Ir-Cp* complexes with N-alkyl substituted 2-methyliminophenol. 152,153

Another structural modification involves the formation of a tethered ring, as shown above for structurally strained complex 103 (Fig. 27). 103 includes the cyclopentadienyl ligand with a tethered pyridine (Cp^{mpy}) that binds to the metal centre, resulting in a unique double chelated Ir-Cpx structure. 103 and its analogues were highly potent towards all human cancer cell lines tested, with IC₅₀ values in the sub-micromolar range. With the aim of thoroughly exploring the SAR, tethered complexes were investigated along with their non-tethered analogues, e.g., with terminal monodentate pyridine for comparison. It was proved that the tethered complexes exhibited higher activity (nM range; Fig. 36) and selectivity. 165

Regarding thiomaltol- and thiopyridone-based complexes (e.g., 105 in Fig. 28) with the chlorido ligand replaced by N-donor 1-methyl-1*H*-imidazole, ^{193,195} or complexes bearing pta as the monodentate P-donor ligand (e.g., 106; Fig. 28), 45,191 the effect of such chemical modification was negligible or less positive than for pyridine-modified complexes.

Less work has been dedicated to different halogenido (bromido, iodido) complexes than the widely studied chlorido ones. 43,46,110,248 In this case it seems that the resulting antiproliferative activity is more dependent on the cell type than on the type of halogenido ligand used. In particular, the azopyridine-based iodido complex was more effective against A549

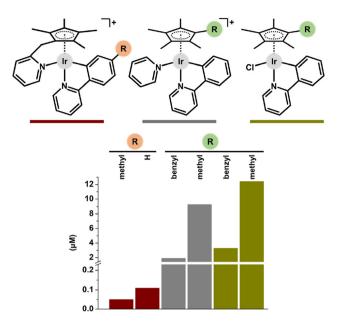


Fig. 36 A comparison of the antiproliferative activity of tethered complexes (red) and their non-tethered pyridine (grey) and chlorido (dark yellow) analogues (studied in MCF-7 cells).

cells (IC₅₀ = 1.0 μ M) than the chlorido analogue (IC₅₀ = 1.5 µM), while the opposite situation was observed in the A2780 cell line ($IC_{50} = 0.25$ (for iodido) vs. 0.12 (for chlorido) μM). 248 Other works reported similarly equivocal results with a more cytotoxic iodido complex in H460 cells, 46 and the iodido complex was outperformed by the chlorido analogue in A2780 cells.43

The Ir-Cp^{bph} hydrogensulfido complex 108 (Fig. 28) was comparably potent (IC₅₀ = $0.6 \mu M$) to its chlorido analogue in A2780 cells, where 108 exceeded the antiproliferative activity of its Cp^* analogue ($IC_{50} = 48.4 \mu M$) and cisplatin ($IC_{50} =$ 1.2 μM). 249 In contrast to inactive Ir-Cp* chlorido complexes (with phen or bpy), their hydrogensulfido analogues were moderately effective in A2780 cells. The last type of monodentate ligand, which was used as a replacement of the chlorido ligand in Ir-Cpx complexes, is represented by a bioactive carboxylato ligand (valproato, 4-phenylbutyrato) discussed in section 6.2.43,250

4.5. Nuclearity

Some research teams have developed multinuclear complexes, which, in addition to mononuclear complexes, offer new chemotypes in the field of anticancer Ir cyclopentadienyl complexes. Multinuclear Ir-Cpx complexes were either derived from their mononuclear analogues (e.g., 83; Fig. 19)^{207,208} or they were prepared with similar ligands of different denticities, which allowed the coordination of a different number of metal centres (e.g., 89; Fig. 21). Both synthetic strategies enable a comparison of the effect of the number of metal centres on the resulting anticancer activity.212 For example, a series of dinuclear Ir complexes, $[Ir_2(\eta^5-Cp^*)_2(\mu-L)(pp)_2](CF_3SO_3)_4$ (e.g., 83; Fig. 19), with a chelating polypyridyl ligand (pp; e.g., dppz)

and various bridging ligands (L), showed a greater ability to enter the cancer cells, consequently resulting in higher antiproliferative activity in MCF-7 and HT-29 cells, 207,208 compared to their formerly studied mononuclear chlorido analogue 5.22

Some multinuclear complexes exhibited higher antiproliferative activity than their mononuclear analogues, 121,152,153,207,212,213,215,227 but other multinuclear Ir compounds were less effective in comparison with mononuclear complexes. 121,207,212-216 Obviously, it is difficult to compare complexes with different nuclearity, because not only the number of central atoms, but also the size and charge of the complex are different for mononuclear and multinuclear analogues.

An interesting comparison of the antiproliferative activity of mono- and multinuclear Ir complexes is obtained by calculating the activity per Ir atom. In this case, the strategy of using a higher number of expensive central atoms appears to be even more inefficient, since the multinuclear complexes in most cases had significantly lower activity per Ir atom than complexes with lower nuclearity (Fig. 37). In total, these results reported in the literature for Ir multinuclear complexes have not demonstrated their development as a suitable strategy.

Very recently, dinuclear complex 88 (Fig. 20), which exhibited low-micromolar antiproliferative activity in various human cancer cells, outperformed its inactive mononuclear analogue and also showed some important advantages within the MoA studies, as discussed in sections 5 and 6.227 In contrast to the above-discussed results, this work clearly demonstrated that the development of multinuclear Ir-Cpx complexes was a viable strategy and a suitable research direction.

4.6. Effect of a counter-anion

The effect of a counter-anion of ionic complexes is usually overlooked. However, in the case of positively charged Ir-Cp^x complex cations, anions should not be understood as innocent in terms of their effect on the resulting biological activity, as demonstrated in some papers dedicated to this topic.

The moderate antiproliferative activity of $[Ir(\eta^5-Cp^*)Cl]$ (impy)]PF₆ (e.g., IC₅₀ = 13.9 μ M in HeLa cells) and [Ir(η^5 -Cp*)Cl (qupy)]PF₆ (e.g., IC₅₀ = 6.7 μ M in HeLa cells) complexes was improved using a different counter-anion (Fig. 38); impy = 2,6diisopropyl-N-(pyridin-2-ylmethylene)aniline, qupy = 2,6-diisopropyl-N-(quinolin-2-ylmethylene)aniline. 98,101 In particular, the $[Ir(\eta^5-Cp^*)Cl(impy)]OTs$ $(IC_{50} = 6.9 \mu M)$ and $[Ir(\eta^5-Cp^*)Cl$ (qupy)]OTs (IC₅₀ = 3.4 μ M) complexes were more effective¹⁰¹ than the PF₆⁻ salts, ⁹⁸ although the tosylate counter-anion used (OTs) was inactive itself.

The cation of the $[Ir(\eta^5-Cp^{bph})Cl(phen)]PF_6$ (14; Fig. 5)⁴¹ complex was used to investigate the effect of seven different counter-ions on the antiproliferative activity (studied in A549 cells).260 Compounds involving smaller counter-anions (Cl-, PF₆⁻, BF₄⁻, SbF₆⁻, CF₃SO₃⁻) exhibited higher antiproliferative activity than their analogues with bulkier anions (BPh₄-, B(3,5-(CF₃)₂Ph)₄). These differences in antiproliferative activity were related to processes associated with the resulting biological effect (e.g., hydrolysis rate, NADH oxidation, cell cycle modification or apoptosis induction), which appeared to follow the same trend as cancer cell cytotoxicity.

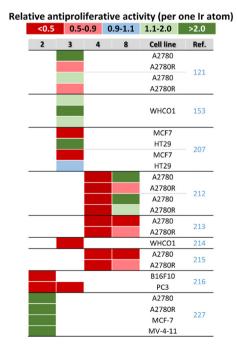


Fig. 37 A comparison of the antiproliferative activity of multinuclear Ir complexes (n = 3, 4 or 8) and their mononuclear analogues: n stands for the number of Ir atoms. Relative activity (RA) = [IC₅₀(mononuclear complex)]/[IC₅₀(Ir multinuclear complex) $\times n$].

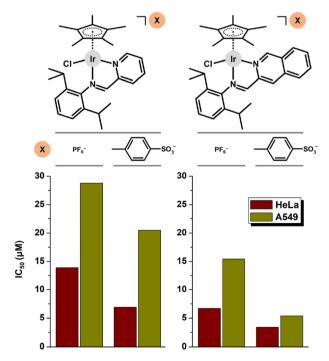


Fig. 38 A comparison of the antiproliferative activity of Ir complexes with different counter-anions.

The same complex cation was used once again for the preparation of micellar systems.²⁶¹ In this work, the $[Ir(\eta^5 - \eta^5 + \eta^5$ Cp^{bph})Cl(phen)]Cl complex was used and studied in two ovarian cancer cell lines (OVCAR-3, SKOV-3 cells).261 The obtained results are different for 14 (PF_6 salt; $IC_{50} = 0.7 \mu M$, RA = 1.7 in A2780 cells) and $[Ir(\eta^5-Cp^{bph})Cl(phen)]Cl(Cl^- salt;$ $IC_{50} = 4.1 \mu M$, RA = 3.7 in OVCAR-3 cells; $IC_{50} = 16.1 \mu M$, RA = 2.3 in SKOV-3 cells). However, these results should not be accepted as evidence of the effect of the anion on the resulting activity because the results were obtained in different ovarian cancer cell lines under different experimental conditions (e.g., exposure time).

Only slightly higher antiproliferative activity was reported for the PF₆ salts of 16-electron complex cations bearing various amine-imine ligands, compared with the co-studied chloride salts.²⁵⁶ No effect was observed for inactive triazolylbased complexes prepared as chloride and tetrafluoridoborate salts. 140

5. Mechanisms of action

In general, anticancer non-platinum complexes represent chemotypes different from those of conventional platinum-based anticancer drugs; this is related to various biological and biochemical differences. Most importantly, anticancer non-platinum complexes (including Ir ones) have a different mechanism of action (MoA), which means that they target different intracellular targets and induce different processes in treated cancer cells, compared to conventional Pt-based drugs.9,16-18 Some papers have been devoted solely to in-depth studies of MoAs, providing a comprehensive overview of the biological effect of these compounds and the mechanism through which cell death is induced. 76,77,262,263 Generally, Ir cyclopentadienyl complexes have a different cytotoxic profile than Pt-based drugs. They primarily target different intracellular targets than DNA (e.g., mitochondria or lysosomes) and induce the generation of ROS and apoptosis in the treated cancer cells. Most papers pay attention to these processes in order to shed light on the MoA of newly developed complexes.

5.1. Hydrolysis and activation

The stability of the newly prepared bioactive compounds is a key parameter for them reaching the target cancer cells in their intact or pharmacokinetically acceptable forms. Similarly to cisplatin, which is hydrolysed from the cis-[PtCl₂(NH₃)₂] prodrug to the cis-[Pt(H2O)(OH)(NH3)2] active form in the cell,²⁶⁴ hydrolysis of Ir-Cp^x complexes involves cleavage of the Ir-Cl bond and formation of the Ir-OH2 species (or Ir-OH depending on pK_a)²⁶⁵ under aqueous conditions. Such Ir-Cl bond hydrolysis was hypothesized as a necessary step (activation) involved in the MoA of anticancer Ir-Cp^x complexes. 41 The studied complexes, $[Ir(\eta^5-Cp^x)Cl(L)]PF_6$ $(Cp^x = Cp^*, Cp^{ph})$ or Cp^{bph}; L = en, bpy, phen, pico), underwent rapid hydrolysis under the aqueous conditions used (1H NMR studies). The hydrolysis rate decreased, while the hydrolysis extent increased with the size of the Cpx ligand used. The equilibrium of the chlorido and aqua species was reversed by the addition of various concentrations of NaCl. In addition to Cpx ring extension, the extent and rate of hydrolysis can also be modified by the type of chelating ligand, 41 its substitution 204 or by the type of monodentate ligand. 43 The process of hydrolytic aquation was also investigated by DFT. 173,174,266

The observed hydrolysis was also discussed as an activation step for interactions with model nucleobases. It was proved that Ir-Cp^x complexes were readily coordinated by nucleobases when they were hydrolysed under aqueous conditions (i.e., in the absence of chloride ions), 41,44 but no interaction was observed for similar complexes in the presence of chloride ions (e.g., with PBS). 111 Nowadays, hydrolytic activation is not considered a necessary activation step for Ir-Cpx complexes, including chlorido complexes, as the most frequently studied ones. This was proved for the hydrolytically stable [Ir(η⁵-Cp^{ph}) (azpy)Cl]PF₆ (116; Fig. 39) complex, which outperformed its readily hydrolysable analogues (14, 15 and 47) in terms of antiproliferative activity in the NCI-60 panel.262 Similarly, other hydrolytically stable chlorido complexes also exhibited antiproliferative activity. 99,197

Besides the chlorido complexes, analogues with different types of monodentate ligand are more stable, as reported for iodido²⁴⁸ and pyridine complexes, ^{44,162} including the pyridine tethered ones,138 but such compounds are still effective in various cancer cells. Complexes with monodentate pyridine are able to partially replace this pyridine with chlorides in the presence of physiological concentrations of Cl ions. 44,163 Hydrolytically stable complexes can also covalently interact with various biomolecules, such as GSH, 248 EtG 99,138,162,164 or N,N-ligands, 165 even without hydrolytic activation. On the other hand, different reactivity of the chlorido (no reactivity) and aqua (reactive) complexes towards GSH was reported.⁹⁸ Also, complexes with monodentate N-donor ligands were shown to undergo the pH-dependent release of this ligand, leading to the activated Ir-aqua species. 138,193 Complex 71 (Fig. 15) was stable at biologically relevant pH values, as studied by HPLC at pH 5.8-7.9. 194

Although the complexes described in this review were tested for their in vitro antiproliferative activity, and thus, dissolved in testing medium, stability studies in these media (such as DMEM) were rather exceptional. 57,107,109 For example, dichlorido complex 11 (Fig. 4) was stable in DMSO-d₆/D₂O mix-

Fig. 39 The structural formula of complex 116.

tures of solvents, as well as in the mixture of DMSO with DMEM.⁵⁷ Its analogue (12) bearing different monodentate P-donor ligands (Fig. 4) was hydrolysed in the presence of water, but the diagua species formed reacted with various concentrations of chlorides, implying that dichlorido complexes were most likely intact when accumulated in cells.⁵⁹

Methodologically, ¹H NMR or UV-Vis spectroscopy ⁴¹ are the most commonly chosen techniques; HPLC is used less frequently, 194-196,211 usually with similar results. In most cases, hydrolytic stability is investigated by ¹H NMR in mixtures of D₂O and some organic solvent (e.g., MeOD-d₄, DMSO d_6 or DMF- d_7) ensuring the solubility of Ir complexes, as their solubility in water is usually insufficient for ¹H NMR experiments. In some cases, DMSO was considered unsuitable for chemical and biological studies of novel Ir-Cpx complexes because the complexes were unstable in this solvent due to its high coordination ability. 116,153,163,179,186 Both isomeric species with S- and O-coordinated DMSO were detected by 1H NMR. 176 On the other hand, unsaturated 16-electron Ir complexes (e.g., 114; Fig. 29) were stable in DMSO and its mixture with water, 254-257 although some evidence for the formation of 18-electron Ir-aqua species has also been reported. 112 Besides DMSO, instability in DCM and methanol was reported for Ir-Cp* complexes involving some ispinesib-derived ligands. 107,109

Special in-solution behaviour was reported for tethered complex 103 and its analogues, which involved a pyridine-substituted Cpx ring (Cpmpy) allowing double chelation of the Ir metal centre. It was observed that DMSO readily coordinated to Ir, which was associated with the tethered ring opening (not observed for DMF). 165 Intriguingly, the Ir-dmso adducts formed reformed the tether ring upon dissolution in water. Similar Ir-Cp^{mpy} complexes interacted covalently with DMSO and methanol, but remained intact in water. 138 Activation of these complexes, which involve the release of pyridine of the Cp^{mpy} ligand from Ir, was also observed at acidic pH (chlorido species formed) and in the presence of EtG (covalent adduct formed) or sodium formate (hydrido species formed).

The rapid formation of Ir-dmso adducts was also reported for 55 and 56 (Fig. 12), 177,178 and others. 174 The representative Ir-dmso adduct of 55 did not undergo the exchange reaction in the presence of methanol and water, suggesting that the dmso adduct was the active entity in biological experiments.

Regarding the mixture of solvents used, hydrolysis was observed to be dependent on the solvent composition.80,211 For example, the [Ir(η⁵-Cp^{bph})(bpy¹)Cl]PF₆ complex was hydrolysed in 10% MeOH (UV-Vis) but was stable in 50% MeOH (UV-Vis, ¹H NMR). ⁸⁰ The addition of NaCl or PBS often mimics the physiological concentration of chloride ions, in either extra- or intracellular environments. 41,59 This often leads to the suppression of hydrolysis observed in the absence of chloride ions. In contrast, the presence of chlorido ions can induce ligand exchange in complexes with a monodentate ligand other than chlorido, as observed for a hydrolytically stable iodido complex that was converted into the chlorido form in the presence of PBS. 110 Also of importance, hydrolysis was proved to be influenced by the counter-anion, with longer halflives of hydrolysis observed for bulkier counter-anions (e.g., BPh₄) than for smaller ones, including the most commonly used one, PF₆-.²⁶⁰

Importantly, hydrolysis of the Ir-Cl bond of anticancer Ir-Cpx complexes should not be understood as a general feature of these compounds, because some works reported the Ir-Cp^x chlorido complexes to be stable under aqueous conditions even in the absence of chloride ions. 121,124,166,172,202,215

In the context of the activation of stable Ir-Cp^x complexes, the possibility of redox activation has to be mentioned as well. This concept was first reported for $[Ir(\eta^5-Cp^*)Cl(dppz)]PF_6$ (i.e., the PF₆⁻ analogue of 5), ²² which released its chlorido ligand through the metal-ligand two-electron dissociative reduction in DMF (i.e., in the absence of water). 267 Another type of redox activation was reported for hydrolytically stable iodido complexes that were redox activated by the reaction of GSH with the azo bond of their azopyridine ligands.²⁴⁸ Such activation resulted in the replacement of the iodido ligand with GS-, which was associated with the GSH-to-GSSG oxidation and the formation of ROS.

5.2. Cellular take up, lipophilicity and intracellular localization

Cellular take up of anticancer Ir-Cp^x metallodrugs is a crucial step for them to be effective. Several factors, such as size and charge (polarity), lipophilicity or targeting transport proteins, influence if and how a compound is taken up by cancer cells. Understanding if and how a new metallodrug is accumulated in cells is important for its development. Cellular take up (or cellular accumulation) studies are therefore very important and frequently performed. The most common techniques for these studies are ICP-MS (or its alternatives, ICP-OES or AAS) fluorescence microscopy; OES = optical emission spectroscopy.

The first reported anticancer Ir-Cpx complexes 5 and 6 (Figs. 1 and 2)²² were studied for their accumulation in HT-29 cells.20 In this case, more effective complex 6 was taken up more by the cells (149.6 ng Ir per mg protein) than less potent 5 (70.4 ng Ir per mg protein). For the $[Ir(\eta^5-Cp^x)Cl(phen)]PF_6$ $(Cp^x = Cp^*, Cp^{ph} \text{ or } Cp^{bph}) \text{ complexes, } log P (-0.82, 0.48 \text{ and }$ 1.11) and cellular accumulation (3.9, 23.5 and 88.8 ng Ir per 10⁶ cells) increased with the Cp^x ring size, which correlated with the antiproliferative activity in A2780 cells (section 4.2).41 In addition to the aforementioned extension of the Cp^x ring, lipophilicity can also be enhanced by changing the charge of the compounds, as reported for a pair of hydrophilic ionic [Ir $(\eta^5-\text{Cp*})\text{Cl(phen)}$ PF₆ (log P=-0.95) and lipophilic electroneutral $[Ir(\eta^5-Cp^*)Cl(ppy)]$ (43; log P = 1.57) complexes. ¹⁵⁴ Electroneutral chlorido complex 47 was markedly less taken up in A2780 cancer cells than its ionic pyridine analogue 101 (Fig. 27).44 The same effect of lipophilicity on the resulting antiproliferative activity was reported for complexes with various pic-based ligands, for which the most cytotoxic complex 38 was more lipophilic (log P = 1.05) than less effective 37 ($\log P = -0.15$) and even an inactive analogue

bearing the hydrophilic carboxy group on the pic ligand (log P=-2.73). 147

Conjugation of the Ir-Cp^x complex to a tumour-targeting cyclic nona-peptide c(CRWYDENAC) (117; Fig. 40) was reported, but the resulting antiproliferative activity was not studied. 268 Also for this targeting Ir complex and some others, HPLC analysis of relative hydrophobicity has been used to determine lipophilicity, in addition to the most commonly used $\log P$ determination. 155,194,268

The inactive $[Ir(n^5-Cp^*)Cl(phen)]PF_6$ complex and its highly active analogue, [Ir(n⁵-Cp*)(bq)Cl] (118; Fig. 40), were studied in more detail in terms of their mechanism of cellular accumulation; Hbq = 7,8-benzoquinoline.⁷⁶ The electroneutral complex 118 is more lipophilic, leading to higher cellular take up and higher in-cell DNA metalation. 118 entered the cancer cells by both energy-independent (passive diffusion) and -dependent transport processes, such as copper influx transporter CTR1. Endocytosis was not evidenced for 118. Importantly, 118 was identified as a substrate of p-glycoprotein and multidrug resistance-associated protein 1 (MRP1) efflux pumps; this is different from cisplatin, which is not recognized by p-glycoprotein and MRP1. Similar results were obtained for complex 22.88

Typically, electroneutral complexes are more lipophilic than their ionic analogues. 41,101,154 In some specific cases, rational modification of the lipophilic electroneutral complexes can lead to an increase in lipophilicity, despite the ionic character of the newly formed complex. This situation was reported for the chlorido complex 43 ($\log P = 1.57$), ¹⁵⁴ which was modified by the monodentate-coordinated pyridyl-BODIPY ligand in the structure of the highly lipophilic complex 104 (log P = 4.19), which could be attributed to the highly lipophilic pyridyl-BODIPY ligand. 163

Within the series of highly potent Ru(II), Rh(III) and Ir(III) complexes, the Ir complex 48 was the most active in T47D cells, but its take up by cells was comparable to that of its Ru analogue, suggesting that the relationship between activity and cellular accumulation is not straightforward for these compounds. 166

c(CRWYDENAC)

Fig. 40 Structural formulas of complexes 117 and 118.

The first investigation into the intracellular organelle distribution was performed for the $[Ir(\eta^5-Cp^x)Cl(phen)]PF_6$ complexes (Cp^x = Cp*, Cp^{ph} or Cp^{bph} (14)). In A2780 cells, the results of ICP-MS intracellular distribution studies showed that the highest amount of Ir (>50%) accumulated in membranes, followed by cytosol/cytoskeleton and <10% of Ir was detected in the nucleus for all three Ir compounds. For electroneutral complexes involving various ppy derivatives (e.g., 44; Fig. 10), the highest Ir level was detected (ICP-MS) in cytosol, followed by membranes, the nucleus and cytoskeleton. 155 Similar dominant localization in cytosol was reported for tetranuclear Ir metallarectangles involving fluorescent BODIPYligands²⁶⁹ based bridging and compounds^{93–95,163,173,186,244} Other complexes accumulated dominantly in mitochondria, ^{63,245,270,271} the nucleus, ^{57,100} the perinuclear region²⁷² or lysosomes (section 5.7).^{82,85} A specific intracellular distribution was reported for BODIPY-bearing complex 56 (Fig. 12), which was detected in mitochondria and the endoplasmic reticulum (ER), from which the complex could be distributed to other organelles (e.g., lysosomes) by lipid droplets. 178 A non-specific (pancellular) Ir distribution was also discussed for Ir cyclopentadienyl complexes. 179

Besides the aforementioned BODIPY, 163,192,271-274 other intrinsically fluorescent moieties (e.g., rhodamine B in 119; Fig. 41)⁸⁵ or the luminescence of Ir complexes¹⁷⁰ were used in numerous studies on the intracellular localization of anticancer Ir-Cp^x complexes. For example, Gupta and co-workers used a BODIPY-containing N,O-donor ligand for live cell imaging, which demonstrated targeted accumulation in the mitochondria.²⁷¹ For 56, the presence of BODIPY allowed its fate in the cell to be tracked: it quickly permeates the plasma membrane and accumulates in the mitochondria and endoplasmic reticulum (see below). 178

A unique study of the localization of the Ir-Cp^x complex was carried out by a combination of cryo-soft X-ray tomography (cryo-SXT) and hard X-ray fluorescence tomography (cryo-XRF) in fully hydrated cancer cells at nanometric resolution. 164 This method overcomes the shortcomings of the aforementioned techniques, where ICP-MS (or AAS) has the disadvantage of

Fig. 41 Structural formulas of complexes 119 and 120

mechanical manipulation of the cells, while microscopic techniques require the presence of a fluorophore in the tracked compound. In this case, 120 (analogue of 103 with ppy instead of ppv¹; Fig. 41) was exclusively localized in mitochondria, as demonstrated by 3D cryo X-ray imaging.

5.3. Cell death type

The application of new compounds to cancer cells may lead to their death in the case of successful accumulation and sufficient anticancer activity. In general, cells can die through different types of cell death, but not all are equally beneficial. The most common cell death types are apoptosis (programmed cell death), necrosis (uncontrolled cell death), autophagy (self-eating) or less common cell death pathways (e.g., ferroptosis, oncosis, paraptosis or pyroptosis).

5.3.1. Apoptosis. In 2010, complex 35 (Fig. 9) was, besides its interaction with DNA, studied for its ability to activate the known pro-apoptotic enzymes caspase-3/7.145 In comparison with the reference apoptosis inducers (staurosporin, cisplatin) used, 35 did not induce apoptosis in the treated cancer cells, implying that the cell death mechanism was most likely different (i.e., non-apoptotic) but remained unidentified. Still, it was concluded that 35 had a different MoA than the conventional Pt-based drug cisplatin.

In 2012, various intracellular processes (induction of ROS formation, induction of apoptosis or cell respiration) associated with the MoA of the Ir-Cpx compounds were investigated, laying the basis for future studies of their MoAs. 208 In particular, both dinuclear dppz-based complexes [Ir₂(μ-L)(η⁵- $Cp^*)_2(dppz)_2[(CF_3SO_3)_4$ (L = 4,4'-ethyne-1,2-diyldipyridine or 4,4'-(benzene-1,4-diyldiethyne-2,1-diyl)dipyridine for 83 in Fig. 19) induced lower cell impedance and a respiration rate decrease connected with acidification alternation of adherent MCF-7 cells. More importantly, this work provided the first detection of apoptosis induced by anticancer Ir-Cp^x complexes in non-adhesive Jurkat leukaemia cells. Flow cytometry of annexin V/propidium iodide (PrI)-stained cells was used and remains one of the most commonly used techniques to study apoptosis with novel anticancer Ir-Cp^x complexes.

Complex 14 (Fig. 5) was studied in great detail for its MoA.⁷⁷ Flow cytometry experiments showed faster induction of apoptosis for 14 than for cisplatin. At longer exposure times, populations of late apoptotic/necrotic cells were detected for both compounds. The induced apoptosis was associated with DNA fragmentation (as proved by an ELISA colorimetric experiment and agarose gel electrophoresis) and mitochondria disruption (tetramethylrhodamine ethyl ester (TMRE) staining). Interestingly, the latter phenomenon was not observed for cisplatin.

To prove that apoptosis induced by anticancer Ir-Cp^x compounds is connected to a redox-mediated MoA and the formation of ROS in the treated cells, various ROS scavengers, such as N-acetyl-L-cysteine (NAC), are applied in non-toxic concentrations to cancer cells together with the Ir complex. For example, 49 (Fig. 10) induced early apoptosis in a higher K562 cell population than in an analogous experiment with coapplied NAC. 169

Apoptosis was also studied by fluorescence microscopy¹¹⁷ or TEM²⁶² through the induction of cancer cell morphology changes (membrane blebbing, chromatin condensation, nucleus pyknosis, DNA fragmentation). Microscopy imaging (high content screening, HCS) was also used for studies on caspase 3 positive apoptotic cancer cells.²⁶³ Western-blot experiments (e.g., anti-apoptotic factor Bcl-2, pro-apoptotic factor Bax or caspases) are often used to provide evidence of apoptosis and its type. 63,169,233,241

When apoptosis is identified as an induced type of cell death, supporting experiments are usually performed to demonstrate that apoptosis-related processes, such as DNA fragmentation, cell cycle modification or expression of caspases, are occurring in the treated cells. 54,59,61,77,119,148,177 Cell senescence was detected together with apoptosis in A2780 cells treated with ppy-based Ir complexes with different Cpx derivatives.259

5.3.2. Necrosis. Since apoptosis is usually studied by flow cytometry with dual staining of cancer cells with annexin V/ PrI, necrotic cells can be detected together with normal (live) and apoptotic (early and late) cells. However, although there are quite a few such studies, only a limited number of Ir-Cp^x complexes (e.g., 121 in Fig. 42) induced a higher proportion of necrotic cells. 180,188 Other complexes (e.g., 53; Fig. 11) did not induce necrosis, as sometimes proved by experiments with specific necrosis inhibitors (e.g., necrostatin-1).96,175,202

5.3.3. Ferroptosis. The phototoxic complex 27 (Fig. 7) was studied for its ability to induce ferroptosis in 4T1 cells, where several ferroptosis-related hallmarks were examined.96 The GSH concentration in solution and in cancer cells decreased in the presence of 27 and laser irradiation, as a result of GSH oxidation to GSSG. Since GSH is important for the subsequent inhibition of glutathione peroxidase 4 (GPX4)-mediated lipid peroxidation (LPO) degradation, GPX4 expression in cancer cells was also studied and proved to be significantly reduced in the presence of 27 and laser irradiation. Similarly, higher intracellular LPO levels were detected by confocal microscopy and markedly reduced by the specific ferroptosis inhibitor ferrostatin-1 (Fer-1). In association with the detection of ferroptosis, other cell death pathways were also examined utilizing

Fig. 42 The structural formula of complex 121.

their specific inhibitors (necrostatin-1, 3-methyladenine), but neither necrosis nor autophagy were induced by 27 in cancer cells. On the other hand, the cancer cell viability was markedly increased when the apoptosis inhibitor z-VAD-FMK was used, proving that 27 triggered cell death through the combined effects of apoptosis and ferroptosis.

5.3.4. Autophagy. Complex **8** was studied in 8505C cells, where, in addition to evidence of apoptosis and necrosis (flow cytometry, Annexin/PrI staining), autophagic vesicles were detected by flow cytometry. The ongoing process of autophagy was demonstrated by an experiment with the specific autophagy inhibitor 3-methyladenine, the application of which led to an increase in the viability of 8505C cells. Similar results were reported for analogical complex **9** (Fig. 4). Nevertheless, in both cases, apoptosis was identified as the main cell death mechanism, whereas autophagy was only noted as an irrelevant process in connection with the MoAs of **8** and **9**. Samilar conclusion that apoptosis predominates over autophagy has been reached for other Ir complexes.

Although complex **79** (Fig. 17) induced apoptosis and various associated processes (*e.g.*, mitochondria disruption, ROS production or caspase-3 activity), it also induced autophagy in A549 cells.²⁰² This was proved by co-treatment with the autophagy inhibitor 3-methyladenine, causing a significant decrease in the cytotoxicity of **79**. In contrast, inhibitors of necroptosis, protein synthesis or proteases did not show the same effect.

5.4. DNA as a target

The pioneering works considered, analogically to Pt-based drugs, DNA as an intracellular target molecule for Ir–Cp^x anticancer complexes. $^{22,34-36,79,207,208,234,275}$ Obviously, it was proved for $[Ir(\eta^5-Cp^*)(dppz)(L)]^{n+}$ complexes, involving an amino acid or simple peptide (L), that these agents effectively intercalated ctDNA and the strength of such interactions increased with the charge of the complex cation (n). Importantly, Ir-dppz complexes also cleaved supercoiled plasmid DNA (after a short irradiation time). Covalent adducts of the studied Ir–Cp^x complexes and model nucleobases (*e.g.*, EtG or adenosine monophosphate) were successfully prepared and characterized by NMR or crystallographically (Fig. 43). 34,35

Later it was proved that the type of DNA interaction of [Ir $(\eta^5\text{-Cp*})(\text{dppz})(L)]^{n+}$ complexes (e.g., 5) was driven by L (covalent for L = Cl, intercalative for L = tu and tmtu) and its size (stronger interaction of the complex containing bulkier

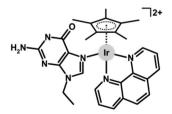


Fig. 43 The structural formula of the adduct of $[Ir(\eta^5-Cp^*)(EtG)(phen)]^{2+}$ with 9-ethylguanine (EtG).

tmtu than for its analogue with unsubstituted tu); tu = thiourea.³⁶ It was proved that the size of the bridging ligand was decisive for the type of DNA interaction for dinuclear complexes.^{207,208,275} For example, the dinuclear complex bridged by pyrazine mono-intercalated DNA, while its analogue with 4,4'-bipyridine induced double-intercalation.²⁰⁷ Similar dinuclear complexes showed nuclease activity towards DNA either in the dark (shorter linkers) or photoinduced (longer ones).²⁰⁸

Another early reported complex 35 (Fig. 9) was also studied for its interaction with DNA. ¹⁴⁵ However, 35 (as well as its Rh analogue) interacted with DNA (altered recognition of the drug-modified DNA by BamHI restriction nuclease), most likely non-covalently (*i.e.*, differently than cisplatin), since the thermodynamic stability of the DNA used was not changed by 35 (circular dichroism experiments).

The $[Ir(\eta^5-Cp^x)Cl(phen)]PF_6$ $(Cp^x = Cp^*, Cp^{ph} \text{ or } Cp^{bph}$ (14)) complexes bound effectively to the DNA of A2780 cells, to an even higher extent (5.5-7.7%) than the DNA-targeting anticancer metallodrug cisplatin (ca. 1%).41 A binding mechanism is most likely combinative for the formation of guanine-N7 covalent adducts (DFT, EtG interaction studies) and intercalation (quenching of the EtBr-DNA fluorescence). The ability to interact with DNA (Cp^{bph} > Cp^{ph} > Cp*) correlated with the antiproliferative activity and cellular take up results (see above). Interestingly, although these complexes derived from an N,N-donor ligand (phen) interacted exclusively with EtG (a model molecule for studying interactions with DNA), their analogues with N,O-41 and C,N-donor 154,155 ligands were also coordinated by 9-methyladenine. EtG was also used in other studies as a model nucleobase for DNA interaction studies. 168 In some works, guanosine monophosphate (GMP) was used for the same purpose.88,111,121,176,214 Other complexes interacted with unsubstituted guanine and adenosine 3'-phosphate 5'-phosphosulfate salt.93

Notably, 14 was, together with 15, 47 and 116, studied in detail for its MoA and it was proved that DNA was one of several targets for these compounds. Specifically, COMPARE analysis (quantitative comparison with >40 000 conventional drugs) provided positive correlations with drugs that were DNA interactors, DNA antimetabolites, topoisomerase inhibitors, protein synthesis inhibitors, mitosis inhibitors and redox mediators, according their MoAs. Especially the identification of a possible link between the MoA of Ir-Cp* complexes and cellular redox homeostasis was essential for further studies in this field (section 5.5). The same research group reported a similar MoA of electroneutral chlorido complex 47 to that of its ionic analogue 101 (Fig. 27), involving the monodentate pyridine ligand (based on the NCI-60 screening and COMPARE analysis).

Reverse phase protein microarrays (RPPA) were used for the detailed description of the MoA of **116**. ²⁶³ As a response to the induced DNA damage, the levels of various proteins (or phosphorylated variants labelled with asterisks) increased (*e.g.*, CHK2*, CDC25A and p53*). Levels of other proteins (*e.g.*, tubulin, CDK1, Rb*) correlated with the results of cell cycle

analysis. Furthermore, the levels of some apoptotic proteins were also determined. Specifically, high levels of inhibitors of apoptosis proteins, survivin and XIAP were detected by RPPA, while the mitochondrial pro-survival protein BCL-X was downregulated. Similarly, BCL-2 and BAK initiator proteins, and PARP* (cleaved by caspase-3) were found to be up-regulated, as also reported elsewhere. 175,200,205

Interestingly, although DNA is nowadays not considered to be the main target for Ir-Cp^x complexes, their ability to reach the cancer cell nucleus and interact with nuclear DNA is surprisingly high, as reported for 14, which showed ca. 13-fold higher level of DNA metalation than cisplatin in A2780 cells.⁷⁷ In contrast, antiproliferative activity experiments performed in the Chinese hamster ovary (CHO-K1; NER-proficient wild-type) cell line and its mutant (MMC-2; NER deficient) indicated a lower degree of DNA damage than that with cisplatin.84

Besides the quenching of the EtBr-DNA fluorescence,41 similar competitive DNA binding experiments have also been performed with different dyes. For example, 45 (Fig. 10) effectively displaced the DNA minor-groove binder Hoechst 33258 from ctDNA, suggesting that 45 was capable of binding to the DNA minor groove. 156 A similar observation was reported for 48. 166 Exceptionally, no DNA interaction was observed for cytotoxic Ir complexes (e.g., 33; Fig. 8) in cell-free DNA experiments. 115 On the other hand, 33 induced DNA damage through the production of ROS, as proved by the detection of phosphorylated histone marker (yH2AX), as also reported for the heterometallic Ir-Re complex 97 (Fig. 24). 245

Heterometallic dppz-derived Ir-Pt complexes (e.g., 122 in Fig. 44) showed specific simultaneous covalent (Pt moiety) and intercalative (Ir-dppz moiety) DNA binding.^{234,235} In addition to the widely published covalent and non-covalent (i.e., intercalative) interactions of Ir-Cpx complexes with DNA, their ability to cleave DNA34,208 has also been described in some papers, 98,204 while some compounds did not show this biological effect.^{80,198,199}

5.5. Redox-mediated MoA

The redox-mediated MoA refers to how a substance (metallodrug) exerts its effect through disruption to cellular redox homeostasis. It is directly connected to the transfer of elec-

Fig. 44 The structural formula of complex 122

trons between such drugs and biomolecules and it plays a critical role in many cellular processes (antioxidant defense, signalling pathways, enzyme activity, gene expressions etc.). It is a fundamental concept in pharmacology and cell biology and its understanding is crucial for drug development. Various transition metal complexes, including Ir-Cp^x ones, act through the redox-mediated MoA.276 They disrupt cellular redox homeostasis either directly through metal or ligand redox centres or indirectly through binding to redox biomolecules. Given that redox-modulating reactions are often catalytic, 44,277 such redox-modulating compounds (including anticancer Ir-Cpx complexes) can be classified under the concept of catalytic metallodrugs.^{278,279} Either way, the primary process is the induction of ROS formation.

The first mention of a possible link between ROS and the anticancer activity of Ir-Cpx complexes was published for dinuclear dppz-based Ir complexes inducing apoptosis and other biochemical changes in Jurkat cells. 208 Later, COMPARE analysis revealed a correlation between the biological effects of 14, 15 and 116 and redox mediators, which led to further biochemical experiments (mitochondrial membrane polarization, TEM visualization of organelle structure) demonstrating the redox-mediated MoA of Ir-Cpx complexes.262 Also for 15, 47 and 116, a synergy with the redox modulator L-buthionine sulfoximine (L-BSO) was observed in A2780 cells. 262,276 L-BSO is an inhibitor of γ -glutamylcysteine synthetase involved in GSH synthesis, the application of which decreases GSH levels and increases the level of ROS in cells. Co-administration of the complexes with a non-toxic concentration of L-BSO led to >5fold improvement of potency in A2780 cells. This was later proved to be associated with an increase of cellular take up of similar complex 118 (Fig. 40), most likely as a result of inhibition of the MRP1/GS-X efflux pump, which eliminates the GS adducts of xenobiotics (e.g., Pt drugs or Ir-Cpx complexes in this study) from cancer cells.⁷⁶ Similarly, the pre-treatment of HeLa cells with L-BSO improved the cytotoxic potency of 53 (Fig. 11).175

Compound 14 was proved, in contrast to cisplatin, to induce mitochondrial membrane disruption (TMRE staining of cells). This disruption is directly connected to the production of ROS in treated cells.⁷⁷ Indeed, ROS production was proved by increased fluorescence in A2780 cells treated with 14 using 2',7'-dichlorodihydrofluorescein diacetate (DCFH-DA) dye (not observed for cisplatin). Similar results were also reported for other Ir complexes. 167,168 In connection with mitochondria disruption, it was also demonstrated by the release of various intra-mitochondrial compounds (cytochrome c) into the cytosol 169,232 or by changes to the oxygen consumption rate (OCR) or ATP synthesis. 115

A significant increase in the ROS level was detected by flow cytometry in A2780 cells treated with pyridine complex 101 (Fig. 27), and this increase was markedly higher than that with the chlorido analogue 47.44 Related to this detection of ROS in cells, model cell-free experiments with NADH demonstrated hydrogen peroxide production in the presence of 101 and oxygen (not observed when performed under an inert atmosphere or in the presence of catalase). High ROS levels were also detected in A2780 cells treated with similar complexes with monodentate-coordinated pyridine derivatives (e.g., 102; Fig. 27). 162 The dichlorido complexes (e.g., 11)57 were also reported to induce the production of high ROS populations. The presence of a second metal in heterometallic complexes did not lead either to higher ROS levels in the treated cells or to a higher extent of NADH oxidation.⁷⁸

The mentioned production of H₂O₂ by 101 (detected by peroxide test sticks)44 was also reported for 55 and its analogues (Fig. 12), for which peroxide production was clearly demonstrated by the Amplex Red® assay. 177 Interestingly, only some of the tested complexes induced detectable H2O2 formation, which the authors attributed to differences in hydride donor strength (hydricity) given by the type of electron donating/withdrawing substituent on the oxazoline-based ligands used. The same trend of H₂O₂ production was observed for these complexes in HeLa cells by advanced flow cytometry experiments with an H₂O₂-selective redox sensor.

Usually, a type of ROS/RNS is not specified, because nonselective ROS probes (e.g., DCFH-DA or H2DCFDA) are used.77,204 Only some reports discussed more specific flow cytometry 2D experiments indicating the production of superoxide radicals. 211,248 A special experiment was conducted by Salmain, Sobczak-Thépot and co-workers, who treated HeLa cells with a fluorescent protein-based H2O2-selective redox sensor for flow cytometry (discussed above in this section). 177,179

In some cases, only a slight increase in intracellular ROS levels was induced by anticancer Ir–Cpx complexes; 101,104,108,109,147,160,161,170,174,193,206,251,258 this was also reported to be comparable with cisplatin. 169 A decrease in ROS (or RNS) was even observed in cells treated with some anticancer complexes (e.g., 8 and 9),54,55 suggesting that the induction of RO(N)S formation should not be viewed as a simple Fenton-like reaction triggered by the presence of metal (Ir) ions. Similar ROS levels were detected in SW620 and HepG2 cells, differing in sensitivity toward Ir-Cp* complexes containing ispinesib-derived ligands. 107 It was also reported that ROS production in treated cancer cells did not disturb the mitochondrial membrane potential as it remained unchanged. 159,198

Sometimes the redox-mediated MoA and involvement of ROS are proved by experiments with ROS scavengers, such as NAC or tempol, which are usually co-applied at non-toxic concentrations to cells treated with anticancer Ir-Cp^x complexes. 100,169,175,200 Pre-treatment with NAC also indicated a link between ROS formation and lysosomal damage (section 5.7), and reduced the number of apoptotic cancer cells. 200 ROS production by the Ir complex (e.g., 119 in Fig. 41) also activated the NF-κB channel, which is related to ROS overproduction in cells.²⁵⁸ Specific scavengers (DMSO for 'OH, SOD for 'O₂ and NaN₃ for ¹O₂) were used for Ir dichlorido complexes (e.g., 11), which showed that the complexes induced the production of all three types of ROS in treated cancer cells.^{59,60}

ROS production in cells is often linked to NADH oxidation induced by Ir-Cp^x anticancer compounds. In most cases where both phenomena have been studied, a correlation has been observed because NADH oxidizing Ir-Cpx complexes also induced ROS production in treated cells. 44 Similarly, some complexes (e.g., 123 in Fig. 45) did not exhibit an oxidative effect towards NADH and did not induce ROS formation in cells. 85 Exceptionally, ROS were produced in cancer cells by complexes that did not interact with NADH. 105,106,159,231 Some recent works discuss the redox-mediated MoA in the context of the levels of specific proteins, the expression of which is regulated by oxidative stress defense pathways (section 5.8). 227,263

5.6. Cell cycle analysis

Although the cell cycle is directly related to cell division and DNA (section 5.4), it is discussed after section 5.5, which discusses ROS and the redox-mediated MoA, because ROS can also damage DNA and induce cell cycle changes. In general, cell cycle analysis is used to determine the distribution of cells in different cell cycle phases, namely G1 (gap 1; also reported as G0/G1), S (synthesis), G2 (gap 2) and M (mitosis), which are closely connected to the effects of new drugs (e.g., anticancer Ir compounds) on cell proliferation. It is most commonly performed using flow cytometry with a specific DNA staining dye (e.g., PrI).

Probably the first investigation of the effect of Ir-Cpx compounds on the cell cycle was performed for dichlorido complex 8, the biological effect of which was associated with apoptosis, necrosis and autophagy (in 8505C cells).54 Cell cycle analysis showed that 8 induced an increase of apoptosis-related sub-G1 cells with fragmented DNA at the expense of the G1, S and G2/ M cell cycle phases, suggesting that apoptosis was the dominant type of cell death for 8. However, another investigation from the same year reported that 48, which induced early apoptosis in HT29 cells, did not induce similar DNA fragmentation, as no sub-G1 cells were detected. 166 Application of 48 led to an increase in the population of both the S and G2/M phases of the cell cycle.

For highly effective complex 14 (Fig. 5), a different type and dynamics of cell cycle modification was determined in comparison with cisplatin.⁷⁷ In particular, 14 only blocked A2780 and HL-60 cells in the G0/G1 phase after 48 h, while cisplatin induced an increase in S-phase cell populations after 24 h. This observation was supported by impedance-based real-time monitoring of the effects on cancer cell growth, the results of

Fig. 45 The structural formula of complex 123.

which for 14 correlated with DNA interfering drugs inhibiting protein translation and inducing G1 (or S) cell cycle arrest. Similar cell cycle modification results (G1 arrest) were reported for more anticancer Ir-Cpx complexes. 168 Other compounds induced an increase in the number of cells in the S phase of the cell cycle (e.g., 70 and 105). 193 In some cases, the cell cycle remains more or less unmodified. 104

The often ambiguous connection between cell cycle alterations, as induced by anticancer Ir-Cpx complexes, and other biological mechanisms can be clarified by additional research findings.²⁶⁰ Specifically, the cytotoxic [Ir(n⁵-Cp^{bph})(bpy)Cl] CF₃SO₃ complex induced S and G2/M arrest, whereas the cell cycle phase distribution of cells treated with the inactive $[Ir(\eta^5-$ Cp^{bph})(bpy)Cl]BPh₄ complex remained more or less unchanged. On the other hand, the very severe changes to cancer cells treated with dinuclear complex 88 did not lead to relevant cell cycle changes, which remained largely unchanged compared to non-treated cells.²²⁷

Thus, the main importance of studies on cell cycle modification lies in distinguishing the MoA from that of cisplatin, which induces characteristic cell cycle changes.

5.7. Specific organelle damage

The effects of compounds on DNA (cell nucleus; section 5.4) and mitochondria (related to ROS induction; section 5.5) have been discussed, but more cellular targets are available. Lysosomes are single-membrane organelles containing various digestive enzymes (e.g., proteases, nucleases or lipases) and having an acidic environment inside. They are essential for maintaining cellular function. Liu and co-workers reported that Ir complexes (e.g., 73 in Fig. 16) disrupted the lysosomal integrity in HeLa cells, which was studied using the acridine orange fluorescent probe (red fluorescence in lysosomes, green fluorescence in cytosol and the nucleus). 197 Other Ir-Cpx compounds were shown to accumulate in lysosomes (e.g., 18)82 or even specifically target these organelles and induce permeabilization of the lysosomal membrane in cancer cells, leading to lysosomal rupture and cancer cell death. 85,103,104,147,170-172,198,199,201,202,206 Lysosome damage was also proved by the concentration-dependent release of cathepsin B into the cytosol. 102

Interestingly, although disruption of the lysosomal membrane has been reported for a number of complexes, further studies with the protease inhibitor leupeptin did not alter the antiproliferative activity of 79.202 This suggests that cell death is not due to lysosomal damage but rather may result from another type of cell death (mitochondrial apoptotic pathway).

Complex 56 (Fig. 12), which partially accumulated in the endoplasmic reticulum (ER), induced ER stress. 178 ER stress, in general, is connected with a complex unfolded protein response (UPR), the key signal activators (e.g., protein kinase RNA-like ER kinase, PERK) of which were upregulated in the treated cancer cells. Along with ER stress, 56 disrupted the integrity of the Golgi apparatus. An effect on the ER was also detected in cells treated with 33, which triggered the integrated

stress response (ISR) as a consequence of induced mitochondrial dysfunction. 115

Complex 57 bearing the terminal bioorthogonal azido group effectively targeted proteins involved in protein folding and actin cytoskeleton regulation. 179 This resulted in the inhibition of the folding activity of heat shock protein HSP90 and disorganization of the cytoskeleton.

5.8. Gene expression analysis

Complexes 47 and 116 (Fig. 39), which were studied in the NCI-60 panel, ²⁶² were also screened in a panel of 916 cell lines from 28 tissue types (Sanger Cancer Genome), where 116 was 78- and 36-fold times more potent than 47 and cisplatin, respectively.²⁶³ Furthermore, 116, in contrast to 47, was highly potent in primary patient-derived ovarian cancer cell lines isolated from patients prior to treatment and after taxane/cisplatin application. Compound 116 had a different pattern of activity towards the cancer cell lines used than other screened anticancer drugs, indicating its unique MoA. For 116, gene expression was studied in A2780 cells by RNA sequencing at different time points (up to 48 h exposure). The highest number (746) of differentially expressed genes was detected at t = 12 h, of which ca. twice as many genes were down-regulated. A detailed analysis of the results showed that the 117treated cancer cells activated stress (general) and oxidative stress response pathways (e.g., Nrf2 and the two AP-1 transcription factors); Nrf2 = nuclear factor erythroid 2-related factor 2. This was linked by flow cytometry to the formation of high ROS levels in A2780 cells. In connection with the induction of apoptosis (flow cytometry), genes for inhibitors of apoptosis, which inhibit the activation of caspase proteins (e.g., BIRC3), were up-regulated. Similarly, dinuclear complex 88 up-regulated HO-1 and NQO1 proteins, the expression of which is regulated by the Keap1/Nrf2 pathway involved in oxidative stress defense and the induction of ROS production in cancer cells.227

Complex 26 (Fig. 7) was studied by RT-PCR (reverse transcription polymerase chain reaction) in 3D spheroids of SCC070 cells, where the expression of stemness regulators, the drug efflux transporter and differentiation markers were investigated.92 However, 26 showed a lower ability to reduce the expression of the tested regulatory genes than its Ru analogues. Gene expression studies (microarray data, supported by RT-qPCR) performed on apoptotic cells treated with 33 (Fig. 8) showed, for example, a significant decrease in histone gene expression, which was consistent with other results (e.g., cell cycle arrest) obtained for this complex. 115

5.9. In vivo studies

In contrast with the above-discussed results obtained on cell cultures in a controlled laboratory environment (in vitro testing), in vivo studies of anticancer activity are performed on whole, living organisms. Obviously, in vivo studies provide scientists with a more accurate and comprehensive picture of how a substance will act on the treated organism. As no Ir cyclopentadienyl complexes have entered clinical trials on

human patients, only results obtained in animals are discussed in this section.

Although the *in vitro* activity of the $[Ir(\eta^5-Cp^*)Cl(pbt)]PF_6$ (124; Fig. 46) complex did not reach 50% cell viability reduction even at 20 mg mL⁻¹ concentration, it was tested for its in vivo activity in mice bearing Dalton's lymphoma ascites tumour cells; pbt = 2-(1*H*-pyrazol-3-yl)benzothiazole. 118 124 increased the life span of tumour bearing mice (T/C = 152% at 15 mg kg⁻¹ dose), but it was toxic at 30 mg kg⁻¹ dose, resulting in premature death of the treated animals.

The in vivo anticancer activity of 76 (Fig. 16) was studied in the CT26 colon cancer mouse xenograft model (3 or 5 mg kg⁻¹ doses for 7 days). 200 After 24 days, there was a significant dosedependent inhibition of tumour volume and weight (62.3 and 56.4%, respectively, for 5 mg kg⁻¹ dose), without body weight loss.

The hexanuclear Ir metallaprism was less effective than its Rh analogue in tumour-induced C57L6/J mice.²²¹ For the Ir complex, treated animals died after three days with no reduction in tumour volume.

The Ir iodido complex was reported to be less toxic in vivo than its chlorido analogue towards zebrafish (Danio rerio) embryos, but both these Ir-Cpx complexes were more toxic than cisplatin. 248

Dinuclear complex 91 involving a triphenylamine-modified TSC (Fig. 22) was studied using the A549 mouse xenograft model (lung cancer).²³¹ The complex was not toxic (no mortality and weight change) and showed promising tumour growth inhibition. The induced tumour volume and weight changes were lower compared to control groups of animals (vehicle and cisplatin-treated mice). The tumour inhibition rate was ca. 57% for 91, which significantly outperformed cisplatin with ca. 12%. Histological analysis of the isolated tumours showed evidence for the paraptosis-like cell death induced by 91. Importantly, the biochemical blood indicators of myelosuppression and hepatotoxicity (decrease in the white blood cell count, absolute value of monocytes, blood urea nitrogen, aspartate aminotransferase, creatinine, alkaline phosphatase, alanine aminotransferase) were, in most cases, less pronounced for 91 than for cisplatin. On the other hand, metastatic infiltrating foci of cancer cells were detected in the lungs and liver, indicating a high possibility of infiltration and metastasis in animals treated with 91. Similar heterometallic complex 125 (Fig. 47) with a ferrocene-modified TSC ligand was also highly anticancer active in vivo in the same mouse model.232

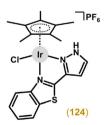


Fig. 46 The structural formula of complex 124

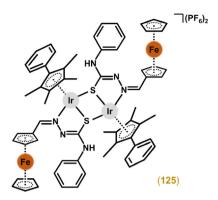


Fig. 47 The structural formula of complex 125.

Complex 33 had a maximum tolerated dose of 1.3 mg kg⁻¹ in healthy BALB/c mice, with predominant accumulation in the liver, kidneys and lungs. 115 In an orthotopic model of lung cancer (A549 cells marked with luciferase) in nude mice, 33 was administered at 0.9 mg kg⁻¹ doses, inducing no signs of toxicity and reducing the primary tumour but not in the neighbouring invaded lymphatic nodes.

Complex 13 (3 mg kg⁻¹ doses) reduced the tumour size (volume, weight) markedly more effectively (1.20 g) than cisplatin (1.45 g) in the A549 lung cancer transplanted mice. 63 No negative side effects or metastasis in the lungs or other organs were observed for 13, representing another advantage over cisplatin.

Drug delivery systems loaded with anticancer Ir-Cpx complexes seem to be a very promising approach (see section 6.4). For example, complex 22, administered to mice bearing the A549 human lung xenograft at 1.25 mg kg⁻¹ dose (higher doses were toxic) exhibited greater tumour growth inhibition (TGI = 78%) than cisplatin (54%). 88 Other improvements to the in vivo anticancer activity were obtained by the formation of liposomes loaded with 22.

The phototoxic ferroptosis-inducing complex 27 (Fig. 7) was studied for its in vivo anticancer activity in 4T1 tumourbearing Balb/c mice. 96 A dose of 5 mg kg⁻¹ (i.p.) was followed by 635 nm laser irradiation for 10 min. 27 itself (i.e., without irradiation) inhibited tumour growth (TGI = 43%) to a lesser extent than that detected in irradiated animals (TGI = 89%), indicating the synergistic effects of chemo- and phototherapy. No relevant toxicity was observed in major organs, which proved the promising biocompatibility of 27.

Anticancer activity-related aspects

In general, the anticancer activity of newly developed (metallo) drugs is often evaluated with respect to the composition of the new compounds (SAR; section 4) and the manner in which they induce cancer cell death (MoA; section 5). In addition, there are other aspects and processes that either influence the resulting biological effect (e.g., interactions with biomolecules)

or represent a specialised research/application area (e.g., targeting or PDT), as discussed in detail in this section.

6.1. Interaction with biomolecules

6.1.1. Small biomolecules

6.1.1.1. NAD(H). The interaction of new Ir-Cp^x anticancer complexes with NAD(H) coenzymes is often studied for its close connection to the redox-mediated MoA.276-278 From a chemical point of view, the reduction of NAD+ to NADH (usually with formate as a hydride source) was studied^{280,281} before the first mention of the reduction of NADH by the Ir-Cpx complex as a catalyst for such a transfer hydrogenation reaction and the discussion of possible biochemical consequences.²⁸² For various metallodrugs, including Ir-Cp^x compounds, the oxidation of NADH is accepted as a source of ROS within a redox-mediated MoA. Similarly, the use of hydrogenation reactions with NADH as a hydride source for the reduction of biologically relevant compounds (quinones) has been described for Ir-Cpx complexes. 283

The first reported $[Ir(\eta^5-Cp^{ph})(H_2O)(phen)]^{2+}$ (126; Fig. 48) complex effectively and repeatedly oxidized NADH to NAD+.282 This process was studied by ¹H NMR and UV-Vis spectroscopy, which remain the most widely used techniques for studies of NAD(H) conversions. The oxidation of NADH was associated with hydride transfer to the metal centre and with the formation of the Ir-H hydrido species detectable by ¹H NMR in very strong fields (ca. -10 ppm). Such hydride subtraction led to the formation of H2, which is an antioxidant by itself. The formation of H2 was indirectly demonstrated by an increase in pH. Importantly for future research, the oxidation of NADH has been also demonstrated as a proton source for the reduction of physiologically relevant biomolecules - in this case, pyruvate was used, which was partially reduced to lactate in the presence of 126 and NADH. For analogous complex 101 (Fig. 27) it was observed that hydride transfer from NADH could be linked to ROS production, as hydrogen peroxide was detected in cell-free experiments in the presence of oxygen.⁴⁴

Some Ir-Cpx complexes retained their integrity and the formation of the Ir-H species was not discussed despite high NADH-to-NAD⁺ oxidation. 163 Other complexes readily oxidized NADH, but the Ir-H 1H NMR signal was not detected.110 Negligible or even no NADH oxidation was observed for anticancer Ir-Cpx complexes. 85,104 On the other hand, another Ir complex was inactive in cancer cells and outperformed by its direct Rh analogue, while their NADH-oxidizing abilities were

Fig. 48 The structural formula of complex 126

comparable.86 The ability to oxidize NADH was also reported for mononuclear dichlorido complexes⁵⁹ and dinuclear Ir-Cp* complexes. 225,227 Detailed kinetic studies were reported for the model compound $[Ir(\eta^5-Cp^*)(H_2O)(phen)]^{2+}.^{284}$

The ability of some Ir-Cpx complexes to reduce NAD+ to NADH in the presence of formate as a hydride source and the positive effects of formate concentration on antimicrobial (antiplasmodial) activity were also observed (anticancer activity was not studied).285 Other antimicrobial-active Ir-Cpx complexes did not reduce NAD⁺ to NADH. ²⁸⁶

6.1.1.2. GSH. Reduced glutathione (GSH) is a tripeptide (γ-Glu-Cys-Gly) that has several important functions in most cells, including cancer cells.²⁸⁷ GSH performs various functions in cells, for example, it is a key antioxidant, plays an essential role in detoxification (of toxins or xenobiotics) and also supports the proper functioning of immune cells (and the immune system as such), as well as maintaining the proper structure and function of proteins.

Probably the first consideration of a possible interaction between mononuclear Ir-Cpx complexes and GSH was reported for 47 and 101.44 Both complexes formed a covalent Ir-SG adduct, as proved by ¹H NMR and mass spectrometry. This process was faster for the more hydrolytically labile chlorido complex 47. Interaction with GSH has also been described for other Ir complexes, either to form similar Ir-SG adducts 133,136,170 or the product has not been specified. 86,99 Some anticancer Ir-Cpx complexes did not interact with GSH. 93,100,102

A specific case was reported for a series of Ir iodido complexes, which formed the abovementioned Ir-SG adduct, which subsequently catalysed GSH oxidation to glutathione disulfide (GSSG).248 The process of GSH-to-GSSG oxidation was linked to the reversible attack of glutathione on the azo bond of the azopyridine ligand. As a consequence, the studied iodido complexes decomposed, releasing the azopyridine ligand and forming the dinuclear trithiolato species, [Ir₂(η⁵- $(\text{Cp*})_2(\mu-\text{SG})_3^+$, with three bridging –SG ligands (Fig. 49). This decomposition mechanism has also been reported elsewhere.111

Importantly, some works have also reported the oxidation of GSH to GSSG in DMSO-containing mixtures of solvents as an effect of Ir compounds, 95,217,244,249 but this should be attributed to DMSO and its known oxidative effect towards GSH.111,288

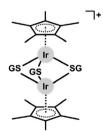


Fig. 49 The structural formula of the $[Ir_2(\eta^5-Cp^*)_2(\mu-SG)_3]^+$ dimer; GSH = reduced glutathione.

6.1.1.3. Amino acids. In the context of studying the interactions of Ir-Cpx complexes with GSH, a higher affinity for sulfur-containing amino acids (N-acetyl-1-methionine or N-acetyl-L-cysteine) over nitrogen-containing ones (N-acetyl-Lhistidine) was observed in HPLC/ESI-MS experiments under biologically relevant conditions for 71 (Fig. 15). 194 Complexes 51 and 52 interacted with Cys and other biomolecules (His, methionine, EtG). 173,174 Similarly, the [Ir(η^5 -Cp*)Cl(bphen)]PF₆ complex interacted rapidly with NAC, but did not show any affinity towards tyrosine and serine.88 In contrast, an affinity towards unsubstituted Cys was observed for another Ir complex, 187 while other complexes did not interact with Cys. 107 DFT calculations were also used for studies of the reactivity of a model Ir-Cpx complex with Cys selenocysteine.289

6.1.1.4. Ascorbic acid. Ascorbic acid (ASA) is an abundant intracellular antioxidant that is frequently used in the field of multi-component platinum(IV) anticancer complexes, where ASA facilitates the reductive release of their axial ligands. ²⁹⁰ In contrast, only a few investigations on anticancer Ir-Cpx complexes have involved ASA in any of its possible chemical or biochemical roles.

Complex 30, which contains the aza bond outside the chelate ring (Fig. 8), making it accessible for various reactions, was shown to interact not only with NADH and GSH, but it also oxidized ASA to dehydroascorbate, as proved by ¹H NMR studies. 111 Other Ir-Cpx mononuclear (54; Fig. 12)176 and dinuclear (88)²²⁷ complexes without similar reactive bonds were stable in the presence of ASA and did not induce any changes to this biomolecule.

6.1.1.5. Mixture of biomolecules. It is apparent that single biomolecule experiments mimic the intracellular environment only imperfectly and should be considered only as a chemical model system for studying reactivity rather than biochemical evidence of the MoA. Aware of this shortcoming, some authors have used a mixture of multiple biomolecules to increase the relevance of such model studies.

In the first article that discussed the oxidation of NADH in the presence of 126, GSH was used as a possible scavenger of the NADH oxidation. 282 However, no effect was observed and NADH was oxidized to NAD⁺ even in the presence of excess GSH.

Complex 30 (Fig. 8) oxidized NADH (to NAD⁺) and ASA (to dehydroascorbate), which was associated with the reduction of the exo-chelate azo bond. 111 In the presence of GSH, the release of the chelating ligand and the formation of the abovementioned $[Ir_2(\eta^5-Cp^*)_2(\mu-SG)_3]^+$ species were observed together with GSH-to-GSSG oxidation. The results of ¹H NMR studies of 30 in various mixtures of NADH, ASA and GSH showed different magnitudes of individual processes - for example, NADH was oxidized to a lesser extent in the presence of GSH, ASA or their mixture. Interestingly, the pro-oxidant effect of ASA on GSH oxidation was related to the recovery of ASA from dehydroascorbate. While the presence of the azo bond on the chelating ligand used was essential for the observed biochemical phenomena, the individual events (e.g.,

NADH or ASA oxidation) did not occur with the free ligand. Thus, 30 should therefore be understood as an example of complexes with a metal-activated ligand.

Highly effective (low-micromolar GI₅₀ values) dinuclear complex 88 oxidized NADH to NAD+ when mixed with NADH or with NADH and GSH. 227 When mixed with both NADH and GSH, 88 formed a covalent adduct with -SG, which was not observed for 88 when mixed with GSH alone. In contrast to GSH, the presence of ASA caused a decrease in the extent of NADH oxidation, which was completely suppressed in the mixture of 88 with all three biomolecules (NADH, GSH, ASA). Even with these in-solution results, 88 induced cancer cell death via a redox-mediated MoA, and the levels of both NAD (H) coenzymes were significantly reduced in treated cancer cells.

6.1.2. Proteins

6.1.2.1. Albumins. Bovine serum albumin (BSA) is a frequently used model transport protein for pre-pharmacokinetic studies of the behaviour of novel Ir complexes in blood. 119 In most cases, fluorescence spectroscopy is used to study the interaction of Ir-Cpx compounds and naturally fluorescent albumins. Such experiments have usually provided a positive response interpreted as the ability of the new compounds to interact with albumins. Since albumins are blood transport proteins, release from the Ir-albumin adducts formed is also important, but has been studied relatively rarely. 168 Some papers have also reported ¹H NMR studies on Ir complexes with albumins, to investigate their stability in the presence of transport proteins. 111,176

Less frequently, human serum albumin (HSA) or apo-transferrin has been used for analogous fluorescence spectroscopy studies of the interactions of Ir-Cpx complexes and blood transport proteins. 59,62,114,133,166,167 Glucose was also studied for its possible binding to 32 in blood, but no interaction was detected using UV-Vis experiments. 114 Complex 22 was studied for its stability in blood plasma, where it showed a lower ability to bind plasma proteins ($t_{\frac{1}{2}} = 6.1 \text{ h}$) than cisplatin ($t_{\frac{1}{2}} =$ 1.8 h).88

6.1.2.2. Other proteins. In 2010, when DNA was considered the only target for Ir-Cpx complexes, experiments were carried out on new Ir complexes and ubiquitin (Ub)⁷⁴ and cathepsin B (catB)⁵³ were employed as model proteins. Although the Ir compounds used, in contrast to Ru analogues, did not interact with Ub and catB, these works paved the way for further research that considered proteins as possible targets for Ir-Cpx compounds. 53,74 DFT analysis of N-acetyl-L-cysteine-N'-methylamide, a model for the Cys residue of, e.g., catB, revealed that Ir (and Rh) complexes had less affinity towards Cys (i.e., formed weaker M-S bonds) than Ru and Os analogues. 53 Low micromolar inhibition activity towards catB was also reported for 43 and 45.156

Complexes 43 and 47 were studied for their interaction with the methionine (Met)-rich protein calmodulin by electroncapture dissociation (ECD) tandem mass spectrometry (MS). 291 The results indicated weak Met binding by the Ir-Cpx compounds used, without loss of the chelating ppy ligand, which

was different from cisplatin, which lost its ligands and crosslinked the protein. Similar Ir-Cpx complexes bearing an aldehyde group on their ppy ligand were also studied by ECD-MS for their interaction with different model peptides (substance P, bombesin). 292 The complexes bind covalently to peptides via histidine (Ir-His bond) and lysine (imine formation of Lys with an aldehyde group).

Enzyme thioredoxin reductase (Trx-R) plays a key role in various intracellular processes, such as protecting from oxidative stress or DNA synthesis and repair. Trx-R was studied as a possible mechanistic target for complexes bearing various picolinamides, where Ir-Cp^x compounds showed nanomolar IC50 values of Trx-R-inhibition and outperformed their Ru analogues. 120 Within another series of anticancer complexes reported by the same research team, both Ir (39; Fig. 9) and Ru compounds showed inhibition effects towards Trx-R in the nanomolar range.148

Tether complex 102, although the best-performing of the reported series of complexes, did not show any inhibitory effect on the enzymatic activity of Trx-R, while some of its less cytotoxic congeners (both tethered and nontethered) inhibited it. 165 The $[Ir(\mu-Cl)(\eta^5-Cp^x)Cl]_2$ dimers with differently substituted Cpx rings showed no correlation between antiproliferative activity and Trx-R inhibition, since the more anticancer active complex inhibited Trx-R less effectively.64 Other complexes did not inhibit Trx-R. 149

Topoisomerase IIa (TOP2A) is a nuclear enzyme that plays a critical role in controlling DNA function. It is also the target of anticancer drugs that generate enzyme-mediated DNA damage. Chlorido complex 70 (Fig. 15) and its 1-methylimidazole analogue 105 (Fig. 28) effectively inhibited TOP2A, although their effects were less pronounced than that of the Ru analogues. 193

A pair of Ir-Cp* complexes was derived from ispinesibbased ligands. 107 Ipsinesib is a kinesin spindle protein (KSP) inhibitor and this effect was also studied for the Ir complexes, which reduced the KSP activity to <20% even at 1 nM concentration. Lower KSP inhibitory activity was reported by the same research group for more stable analogues with different binding of ipsinesib on a carrier ligand (e.g., 29; Fig. 8). 109

Complex 56 (Fig. 12), which induced various effects in cancer cells, including ER stress and Golgi apparatus dispersion, also altered the gel electrophoretic mobility studied in HeLa cell extract (in vitro) and in live HeLa cells (in vivo). 178 This observation implied covalent interactions with protein(s) that were not further specified. Studies with N-acetyl histidine, NAC methyl ester, phenylbutylamine (mimicking lysine) and butyramide (mimicking glutamine and asparagine) were performed for 56 as model experiments for such protein interactions. Analogous complex 57 is functionalized by a bioorthogonal azido probe allowing the identification of intracellular protein targets by bioorthogonal click reactions. 179

6.2. Complexes with bioactive ligands

6.2.1. Pharmacological context. Regarding the design of these complexes, the use of bidentate bioactive ligands does not appear to be a viable strategy. Either such bidentate

ligands are not released from the complex, which suppresses their own activity, or they are released from the complex, but this leads to the formation of inactive metal-based metabolites. More preferable is the use of complexes bearing bioactive monodentate ligands (multi-component complexes), which release an aqua/hydroxido complex species that has its own biological activity. The use of carrier ligands to bind releasable bioactive substituents also appears promising for the development of multi-component complexes.

6.2.2. Complexes with bidentate bioactive ligands. In some works, ligands with their own biological activity were used for the preparation of anticancer Ir-Cpx complexes. Since the release of such ligands from the complexes has not been demonstrated, these ligands cannot be assumed to have an independent biological effect. For example, the $[Ir(\eta^5-Cp^*)Cl$ (cur¹)] complex involves a bioactive curcumin derivative, cur¹, which, based on UV-Vis studies, remains in the complex under aqueous conditions; $Hcur^1 = (1E,6E)-1,7-bis(phenyl)-1,6-hepta$ diene-3,5-dione. 190 The opposite situation, where the bioactive ligand used is released immediately, is also not pharmacologically viable. For example, complex 127 (Fig. 50), a pta analogue of 68 (Fig. 14), was studied for its stability under the simulated physiological conditions at different NaCl concentrations (5 mM, 100 mM), where this complex was immediately decomposed and hydrolysed, which was connected with the release of bidentate-coordinated curcumin. 45 Similar results were reported for the pta analogue 106 (Fig. 28) containing β-diketone dibenzoylmethane. 191 The released organic ligand usually accumulates less in cancer cells and the Ir-containing $[Ir(\eta^5-Cp^*)Cl_2(pta)]$ metabolites (i.e., and $[Ir(\eta^5-Cp^*)]$ $(H_2O)_2(pta)$ ²⁺ for **106** and **127**; Fig. 50) usually have very little biological effect.53

Dinuclear complexes containing highly cytotoxic avobenzone also showed cytotoxic potency in the low-micromolar range as did the free avobenzone. 192 Highly active C,N-coordinated ppy ligands containing androsterone were used to prepare a series of Ir complexes, but their activity was not higher than that of the free organic derivatives. 157 These complexes, however, were not studied for their in-solution stability.

Other Ir complexes, derived from bidentate-coordinated moderately cytotoxic ispinesib-derived ligands, were unstable in the DMEM testing medium. 107 Based on this observation, the authors also studied stability in the presence of Cys and His, which represent highly-concentrated components of DMEM. The results showed extensive release of bidentate ligands in the presence of His, which coordinated to the Ir centre. A similar synthetic strategy was used with the pyridine-2-ylmethanimine bidentate ligand bearing ispinesib or 7-chloroquinazolin-4(3H)-one as bioactive functionalities. 108,109

6.2.3. Multi-component complexes. approaches can be used to obtain multi-component Ir-Cpx complexes. First, the $[Ir(\eta^5-Cp^x)(L^L)Cl]^{0/+}$ complexes contain carrier ligands (i.e., a chelating L^L ligand or Cpx) substituted (biofunctionalized) by a bioactive substituent via a cleavable bond allowing its release under physiological (preferably intracellular) conditions. Or second, complexes of the general

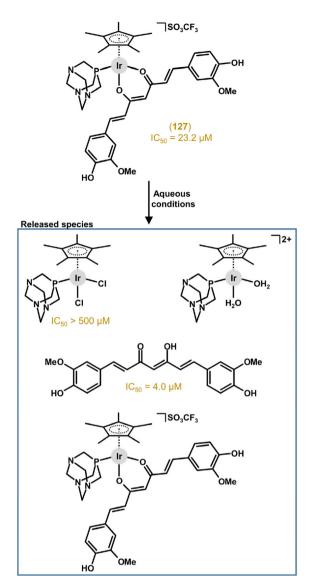


Fig. 50 The structural formula of complex 127 and the route to its decomposition in the presence of water (water: DMSO mixture; ¹H, ³¹P NMR studies), given together with the IC₅₀ values determined in A2780 cells.

formula $[Ir(\eta^5-Cp^x)(L^L)(X)]^{0/+}$ involve a releasable monodentate bioactive ligand X.

The strategy with releasable substituents on a carrier ligand was used for the first time for the complex involving bpy conjugated to lipoic acid (LA) through the peptide bond. 136 This inactive complex (IC₅₀ > 200 µM in various cancer cells) was stable in the presence of water, thus LA was not released from the complex. The antimalarial drug artemisinin was used for the biofunctionalization of a series of Ir-Cp^x complexes (e.g., 20; Fig. 6) through the ester bond of their chelating bpy-based ligands. 83 Compounds were studied for their anticancer and antimicrobial activity, but stability studies were not conducted.

Another series of Ir-Cp* complexes is based on double-substituted bpy diesters bearing two different bioactive substitu-

ents via the ethyl linker (e.g., GST inhibitor ethacrynate and COX inhibitor flurbiprofen for the most effective Ir complex 128 (Fig. 51)); GST = glutathione S-transferase, COX = cyclooxygenase.84 These Ir complexes (and their Ru analogues) underwent a transesterification process in methanol and in a mixture of 1% DMSO/99% RPMI, leading to the release of bioactive substituents as carboxylates or hydroxyethyl esters. With respect to the biological type of substituent used, the inhibition of GST and COX was studied and shown to be induced by the complexes. Since these complexes also metalated DNA, they could be considered as representatives of multi-modal (multi-targeted) anticancer complexes that induced cell death in treated cancer cells through multiple independent processes.

Complexes involving a bpy derivative biofunctionalized with sulfonamide or dichloroacetate (dca) bioactive substituents were inactive in the human cancer cells used. 52,86 Complexes with two substituents (e.g., dca) conjugated to bpy via ester bonds were examined by mass spectrometry in the presence of porcine liver esterase (PLE).52 The results showed that although the free bpy derivative readily released its carboxy substituents in the presence of PLE due to enzymatic cleavage, the same ligand was stable after its coordination to the Ir complex, which was not cleaved by PLE to yield independent bioactive species.

Regarding the second design of multi-component [Ir(η⁵- $Cp^{x}(L^{L})(X)^{0/+}$ complexes, the first complexes with releasable monodentate bioactive ligands (X) were derived from the moderately effective $[Ir(\eta^5-Cp^*)Cl(dpa)]PF_6$ complex; dpa = N-(pyridin-2-yl)pyridin-2-amine (dipyridylamine).43 However, its analogues with O-coordinated HDAC inhibitors valproate (vp) or 4-phenylbutyrate (pb) were comparably (for pb) or even less (for vp) effective in A2780 cells.

Another $[Ir(\eta^5-Cp^{ph})(pb)(phen)]PF_6$ (129; Fig. 52) complex also contains pb. 250 This complex readily released pb in the presence of water, providing two bioactive species (i.e., pb and an Ir-based entity, $[Ir(\eta^5-Cp^{ph})(H_2O)(phen)]^{2+}$ under simulated physiological conditions. A specific effect of both biologically independent species was detected in cancer cells. In particular, 129 inhibited the HDAC activity (released pb ligand) and

Fig. 51 The structural formula of multi-component complex 128 involving GST inhibitor ethacrynate (blue) and COX inhibitor flurbiprofen

Fig. 52 The structural formula of complex 129

induced a high ROS population (released $[Ir(\eta^5-Cp^{ph})(H_2O)(phen)]^{2+}$ species). **129** also exhibited the ability to overcome acquired resistance against cisplatin and showed higher selectivity towards cancer cells over normal ones, both to a greater extent than that of its chlorido analogue $[Ir(\eta^5-Cp^{ph})Cl(phen)]PF_6$.

6.3. Complexes for photodynamic therapy

Photodynamic therapy (PDT) is a pharmacological concept that utilizes light-sensitive drugs to treat various diseases, including cancer. In principle, PDT consists of the application of a drug, its accumulation in the diseased tissue (cells) and irradiation with a specific wavelength of light, which leads to the production of highly toxic species (ROS, singlet oxygen) that damage cells and cause their death. In the field of Ir complexes, PDT is more often studied for octahedral polypyridyl or cyclometalated complexes, while studies on half-sandwich Ir–Cp* compounds are relatively rare.

The possible potential of Ir–Cp^x complexes for PDT was described in 2013 for the dinuclear trithiolato Ir complex, which was (similarly to its Ru and Rh congeners) able to generate ROS upon irradiation with UV light, as proved by the cleavage of DNA.²¹⁸ The observed DNA cleavage was significantly inhibited by sodium azide (NaN₃), which was used as a known ROS quencher.

The $[Ir(\eta^5-Cp^*)Cl(PBI)]PF_6$ (130; Fig. 53) complex was derived from a perylene bisimide (PBI) derivative, which is known to have a high fluorescence quantum yield and be a suitable ligand for complexes with accelerated intersystem crossing (ISC) from the singlet to triplet excited state, greatly promoting singlet oxygen (1O_2) production. 270 Indeed, 130, which is photostable in aqueous solution, produced 1O_2 upon irradiation at 420 nm. Importantly, this feature translated into high phototoxicity in various cancer cells (nanomolar IC₅₀ values, PI = 7.8–23.0).

For other complexes (*e.g.*, **131**; Fig. 53) derived from N,O-coordinated lidocaine and involving (pyren-1-yl)ethynyl derivatives of phenylcyanamide, their photodynamic properties have also been described.²⁵¹ Both complexes were highly photostable in solution and induced $^{1}O_{2}$ formation. Their phototoxicity in HeLa cells was excellent with PI = 278 and 417 (450 nm light irradiation). The complexes accumulated in the nucleus

Fig. 53 Structural formulas of complexes 130 and 131.

and effectively induced ROS formation (in-cell experiment) and DNA photocleavage (cell-free experiment). Interestingly, the observed DNA photocleavage was inhibited by hydroxyl (DMSO, KI, catalase) and superoxide (superoxide dismutase) radical scavengers, while the $^{1}O_{2}$ quenchers (TEMP, DABCO, NaN₃) did not inhibit it. The number of early apoptotic HeLa cells was higher in the irradiated population than in the dark.

Su et al. developed iridium-thiosemicarbazone complexes (e.g., 62 in Fig. 13) for dual chemo- and photodynamic therapy by introducing a photosensitizer moiety into the TSC ligand. 62 showed remarkable phototoxic behaviour against SKOV3 cells (IC₅₀ = 2.3 μ M, λ_{irr} > 400 nm), as well as up to 7.4-fold lower toxicity in the dark. 184 Photostable complex 27 (Fig. 7) produced 1O2, superoxide and hydroxyl radicals, and extensively oxidized NADH upon irradiation by 635 nm light.96 In connection, high NADH photooxidation was also detected in cancer cells, leading to a decrease of ATP production and disruption to mitochondria. The irradiation of 27-treated 4T1 cancer cells improved its moderate dark cytotoxicity (IC50 = 38.4 μ M) to low-micromolar values (IC₅₀ = 2.0 μ M), resulting in PI = 18.8. Approximately 2-fold higher cytotoxicity and a lower PI of 10.2 were detected for non-cancerous LO2 cells. Apoptosis and ferroptosis were detected in irradiated cancer cells.

The strategy of using π -expansive ligands was applied to prolong the excited state lifetimes; this is known to be beneficial for the photobiochemical properties including photocytotoxicity. Complexes were photostable and induced the production of $^{1}O_{2}$. Chlorido complexes, especially their analogues bearing a monodentate heterocyclic N-donor ligand (*e.g.*, imidazole), exhibited a higher antiproliferative activity when irradiated than in the dark. Thus, complexes with the most extended pbpn ligand showed higher activity, as exemplified by the chlorido complex 58 (Fig. 12) with $IC_{50,dark} = 2.2 \, \mu M$ and $IC_{50,blue}$ light = 6.9 nM in A549 cells (PI = 323). An analogue

of **58** with *N*-(ethylpiperidyl)imidazole (Imepip; **121** in Fig. 42) instead of the chlorido ligand exhibited PI values of 1317 (2D culture of A549 cells) and 240 in the advanced model of 3D spheroids. **121** was highly selective towards cancer cells, even when irradiated, and showed no haemolytic activity against red blood cells (RBCs). Relevant differences were also discussed for other processes (ROS production, NADH oxidation, mitochondria disruption) studied under dark and light conditions.

An extensive series of Ir–Cp* chlorido complexes involving various 2,2'-(phenylmethanediyl)bis(1H-pyrrole) derivatives as chelating N-donor ligands showed, in some cases, higher antiproliferative activity upon white light irradiation than in the dark. ²⁹⁴ Complex 32 induced the formation of $^{1}O_{2}$ when irradiated by visible light ($^{400-700}$ nm). 114 Its antiproliferative activity in HeLa and MCF-7 cells was higher after irradiation with yellow light than in the dark (PI = $^{2.2}$ and $^{2.4}$, respectively).

6.4. Other aspects

6.4.1. Hypoxia. Complex 39 (Fig. 9) was studied at three different O2 concentrations. 148 In contrast to some co-studied Ru complexes, the potency of 39 decreased with a decrease of O_2 concentration (IC₅₀ = 5.1 μ M for 21% O_2 and 20.0 μ M for 0.1% O2), implying only low potential for the treatment of hypoxic tumours. Ir complex 23 (Fig. 7) was comparably potent in MDA-MB-231 cells under normoxia and hypoxia conditions, but its activity in T47D cells was lower under hypoxia conditions compared to that under a normal oxygen concentration.⁸⁹ Similar results, indicating comparable anticancer potency under both O2 concentrations used, were also reported elsewhere for other Ir complexes studied in HeLa and CaCo-2 cells. 95 Interestingly, the Ir complexes (e.g., 132; Fig. 54) were effective under hypoxia conditions even when 1 mM GSH was co-administered to the treated cancer cells, and showed high antiproliferative activity in HCT-116 cancer stem cells (CSCs).

Phototoxic complex 27 was highly effective under normoxia (see above) and hypoxia conditions, where its light IC_{50} values equalled 5.2 μ M (PI = 11.2), indicating that $^{1}O_{2}$ production played only a partial role in the MoA. 96 This proved to be connected to other ROS (superoxide and hydroxyl radical) detected in additional experiments with species-specific ROS probes.

Fig. 54 The structural formula of complex 132

6.4.2. Antimetastatic activity. Antimetastatic activity studies are used to investigate the ability of new compounds to prevent the formation of metastasis. The representative complex **76** (Fig. 16) showed promising antimetastatic activity *in vitro* (wound healing and transwell migration assays, and colony and spheroid formation – studied in A549 cells), ²⁰⁰ as also reported for some other complexes. ^{63,105,113,151,159-161,189,232,239-241,256}

6.4.3. Angiogenesis. Angiogenesis is the process by which new blood vessels are formed from old ones. Regarding its connection to cancer, it plays a key role in cancer progression, as tumours need a high and constant supply of oxygen and nutrients (tumour angiogenesis). Tumour angiogenesis is essential for growth and metastasizing to distant organs.

Complex 133 (see section 7.3 for the structural formula), which is the phenyl-substituted derivative of 48, was studied *in vitro* for its ability to inhibit tube formation in EA.hy926 normal endothelial cells (studied on matrigel matrix from Engelbreth–Holm–Swarm (EHS) mouse sarcoma cells). ¹⁶⁷ 133 exhibited higher antiangiogenic activity than cisplatin, but it was less antiangiogenic than the co-studied Ru analogues, based on three evaluated parameters – total vessel length, number of meshes, and total mesh area.

As an *in vitro* model experiment, Liu and co-workers studied the level of matrix metalloproteinase 9 (MMP-9) in A549 cells by flow cytometry, because MMPs are known to be related to angiogenesis and tumour invasion in general.¹⁵⁹

Treatment of zebrafish embryos with 22 strongly inhibited their subintestinal venous plexus (SIVP) (studied by confocal microscopy), which indicated a high and dose-dependent antiangiogenic effect.⁸⁸ Importantly, an effective antiangiogenic dose of 22 did not induce lethality and morphological changes in the treated embryos. The antiangiogenic effect of 22 is related to its inhibitory activity towards VEGFA and BMP signalling, which are found to be downregulated in zebrafish embryos (VEGFA is a key proangiogenic factor in neovascularization, BMPs promote angiogenesis by inducing cell proliferation and migration).

6.4.4. Immunotherapy. Anticancer immunotherapy involves various related phenomena such as programmed death-ligand 1 (PD-L1). This is a protein on the surface of cancer cells that helps them evade the immune system. Upregulation of PD-L1 expression is involved in chemotherapy resistance. Higher PD-L1 expression was detected for cisplatin-treated A549 cancer cells than for **76** (Fig. 16) after 48 h as well as after 7 days. ²⁰⁰ This observation suggests that **76** has a lower ability to induce immunosuppression and resistance to chemotherapy than cisplatin. Interestingly, the treatment of A549 cells with a combination of **76** and cisplatin resulted in a slight decrease in PD-L1 expression.

6.4.5. Chemosensitizers. It was reported for some inactive Ir–Cp^x complexes that they acted as selective chemosensitizers for cancer cells treated with other drugs. For example, the IC_{50} values of carboplatin decreased by 30–50% after pre-treatment with $[Ir(\eta^5-Cp^*)(bpy)Cl]Cl.^{143}$ In cancer cells, the application of non-toxic concentrations of Ir complexes led to an increase of

the ROS populations and NAD+/NADH ratios. Importantly, chemosensitizing effects were not observed in non-cancerous cells. The highly cytotoxic complex 76 was tested in combination with cisplatin in A549 cells, but only mild synergistic cytotoxicity was observed with a combination index of 0.88.200

6.4.6. Theranostics. The pharmacological concept of theranostics is a rapidly developing field that is based on molecular imaging and therapy using a single substance (or technique). The first Ir-Cp^x complexes, which were discussed as theranostic agents, involve monodentate-coordinate isomeric 3- or 4-pyridyl-BODIPY ligands (e.g., 104; Fig. 27). 163 As mentioned above (section 3.4), 104 outperformed its chlorido analogue in various cancer cell lines. While the photostable complex retained high activity, the presence of BODIPY, which is a fluorescence imaging reporter, enabled observation of the dynamics of cellular take up, accumulation and distribution of the metallodrug (104) directly in living cancer cells, where the complexes showed extremely fast accumulation (t < 90 s).

As mentioned above, some Ir-Cp^x anticancer complexes are fluorescent or luminescent by themselves (i.e., without a fluorophore); this has been exploited, e.g., for intracellular localization of such complexes, and in principle these compounds can be viewed theranostics. 63,85,93,159,163,170,192,198,272

6.4.7. Drug delivery. The Ir-phen complex $[Ir(\eta^5-Cp^{bph})Cl]$ (phen)]Cl and its Ir-dppn (134) and Ru-dppn analogues were used for the preparation of polymeric micelles through coordination between the dechlorinated aqua species and poly(ethylene glycol)-b-poly(glutamic acid) (Fig. 55).261 The formation of micelles led to higher cellular accumulation of complexes, higher antiproliferative activity and DNA metalation. Micelles involving the Ir-dppn species were readily accumulated and retained in tumours in A2780Cis subcutaneous xenografts (5 mg kg⁻¹ dose administered by intravenous injection). Importantly, micelles loaded with Ir-dppn species displayed higher anticancer activity (tumour volume was reduced by 70.2%) than the complex itself (tumour volume was reduced by 56.9%), thus showing great promise for future studies.

Complex 22, which was highly effective in vitro and in vivo, was encapsulated in liposomes (ca. 80 nm) formed from FDAapproved DSPE-PEG2000-biotin.88 Loaded liposomes had

Fig. 55 The structural formula of the adduct of 134 with poly(ethylene glycol)-b-poly(glutamic acid).

higher antiproliferative activity in vitro in HeLa cells ($IC_{50} = 16$ nM) than 22 itself ($IC_{50} = 150$ nM). Encouragingly, the loaded liposomes also showed higher anticancer activity in vivo (TGI = 85%) even though they were applied at lower doses (0.2 mg Ir per kg) than 22. Despite the lower doses, 22-loaded liposomes induced a gradual loss of body weight of treated mice and signs of systemic toxicity and poor biocompatibility. This is associated with markedly higher accumulation of 22 in important organs when loaded into liposomes - for example, 145-fold higher Ir accumulation in the brain was found for 22loaded liposomes compared to 22 itself.

Encapsulation of dichlorido complex 11 (Fig. 4) into Pluronic P-123 micelles was reported to be beneficial for the resulting antiproliferative activity, which was several times higher (IC₅₀ = $4.1 \mu M$ in DU-145 cells) than that for the free complex in the same cells ($IC_{50} = 11.8 \mu M$).⁵⁷ The same research group loaded heterometallic Ir-Cu complex 99 (Fig. 25) into cholesterol/phosphatidylcholine liposomes of >100 nm in size.²⁴⁶ These loaded liposomes, however, were less effective in cancer cells than 99 itself.

Complex 47 was readily loaded into amphiphilic hyaluronan-based delivery formulations, which were pH- and reduction-responsive (dissociation in the presence of 20 mM GSH).²⁹⁵ The 47-loaded formulations were even more potent in vitro than free 47 in A549 cells. In vivo, micelles efficiently accumulated in the tumour, where they enhanced tumour inhibition without body weight loss in A549 tumour-bearing female Balb/c nude mice, indicating negligible systemic toxicity of the hyaluronan-based formulations used.

Another delivery system developed for anticancer Ir-Cp^x compounds was based on biocompatible anisotropic polymeric materials, which are known for their long circulation times under physiological conditions.²⁹⁶ Specifically, poly(2hydroxypropyl-methacrylamide)-based polymer was loaded with [Ir(η^5 -Cp^{ph})Cl(ppy)] (135), a Cp^{ph} analogue of 43, and such formulations (Fig. 56) exhibited higher potency in human cancer cells than the free Ir complex, although the intracellular Ir level was more or less comparable for cells treated with the formulations and the complex.

6.4.8. 3D cancer cell spheroids. In the context of in vivo studies of the anticancer activity of Ir-Cp^x complexes (section 5.9), experiments performed on 3D cancer cell spheroids should also be mentioned. In contrast to two-dimensional (2D) cell cultures, which are usually used for in vitro studies, spheroids are three-dimensional (3D) cell cultures that mimic some aspects (e.g., cell-cell interaction, hypoxia, drug penetration or effects of extracellular matrix) of real tissues or tumours (in the case of cancer cell spheroids). Spheroids thus represent a valuable in vitro tool for basic insights into in vivo anticancer activity.

The $[Ir(\eta^5-Cp^{ph})Cl(paza)]PF_6$ complex, containing N1pyridin-2-yl-7-azaindole (paza) as a chelating N,N-donor ligand (136; Fig. 57), exhibited ca. 1.5-fold higher anticancer potency in MCF-7 spheroids than cisplatin; this correlated with the results obtained on 2D cultures of MCF-7 cells. 181 Importantly, the potency of this complex was only slightly lower in 3D (IC₅₀

Fig. 56 A conjugate of complex 135 with poly(2-hydroxypropyl-methacrylamide)-based polymer.

Fig. 57 The structural formula of complex 136.

= 22.9 μ M) than in 2D (IC₅₀ = 6.9 μ M) cultures, which was not the case for other Ir complexes, such as 71, which was markedly less effective in A549 and CH1/PA-1 spheroids (IC₅₀ = 136 and 114 μ M, respectively) than in 2D cultures (IC₅₀ = 1.1 and 0.6 μM, respectively). 194 The authors also reported that benzylsubstituted complex 71 was distributed differently (metabolising cells on the surface of the spheroid) than its methyl analogue (necrotic cells in the spheroid core), based on laser ablation-ICP-MS studies.

Complex 26 (Fig. 7) was less effective against 3D spheroids of SCC070 cells, representing a stemness pathway-activated oral squamous cell carcinoma (OSCC), than co-studied Ru complexes. 92 The lower activity of 26 than that observed for the best-performing Ru compounds is discussed as being connected to the lower potency for inhibiting stemness gene expression (miRNA studies).

Dichlorido complexes with various monodentate diphenylphospane derivatives (e.g., 11; Fig. 4), as well as heterometallic analogue 98, were effective in 3D spheroids of A549 and DU-145 cancer cells (IC₅₀ not specified). 57,60,246

Other types of biological activity

Besides widely studied anticancer Ir(III) cyclopentadienyl complexes, fewer studies have been dealing with the antimicrobial activity of such compounds, and only a few investigations have been dedicated to research on different types of biological activity (antioxidant activity, treatment of Alzheimer's disease) exhibited by Ir-Cpx complexes.

Antimicrobial activity

Many microbial (bacterial, fungal) infections are connected with problems of resistance towards the drugs used (e.g., bacteria against antibiotics). Microbial resistance to conventional and many newly developed drugs has raised considerable interest in research on new classes of antimicrobial agents. The application of transition metal complexes derived from various d-block elements seems to be a reasonable research and development strategy. 297-299 In contrast to organic antimicrobial compounds, metal complexes offer a variety of structural types thanks to various oxidation states and coordination numbers of the studied complexes.

The first report on the antimicrobial activity of Ir-Cp^x complexes dates back to 2010, but the $[Ir(\eta^5-Cp^*)Cl(qui)]$ (34; Fig. 9) complex was insufficiently active against Gram positive (+ve) strains, Staphylococcus aureus, Micrococcus luteus, Enterococcus faecalis and Staphylococcus epidermidis, and even inactive against Gram negative (-ve) strains, Escherichia coli, Klebsiella pneumoniae and Pseudomonas aeruginosa. 144

Later, most of the structural types of Ir-Cpx complexes that were discussed in Section 3 for anticancer activity were also investigated for antimicrobial activity. Specifically, mononuclear dichlorido complexes (137),300 mononuclear chlorido complexes with bidentate N,N- (138),³⁰¹ N,O- (34),¹⁴⁴ N,S- (139),³⁰² C,N- (140)³⁰³ or O,O- (141)³⁰⁴ donor chelating ligands, and homometallic (142)305 and heterometallic (143)236 multinuclear complexes were tested for their antimicrobial activity (Fig. 58).

Similar to the anticancer Ir-Cp^x complexes, in some cases, their antimicrobial analogues have been described with a basic description of their MoA and a discussion of the SAR. For example, various processes known to be related to the MoA of biologically (anticancer and antimicrobial) active Ir-Cp^x complexes have been studied. Examples include stability hydrolysis, 131,306 studies and DNA interaction

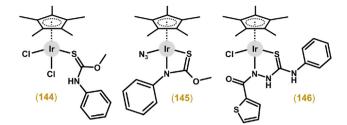
Fig. 58 Structural formulas of complexes 137-143 studied for their antimicrobial activity

cleavage, 128,129,252,300 or NAD(H) transfer hydrogenations. 285,286 Regarding SARs, the influence of the cyclopentadienyl ring (Cp*, Cp^{ph}, Cp^{bph}), 131,301,306 the monodentate ligand (chlorido vs. bromido and iodido), 306 the central atom (Ir vs. Ru, Rh, Os other d-block metals)^{301,307} and the donor set effect^{286,308,309} has been studied in the context of antimicrobial Ir-Cpx complexes. In some works, the authors also paid appropriate attention to safety and toxicity, usually studied as the potency towards normal (healthy) cells, 83,131,286,306,310 or by using advanced models. 128,129,301,306,311,312 A detailed overview and relevant discussion of this field are beyond the scope of this text.

7.2. Antioxidant activity

Antioxidant activity refers to the ability of a compound to neutralize free radicals by the transfer of electrons. In the body (cells), antioxidants help to protect cells from oxidative stress, which is known to be associated with various diseases, including cancer or neurodegenerative disorders.

The $[Ir(\eta^5-Cp^*)Cl_2(pct^1)]$ (144; Fig. 59) complex, which involves monodentate S-donor O-methyl phenylcarbamothioate (pct¹) and has higher antimicrobial activity than the reference drug kanamycin, was also studied for its antioxidant activity by the DPPH free radical scavenging method (DPPH = 1,1-diphenyl-2-picryl-hydrazyl). 313 Its DPPH radical scavenging activity (DRSA) was 90% (tested at 1 mg mL⁻¹ concentration),



Structural formulas of complexes 144-146 studied for their antioxidant activity.

which was comparable with the reference compound used (ASA). Similar antioxidant potency (92%) was reached by the electroneutral azido $[Ir(\eta^5-Cp^*)(pct^1)(N_3)]$ (145; Fig. 59) complex with a bidentate N,S-coordinated pct1 ligand. Also of interest, within both series of these dichlorido and azido complexes, the extent of antioxidant activity followed the order of Ir \gg Ru > Rh.

The same order of antioxidant activity was observed for Ir, Rh and Ru chlorido complexes containing a coumarin-N-acylhydrazone hybrid ligand.314 A similar Ir-Cp* complex containing 3-methoxy-benzhydrazide showed the highest DPPHscavenging ability, which was almost of the same level as that for the positive control (ASA) and higher than those of the Ru and Rh analogues and the co-studied Ir complex containing a different chelating N,O-ligand 4-hydroxy-(i.e., benzhydrazide).315

The next study by the same research group reported on a similar series of dichlorido and diazido complexes and showed that the dichlorido complexes were inactive in the antioxidant activity screening, while diazido complexes showed some DPPH scavenging activity.316 Remarkably, the Ir diazido complex containing a benzothiazole-based ligand was markedly less effective than its Rh analogue, but in the case of Ir and Rh complexes with a benzimidazole-based ligand, their antioxidant effect was comparable.

Within extensive series of Ru, Rh and Ir complexes with various thiourea-based N,S-donor ligands, it was the Ir complexes (e.g., 146 in Fig. 59) that outperformed their analogues, since they showed remarkable antioxidant activity almost as high as the positive control (ASA).317 Similar results were reported for complexes involving 3-acetyl-coumarin-substituted TSC.318 Within dinuclear Ir and Rh complexes containing a salicylaldehyde based TSC bridging ligand, Rh complexes exhibited slightly higher antioxidant activity.319

In some cases, the antioxidant activity was negligible, as reported for a series of antimicrobial active Ir complexes with various monodentate N-donor pyridine-4-carbothioamides³²⁰ or other ligands. 141,321

7.3. Alzheimer's disease

Alzheimer's disease (AD) is an incurable neurodegenerative brain disorder and one of the most common causes of dementia. The lack of effective drugs motivates medicinal chemists to develop and investigate potential drugs for the treatment of

AD. Among them, various types of transition metal complexes have been reported.322 It is known that the aggregation of amyloid-β (Aβ) peptides is directly connected to AD pathogenesis, which is why Aß aggregates represent an important target for newly developed AD drugs.

Regarding Ir cyclopentadienyl complexes, probably the only report on these complexes and their inhibition of Aβ aggregation was published by Barnham, Ruiz and co-workers in 2015. 323 In this study, the [Ir(η^5 -Cp*)(bzim 1)Cl]PF₆ (48; Fig. 60) complex was studied together with the Ru analogue, [Ru(n⁶pcym)(bzim¹)Cl]PF₆, and Pt complex, [Pt(bzim¹)Cl₂]. Although all three complexes inhibited Aβ aggregation effectively, it was only the Ir complex 48 that protected the primary cortical neurons from the neurotoxic effects of AB. Earlier, 48 was also reported to be highly effective against various cancer cells (section 3.2.3).166

7.4. Platelets

Platelets (thrombocytes) are small fragments of cells in the blood that play a critical role in preventing bleeding by forming clots. They also play a role in arterial thrombosis and cancer metastasis. The $[Ir(\eta^5-Cp^*)Cl(pip)]BF_4$ (147; Fig. 61) complex, derived from 1-(pyridin-2-yl)imidazo[1,5-a]pyridine derivative (pip), was studied as a potential antiplatelet drug.³²⁴ 147 efficiently inhibited the collagen-stimulated aggregation of the patient-derived platelets, even in the presence of known inhibitors of this process. The complex also interfered with other associated processes, such as ATP release, intracellular Ca²⁺ mobilization or the phosphorylation of various regulatory proteins (e.g., Akt, p38, MAPK or JNK1). 147 influenced the bleeding time in the tail transection model of mice. Specifically, the bleeding time was prolonged to 323 s (2 mg

Fig. 60 Structural formulas of complexes 48 and 133.

Fig. 61 The structural formula of complex 147.

kg⁻¹ dose of 147; no rebleeding observed) from 151 s observed for the control group. The observed results are promising in terms of possible prevention or treatment of thromboembolic disorders or disruption of tumorigenic or pro-metastatic interactions between platelets and tumour cells.

8. Conclusion

This work provides the reader with an overview of the current knowledge on anticancer iridium(III) cyclopentadienyl (Ir-Cp^x) complexes. Although the structure of Ir-Cpx complexes is rather strict (i.e., a Cp^x ligand and three additional positions), various synthetic approaches can be used to modify their (bio) chemical and biological properties, including reactivity and anticancer activity. Over the years, various structural types of Ir-Cpx complexes have been developed and studied for their anticancer activity, which are categorized in the text according to their nuclearity, number of coordinated ligands, and type of donor atom, allowing for a detailed discussion of the SARs. In this regard, the development of Ir-Cpx complexes involving an extended cyclopentadienyl ligand (e.g., Cpbph), a C,N-donor chelating ligand, and a kinetically stable monodentate ligand (e.g., pyridine or its derivatives) appears to be a suitable strategy for the development of novel bioactive Ir-Cpx complexes. The MoA of anticancer Ir-Cpx complexes, although still not fully understood, differs not only from that of Pt drugs but also from those of the structurally similar half-sandwich Ru(II), Rh(III) and Os(II) analogues; this highlights their potential for novel therapeutic approaches. Importantly, several representatives have also been shown to be highly active in vivo, either alone or advantageously as a cargo in various drug delivery systems. The reviewed results and findings clearly indicate that the research and development of novel Ir-Cpx complexes is a viable strategy in the field of bioinorganic, bioorganometallic and medicinal chemistry, as many of the reviewed Ir-Cpx complexes meet the basic criteria for new alternatives to conventional anticancer platinum-based drugs.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the Czech Health Research Council of the Ministry of Health of the Czech Republic (AZV Project NU22-08-00236).

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