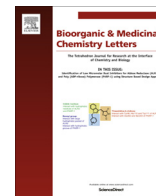




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## Novel non-trimethoxyphenyl piperlongumine derivatives selectively kill cancer cells

Youjun Zhang<sup>a,d</sup>, Hao Ma<sup>a,b,d</sup>, Yuelin Wu<sup>c</sup>, Zhongli Wu<sup>a</sup>, Zhengguang Yao<sup>b</sup>, Wannian Zhang<sup>a,b</sup>, Chunlin Zhuang<sup>a,\*</sup>, Zhenyuan Miao<sup>a,\*</sup>

<sup>a</sup> Second Military Medical University, 800 Xiangyin Road, Shanghai 200433, China

<sup>b</sup> Ningxia Medical University, Yinchuan 750004, China

<sup>c</sup> Shanghai Institute of Technology, 100 Haiquan Road, Shanghai 201418, China

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### ABSTRACT

Piperlongumine (**PL**) is a natural alkaloid with broad biological activities. Twelve analogues have been designed and synthesized with non-substituted benzyl rings or heterocycles in this work. Most of the compounds showed better anticancer activities than the parent **PL** without apparent toxicity in normal cells. Elevation of cellular ROS levels was one of the main anticancer mechanisms of these compounds. Cell apoptosis and cell cycle arrest for the best compound **ZM90** were evaluated and similar mechanism of action with **PL** was demonstrated. The SAR was also characterized, providing worthy directions for further optimization of **PL** compounds.

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Piperlongumine (**PL**, Piplartine, 5,6-dihydro-1-[(2*E*)-1-oxo-3-(3,4,5-trimethoxyphenyl)-2-propenyl]-2(1*H*)-pyridinone, [Scheme 1](#)) is an active alkaloid isolated from the root of plant species *Piper longum* L.<sup>1</sup> The therapeutic potentials include anti-cancer,<sup>2–4</sup> anti-diabetes,<sup>5</sup> antiplatelet aggregation,<sup>6</sup> anti-inflammation,<sup>7,8</sup> anti-fungal activity<sup>9,10</sup> and neurodegenerative diseases.<sup>11</sup> In 2011, Schreiber group reported the **PL** selectively killed cancer cells probably due to elevation of ROS level.<sup>3</sup> However, the exact protein target (s) has not well characterized. Further structure-activity relationship (SAR) study showed the **PL** compounds had two key pharmacophores: C2–C3 and C7–C8 double bonds ([Scheme 1](#), highlighted in red) where contain two classical Michael acceptors.<sup>12</sup> Comparing these two Michael acceptors, the C2–C3 double bond is more reactive with cysteines of the target proteins. Removal of C7–C8 double bond led to a decrease in cytotoxicity without decreasing the ROS level. In 2014, our group further extended the SARs by introducing halogen or morpholine substituents at C2 and alkyl substituents at C7 position.<sup>13</sup> The 2-halogenated piperlongumines (e.g. **ZM30**, [Scheme 1](#)) showed potent *in vitro* and *in vivo* anticancer activities due to its higher reactivity of C2–C3 Michael

acceptor. The 2-morpholine substituted ones ( $IC_{50} > 100 \mu M$ ) were deactivated probably due to steric hindrance. Compound **ZM30** showed better activity than **PL** against A549 cells. However, the selectivity for the cancer cells (cancer cells, A549,  $IC_{50} = 19.83 \mu M$ ; normal cells, MRC-5,  $IC_{50} = 14.30 \mu M$ ) was poor.

Based on above information and SAR study, the importance of the trimethoxyphenyl group has not been evaluated, which appears in lots of natural anticancer agents, such as colchicine and combretastatin A4. Herein, non-substituted benzyl rings and heterocycles were designed to replace the trimethoxyphenyl group ([Scheme 1A](#)). We also proposed to replace the C7–C8 double bond by the bioisosteric groups, such as cyclopropyl group ([Scheme 1B](#)) and triple bond ([Scheme 1C](#)). Removal of the C7–C8 olefin ([Scheme 1D](#)) is another aspect for evaluation.

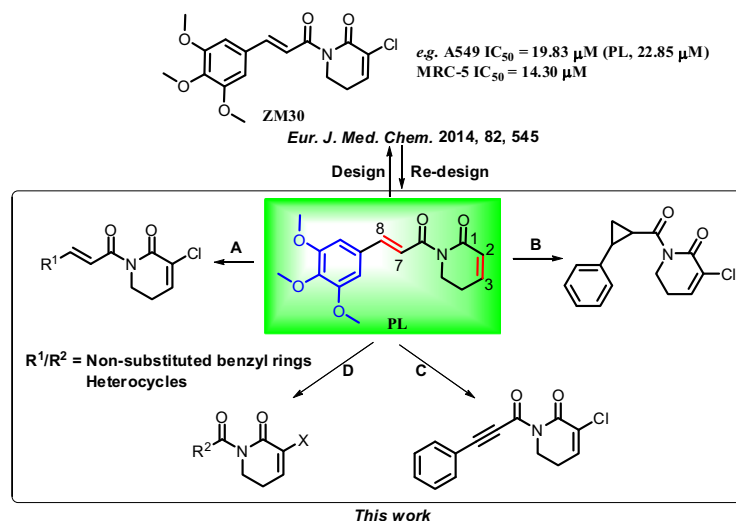
Twelve analogues ([Scheme 2](#)) were obtained to evaluate the *in vitro* cytotoxicity against six cancer cell lines (human lung carcinoma A549, human colorectal carcinoma HCT116, human breast carcinoma MDA-MB-231, human Hepatic adenocarcinoma SK-Hep-1, human osteosarcoma U2OS and Saos-2) and a normal cell line (human lung fibroblast cell lines WI38) by MTT assay. **PL** was used as a reference compound. The  $IC_{50}$  values for each compound are summarized in [Table 1](#).

Overall, most of the novel **PL** analogues showed better cytotoxicity than the parent compound **PL**, except **ZM83**, **ZM85** and **ZM89**.

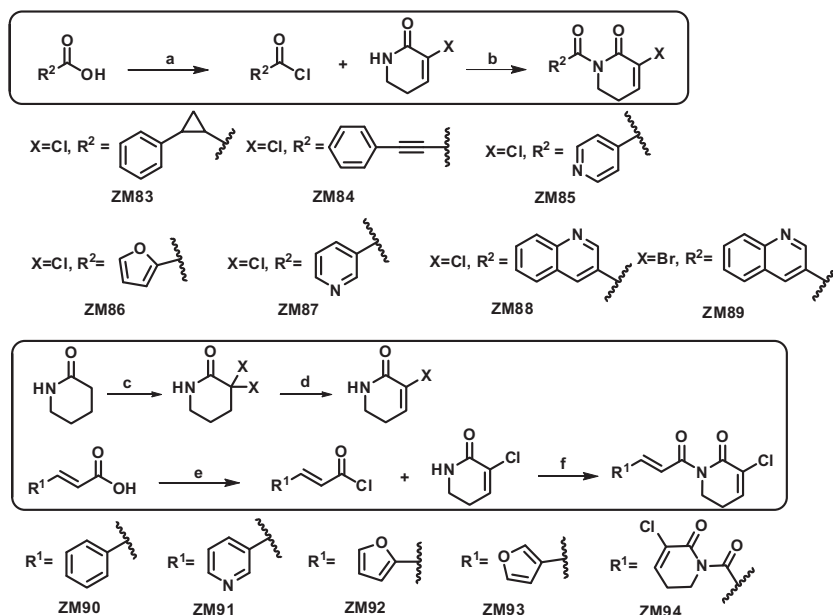
\* Corresponding authors.

E-mail addresses: [zcnathan@163.com](mailto:zcnathan@163.com) (C. Zhuang), [miaozhenyuan@hotmail.com](mailto:miaozhenyuan@hotmail.com) (Z. Miao).

<sup>d</sup> These authors contributed equally to this work.



**Scheme 1.** The design strategy of non-trimethoxyphenyl piperlongumine derivatives.



**Scheme 2.** Conditions and reagents: (a) anhydrous DCM, oxalyl chloride, one drop of DMF, 3 h; (b) anhydrous THF, TEA, room temperature, overnight; (c) For chlorination:  $PCl_5$ ,  $CHCl_3$ ; room temperature, crude product for next step; For bromination,  $PCl_5$ , DCM, 0 °C, then ZnI,  $Br_2$ , room temperature; (d)  $Li_2CO_3$ , LiCl, anhydrous DMF, 130 °C, 7 h; (e) anhydrous DCM, oxalyl chloride, one drop of DMF, 3 h; (f) anhydrous THF, TEA, room temperature, overnight.

These compounds were sensitive to human osteosarcoma cells with the  $IC_{50}$  values in nanomolar or low micromolar range. To our delight, all the compounds show no apparent cytotoxicity against normal cells, recovering the selectivity of **PL**. The SAR study demonstrated the following results: (1) The trimethoxyl group was removed from **ZM30** to obtain **ZM90**. This compound showed excellent cytotoxicity against all the six cell lines, especially the SK-Hep-1 ( $IC_{50}$  = 710 nM) and Saos-2 ( $IC_{50}$  = 11 nM), with only 84.6  $\mu$ M of the normal WI38 cells. This result indicated that the trimethoxyl group is not a pharmacophore for the **PL** compounds. (2) **ZM84** with triple bond showed excellent cytotoxicity against five cell lines ( $IC_{50}$  = 420–1730 nM) except A549. (3) The heterocycle-substituted **PL** compounds (**ZM91–94**) exhibited good activities. **ZM91** with 3-pyridinyl group was potent against the six cell lines ( $IC_{50}$  = 530–2970 nM). The activities of **ZM92** with 2-furyl, **ZM93** with 3-furyl and **ZM94** with double 2-halo-lactams were comparable with that of **PL** towards A549 cells. For the other five cell lines,

they showed 2–9-fold better activities than **PL**. (4) Removal of the C7–C8 olefin to directly connect the chlorides to the lactam was unfavorable to the cytotoxicity. Compared with **ZM91** and **ZM87**, the C7–C8 olefin was removed, leading to 2–5-fold decrease in the cytotoxicity. Compounds **ZM85** and **ZM87–89** showed moderate cytotoxicity.

To summarize the SAR, C7–C8 olefin is of great importance to the cytotoxicity. The alkynyl was compatible to replace the double bond but not for the cyclopropyl group. The enhancement of the molecular flexibility or disruption of the conjugated system of  $\alpha$ ,  $\beta$ -unsaturated system were proposed to be the main reasons. Moreover, the trimethoxyl group is not a critical pharmacophore to the **PL** analogues.

It is reported that the antitumor mechanism of **PL** is to increase the level of ROS and apoptotic cell death.<sup>3</sup> We further evaluated the cellular ROS levels of the most potent compounds (**ZM84**, **ZM90**, and **ZM91**) using two sensitive cancer cell lines (HCT-116 and

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