Synthesis and antiproliferative evaluation of new isomeric ellipticine quinones

[Síntesis y evaluación de la actividad antiproliferativa de nuevas elipticinaquinonas isoméricas]

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Abstract: The synthesis of new isomeric ellipticine quinones 3a-c and their in vitro antiproliferative activities on cancer cell lines is reported. The designed N-heterocyclic quinones 3a-c were synthesized through a three step sequence which involves: a) one-pot preparation of 4-methoxycarbonyl-3,4-dimethyldioquinoline-5,8-quinone 1 from 2,5-dihydroxycetophenone, methyl aminocrotonate and silver (II) oxide; b) regioselective amination of 1 with arylamines to give aminooquinones 2a-c and c) palladium-catalyzed intramolecular oxidative coupling of 7-aminooquinoline-5,8-quinones 2a-c. The in vitro antiproliferative activity of the new angular quinones was evaluated against one normal cell line (lung fibroblasts) and gastric, lung and bladder cancer cell lines in 72-h drug exposure assays. The new compounds displayed similar or higher antiproliferative activity with respect to their quinone precursors 2a-c. The isomeric ellipticine quinone 2b appears as the more active member on bladder cancer cell line (IC50: 2.4 µM), comparable to etoposide used as anticancer reference drug.

Keywords: Ellipticine; quinones; oxidative coupling; antiproliferative activity

Resumen: Se describe la síntesis de las nuevas quinonas 3a-c, isoméricas de elipticina, y sus actividades antiproliferativas in vitro en líneas de células de cáncer. Las quinonas N-heterocíclicas 3a-c se sintetizaron a través de una secuencia que involucra: a) preparación de 4-metoxicarbonil-3,4-dimetiloxiquinolina-5,8-quinona 1 a partir de 2,5-dihidroxicetofenona, metilo aminocrotonato y óxido de plata (II); b) aminación regioselectiva de 1 con arilaminas para producir las aminooquinonas 2a-c y c) acoplamiento oxidante intramolecular de 7-aminooquinolina-5,8-quinonas 2a-c catalizado con paladio. La actividad antiproliferativa in vitro de los nuevos compuestos fue evaluada en una línea celular normal (fibroblastos de pulmón) y líneas de células de cáncer gástrico, pulmón y vejiga en ensayos de exposición de 72 horas a la droga. Las quinonas 3a-c exhiben interesantes propiedades antiproliferativas destacando la elipticinaquinona isomérica 2b en células de cáncer de vejiga (IC50: 2.4 µM) comparado con etoposide usada como droga anticáncer de referencia. Los nuevos compuestos mostraron actividades antiproliferativa similar o mayor respecto de las correspondientes quinonas precursoras 2a-c. La elipticina quinona isomérica 2b corresponde al miembro más activo en células de cáncer de vejiga (IC50: 2.4 µM), comparable a la del etopósido, usada como droga anticáncer de referencia.

Palabras clave: Ellipticina; quinonas; acoplamiento oxidante; actividad antiproliferativa.
INTRODUCTION
Quinone moieties are present in many drugs such as doxorubicin, mitomycin, mitoxantrone, and saintopin, which are used clinically in the therapy of solid cancers. Anticancer quinones are currently the focus of intensive research because of their biological activity and complex modes of action, which differ depending on their particular structure. A number of natural and synthetic heterocyclic quinones have important biological activities such as antitumoral, antiprotozoan, and antibiotic activities (Tsizin et al., 1978; Bass et al., 2013). Many of these compounds possess antineoplastic chemotherapeutic properties (Kock et al., 2005). Among them, carbazolequinone alkaloids (Figura 1) exhibit notable biological properties such as cardiotonic, antituberculosis, and neuronal cell-protecting activities (Shin-Ya et al., 1997; Kazumi et al., 1989; Knölker et al., 2003; Choi et al., 2006; Choi et al., 2008). Pyrido- and quinolinocarbazole alkaloids (Figure 1) are also well-known for their wide range of potent biological activities (Gribble et al., 1990; Knölker et al., 2008). Ellipticine (5,11-dimethyl-6H-pyrido[4,3- b]carbazole) and 9-methoxyellipticine (Figure 1) were isolated from the leaves of Ochrosia elliptica Labill by Goodwin (Goodwin et al., 1959). The biological activity of ellipticine was considered to be based mainly on DNA intercalation and topoisomerase II inhibition. The first clinical success of celiptium (Figura 1) (Juret et al., 1978; Paoletti et al., 1980; Dodion et al., 1982; Juret et al., 1982; Clarysse et al., 1984) led to extensive studies into the synthesis of ellipticinium derivatives, and several of these progressed to clinical trials (Rouesse et al., 1985; Ohashi & Oki, 1996). Since the commercialization of some ellipticine derivatives and their successful clinical uses prompted tremendous development in the chemistry and biology of pyridocarbazole alkaloids.

Figure 1
Structure of ellipticine and some analogues

R = H, Ellipticine
R = OMe, 9-Methoxyellipticine

Calothrixin B

Ellipticine quinone
Ellipticine quinone (Gribble et al., 1984; Kecha et al., 1985; Bennasar et al., 2005) is a pivotal synthetic intermediate in the early Gribble syntheses of ellipticines that shows antitumor activity (Bernardo et al., 2004).

The only known quinolino[4,3-b]carbazole alkaloid, calothrixin B (Figure 1) (7H-indolo[3,2-j]phenanthridine-7,13(12H)-dione), was first obtained from a blue-green algae Calothrix cyanobacteria in 1999 (Rickards et al., 1999). It is a pentacyclic quinone that exhibits antimalarial activity as well as activity against human HeLa cancer cells and inhibition of RNA polymerase (Chen et al., 2003; Khan et al., 2009).

Based on the above precedents and recent results in the high yield synthesis of antiproliferative phenylaminoisoquinoline-5,8-quinones endowed with in vitro topoisomerase I inhibition ability (Valderrama et al., 2009; Monsalve et al., 2012), we were interested to synthesize new isomeric ellipticine quinones to evaluate their in vitro antiproliferative activity on a panel of three cancer cell lines.

MATERIALS AND METHODS

General

All reagents and solvents were commercially available reagent grade. Melting points were determined on a Stuart Scientific SMP3 apparatus and are uncorrected. 1H-NMR spectra were recorded on Bruker AM-200 and AM-400 instruments in CDCl3 + DMSO-d6. 13C-NMR spectra were obtained at 50 and 100 MHz in CDCl3 + DMSO-d6. Chemical shifts are expressed in δ ppm downfield relative to TMS, and the coupling constants (J) are reported in Hertz. The HRMS were obtained on a Thermo Finnigan spectrometer, model MAT 95XP. Silica gel Merck 60 (70–230 mesh) was used for preparative column chromatography, and TLC aluminum foil 60F254 for analytical TLC.

Chemistry

Synthesis of 1,3-Dimethyl-4-methoxycarbonylisoquinoline-5,8-quinone 1:

A suspension of 2,5-dihydroxyacetophenone (1.0 mmol), silver(II) oxide (2.2 mmol), and MgSO4 (1g) and dichloromethane (25 mL) was stirred for 1 h. Silver (II) oxide (2.2 mmol) was added to the mixture and the stirring was continued for 90 min. The mixture was filtered and the solvent was removed to yield crude quinone 1 (231 mg, 94%) which was chromatographed on silica gel (9:1 dichloromethane/ethyl acetate) to yield pure quinone 1 (74%).

Synthesis of 7-aminooisoquinolinequinone derivatives 2a-c:

A suspension of quinone 1 (1 mmol), the required arylamine (2 mmol), CeCl3.7H2O (0.05 mmol), and ethanol (20 mL) was left with stirring at rt after completion of the reaction as indicated by TLC. The reaction mixture was partitioned between chloroform/water, the organic extract was washed with water (2 x 15 mL), dried over Na2SO4, and evaporated under reduced pressure. The residue was column chromatographed over silica gel (CH2Cl2/ethyl acetate 90:10) to yield the corresponding aminoquinones 2a, 2b and 2c in 93%, 89% and 90% yield respectively. The spectral properties of the compounds 2a-c (1H, 13C RMN) were comparable with those previously described for these compounds (Valderrama et al., 2006).

Synthesis of pyrido[3,4-b]carbazole-5,11-dione derivatives 3a-c:

A suspension of the aminooisoquinolinequinone 2a, 2b or 3c (1 mmol), Pd(OAc)2 (1.2 mmol) and glacial acetic (5mL) was refluxed under nitrogen atmosphere after completion of the reaction as indicated by TLC. The reaction mixture was cooled, neutralized with solid sodium hydrogencarbonate and filtered. The filtrate was diluted with water (20 mL) and then extracted with ethyl acetate (2 x 15 mL). The organic extract was chromatographed on silica gel (CH2Cl2) to give the pyrido[3,4-b]carbazole-5,11-dione derivatives 3a-c.

Methyl 1,3-dimethyl-5,11-dioxo-10,11-dihydro-5H-pyrido[3,4-b]carbazole-4-carboxylate 3a:

Orange solid (60% yield), mp 108.5-110°C; IR: νmax 3317 (NH), 1725 (C=O quinone); 1H RMN (400 MHz, CDCl3 + DMSO-d6): δ 2.62 (s, 3H, 3-Me), 7.08 (s, 3H, 1-Me), 4.10 (s, 3H, CO2Me), 7.43 (m, 2H, arom.), 7.50 (d, J = 8.0 Hz, 1H, arom.), 8.26 (d, J = 8.0 Hz, 1H, arom.), 9.62 (s, 1H, NH). 13C NMR (400 MHz, CDCl3 + DMSO-d6): δ 22.7, 26.0, 53.0, 113.8, 116.9, 121.7, 123.2, 124.1, 124.3, 125.8, 127.2, 138.0, 138.5, 139.5, 160.0, 160.6, 169.6, 178.7, 178.7. HRMS (APCI): [M+] calcd for C19H14N2O4: 334.09536; found: 334.09484.
Methyl 7-methoxy-1,3-dimethyl-5,11-dioxo-10,11-dihydro-5H-pyrido[3,4-b]carbazole-4-carboxylate 3b:
Red solid (53% yield), mp 233-234°C; IR: \( \nu_{\text{max}} \) 3283 (NH), 1726 (C=O), 1667 and 1657 (C=O quinone); \(^1\)H RMN (400 MHz, CDCl\(_3\) + DMSO-d\(_6\)): \( \delta \) 2.61 (s, 3H, 3-Me), 3.02 (s, 3H, 1-Me), 3.89 (s, 3H, OMe), 4.10 (s, 3H, CO\(_2\)Me), 7.06 (d, \( J = 9.0 \) Hz, 1H, aram), 8.38 (d, \( J = 9.0 \) Hz, 1H, aram), 9.45 (s, 1H, NH). \(^{13}\)C NMR (400 MHz, CDCl\(_3\) + DMSO-d\(_6\)): \( \delta \) 22.8, 30.9, 53.4, 55.8, 103.2, 114.2, 119.9, 121.9, 125.3, 126.0, 132.6, 137.3, 139.3, 157.9, 160.5, 160.9, 169.7, 178.1, 178.8. HRMS (APCI): [M+] calcd for C\(_{25}\)H\(_{28}\)N\(_3\)O\(_4\): 394.1153; found: 394.1153.

Methyl 6,9-dimethoxy-1,3-dimethyl-5,11-dioxo-10,11-dihydro-5H-pyrido[3,4-b]carbazole-4-carboxylate 3c:
Purple solid (49% yield), mp 245.5 - 247.5 °C; IR: \( \nu_{\text{max}} \) 3242 (NH), 1727 (C=O), 1668 and 1659 (C=O quinone); \(^1\)H RMN (400 MHz, CDCl\(_3\) + DMSO-d\(_6\)): \( \delta \) 2.94 (s, 3H, 3-Me), 3.33 (s, 3H, 1-Me), 3.83 (s, 3H, OMe), 3.90 (s, 3H, OMe), 3.93 (s, 3H, CO\(_2\)Me), 6.67 (d, \( J = 8.6 \) Hz, 1H, aram), 6.88 (d, \( J = 8.6 \) Hz, 1H, aram), 8.26 (s, 1H, NH). \(^{13}\)C NMR (400 MHz, CDCl\(_3\) + DMSO-d\(_6\)): \( \delta \) 22.1, 26.0, 53.0, 56.5, 56.7, 104.9, 108.1, 116.3, 125.9 (2C), 130.9, 138.5 (2C), 142.1, 149.3, 159.4, 159.9, 169.2, 176.6, 178.1. HRMS (APCI): [M+] calcd for C\(_{21}\)H\(_{18}\)N\(_2\)O\(_6\): 394.11649; found: 394.1153.

Electrochemical Measurement (Prieto et al., 2007)
Cyclic voltammograms of compounds were obtained on a Bioanalytical System BAS CV-50W electrochemical analyzer. A small capacity measuring cell was equipped with a platinum disc as working electrode, an Ag/10 nM Ag (MeCN) reference electrode for non aqueous solvent, with a platinum wire auxiliary electrode, a mechanical mini-stirrer, and a capillary to supply an inert argon atmosphere. A 0.1 M solution of tetraethylammonium tetrafluoroborate in acetonitrile was used as supporting electrolyte.

Anticancer assay (Rodríguez et al., 1999)
The cell lines used in this work were obtained from the American Type Culture Collection (ATCC, Manasas, VA, USA). They included MRC-5 normal human fibroblasts (CC-171), AGS human gastric adenocarcinoma cells (CRL-1739), SK-MES-1 human lung cancer cells (HTB-58, and J82 human bladder carcinoma cells (HTB-1). After the arrival of the cells, they were proliferated in the corresponding culture medium as suggested by the ATCC. The cells were stored in medium containing 10% glycerol in liquid nitrogen. The viability of the cells after thawing was higher than 90% assessed by trypan blue exclusion test. Cells were sub-cultured once a week and medium was changed every two days. Cells were grown in the following media: MRC-5, SK-MES-1, and J82 in MEM, and AGS cells in Ham F-12. The MEM medium contained 2 mM \( L \)-glutamine, 1 mM sodium pyruvate, and 1.5 g/L sodium hydrogen carbonate. Ham F-12 was supplemented with 2 mM \( L \)-glutamine and 1.5 g/L sodium hydrogen carbonate. All media were supplemented with 10% heat-inactivated FBS, 100 IU/mL penicillin, and 100 µg/mL streptomycin in a humidified incubator with 5% CO\(_2\) in air at 37 °C. For the experiments, cells were plated at a density of 50,000 cells/mL in 96-well plated. One day after seeding, the cells were treated with the medium containing the compounds at concentrations ranging from 0 to 100 µM during 3 days, and finally the MTT reduction assay was carried out. The final concentration of MTT was 1 mg/mL. The compounds were dissolved in DMSO (1% final concentration) and complete medium. Untreated cells (medium containing 1% DMSO) were used as controls. Each experiment was carried out in sextuplicate.

RESULTS AND DISCUSSION
We explore the access to isomeric ellipticine quinones from phenylaminoisoquinolinequinones by using a well-documented carbazolequinone synthetic method based on the palladium-catalyzed intramolecular oxidative coupling reaction of arylamino-1,4-quinones (Akerman et al., 1975). This method has been successfully employed for the synthesis of ellipticine and related alkaloids from diarylamines (Miller & Mook, 1980; Motoi et al., 1991; Knölker & Fröhener, 1998). The entry to the target isomeric ellipticine quinones \(3a-c\) was planned from aminooisoquinoline-5,8-quinones \(2a-c\) by using the palladium-catalyzed oxidative coupling reaction. The elected aminooisoquinoline-5,8-quinones \(2a-c\) were prepared from isoquinolinequinone 1 which in turn was synthesized through a previously reported one pot procedure from 2,5-dihydroacetophenone, methyl aminocrotonate and silver (II) oxide (Valderrama et al., 2006). Scheme 1 outlined the reaction sequence to prepare the ellipticine quinones \(3a-c\).
The oxidative cyclization of 2a to pyridocarbazolquinone 3a was examined by using stoichiometric amounts of Pd(OAc)$_2$ in glacial acetic acid at reflux. After several trials the cyclization products 3a-3c were isolated in 60, 53 and 49% yields respectively.

The structure of the new compounds 3a-c were fully established by mean of their $^1$H/$^{13}$C NMR and high resolution mass spectra.

Scheme 1
Synthesis of isomeric ellipticine quinones 3a-c

The redox potentials of compounds 3a-c were measured by cyclic voltammetry in acetonitrile as solvent, at room temperature, using a platinum electrode and 0.1 M tetraethylammonium tetrafluoroborate as the supporting electrolyte (Prieto et al., 2007). All compounds show two one-electron reduction waves to form the corresponding anion-radical and dianion. The first half-wave potential values, $E^{1/2}$, evaluated from the voltammograms, are summarized in Table 1. The data indicate that the $E^{1/2}$ values for the first electron, which is related with the formation of the semiquinone radical anion, are in the potential range 578-624 mV. Comparison of the half wave potentials of 3a and 3b with those of their respective precursors 2a and 2b indicate that reduction of the products are located at a more positive region with respect to their precursors. The results revealed that the donor-acceptor interactions between the isoquinolinequinone nucleus (acceptor) and the arylamine group (donor) in 2a and 2b is more favorable than that of the acceptor with the fused indole fragment in compounds 3a and 3b. In the case of quinone 3c and its precursor 2c it was observed that the interaction of the acceptor with their respective donors is more favorable in 3c than 2c.
Table 1
Electrochemical potentials of compounds 2a-c and 3a-c.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Compound</th>
<th>R^1</th>
<th>R^2</th>
<th>R^3</th>
<th>-E^1/2 (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Structure" /></td>
<td>2a</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>592</td>
</tr>
<tr>
<td><img src="image" alt="Structure" /></td>
<td>2b</td>
<td>H</td>
<td>OMe</td>
<td>H</td>
<td>622</td>
</tr>
<tr>
<td><img src="image" alt="Structure" /></td>
<td>2c</td>
<td>OMe</td>
<td>H</td>
<td>OMe</td>
<td>573</td>
</tr>
<tr>
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<td>3a</td>
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<td>578</td>
</tr>
<tr>
<td><img src="image" alt="Structure" /></td>
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<td>H</td>
<td>OMe</td>
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<td>588</td>
</tr>
<tr>
<td><img src="image" alt="Structure" /></td>
<td>3c</td>
<td>OMe</td>
<td>H</td>
<td>OMe</td>
<td>624</td>
</tr>
</tbody>
</table>

The newly synthesized isomeric ellipticine quinones 3a-c were evaluated for their in vitro anticancer activities against human normal cell: MRC-5 human lung fibroblasts and three human tumor cells: AGS gastric adenocarcinoma, SK-MES-1 lung cancer, and J82 bladder carcinoma, in 72 h drug exposure MTT assays. Etoposide, a clinically used anticancer agent, was used as a positive control. The antiproliferative activity of the compounds was measured using a conventional microculture tetrazolium reduction assay (Scudiero et al., 1988; Van de Loosdrecht et al., 1994). The antiproliferative activities by each of the heterocyclic quinones are expressed in terms of IC_{50} (Table 2). The previously reported antiproliferative activity of arylaminoisoquinolinequinone 2a-c were included in Table 2 together with those of their cyclization products 3a-c to get information on the differences in the antiproliferative activity as consequence of the eventual redox cycling and/or DNA-binding biological mechanism.

Table 2
Antiproliferative activity of isomeric ellipticine quinones 3a-c and its precursors 2a-c

<table>
<thead>
<tr>
<th>N°</th>
<th>R^1</th>
<th>R^2</th>
<th>R^3</th>
<th>MRC-5^b</th>
<th>AGS^c</th>
<th>SK-MES-1^d</th>
<th>J82^e</th>
</tr>
</thead>
<tbody>
<tr>
<td>2a</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>5.6</td>
<td>2.1</td>
<td>4.2</td>
<td>5.8</td>
</tr>
<tr>
<td>2b</td>
<td>H</td>
<td>OMe</td>
<td>H</td>
<td>9.0</td>
<td>2.3</td>
<td>7.2</td>
<td>7.4</td>
</tr>
<tr>
<td>2c</td>
<td>OMe</td>
<td>H</td>
<td>OMe</td>
<td>31.3</td>
<td>19.9</td>
<td>&gt;100</td>
<td>&gt;100</td>
</tr>
<tr>
<td>3a</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>2.4</td>
<td>1.2</td>
<td>3.9</td>
<td>2.9</td>
</tr>
<tr>
<td>3b</td>
<td>H</td>
<td>OMe</td>
<td>H</td>
<td>2.5</td>
<td>2.4</td>
<td>7.5</td>
<td>2.4</td>
</tr>
<tr>
<td>3c</td>
<td>OMe</td>
<td>H</td>
<td>OMe</td>
<td>&gt;100</td>
<td>38.6</td>
<td>33.9</td>
<td>&gt;100</td>
</tr>
<tr>
<td></td>
<td>Etoposide</td>
<td></td>
<td></td>
<td>3.9 ± 0.2</td>
<td>0.36 ± 0.02</td>
<td>2.5 ± 0.2</td>
<td>2.8 ± 0.2</td>
</tr>
</tbody>
</table>

a Data represent mean average values for six independent determinations.
b Human lung fibroblasts cells.
c Human gastric adenocarcinoma cell line.
d Human lung cancer cell line.
e Human bladder carcinoma cell line.
The screening showed that compounds 3a-c exhibit significant antitumor activity in the range IC_{50}: 1.2-38.9 µM. As indicated in Table 2, the antitumor activity of compounds 3a and 3b on bladder cancer cells were comparable to that shown by the reference drug etoposide (IC_{50} = 2.8 µM). Comparison between the IC_{50} and E_{1/2} values, indicate that for compounds 3a and 3b, the more positive the E_{1/2} (respect to compounds 2a and 2b) the stronger the antitumor promoting effect on AGS, J82 and SK-MES-1 cell lines. On the contrary, 3b shows less cytotoxic activity in all the cell lines compared to 2b. Analyses of the data revealed that the first reduction potential E_{1/2} is an important parameter determining the antitumoral activity on AGS gastric adenocarcinoma, SK-MES-1 lung adenocarcinoma and J82 bladder carcinoma cell lines.

**CONCLUSIONS**

In conclusion, we have described preliminary results on the synthesis and antiproliferative evaluation of three new isomeric ellipticine quinones. The new quinones expressed moderate to high in vitro antiproliferative activity against three human cancer cell lines: AGS (gastric), SK-MES-1 (lung) and J82 (bladder) cell lines. Compound 3b appears as a promising active compound against bladder cancer cell line, with IC_{50} value at 2.4 µM, comparable to that of the anti-cancer agent etoposide.

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