Meisoindigo inhibits cellular proliferation via down-regulation of the PI3K/Akt pathway and induces cellular apoptosis in glioblastoma U87 cells

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Objective: The current study was to explore whether meisoindigo was effective in suppressing proliferation and inducing apoptosis of human glioblastoma multiforme U87 cells and to explore its possible mechanisms.

Method: Morphological changes were observed by light microscopy. Cell counting kit-8 (CCK-8) assay was performed to detect cellular proliferation. Apoptosis was monitored by flow cytometry. Akt, phospho-Akt, PI3K, p65, phospho-p65 and apoptosis-related proteins caspase-3 and caspase-9 were examined by Western blotting assays. Immunofluorescence was used to evaluate level of P65 expression in cells. Result: Meisoindigo inhibited the proliferation of U87 cells, and the inhibitory effect increased in a dose dependent manner. Moreover, meisoindigo exposure triggered an increase in the level of caspase-3 and caspase-9, supporting its role in the activation of apoptosis. Furthermore, meisoindigo reduced the expression of PI3K, Akt, phospho-Akt, NF-κB, p65 and phospho-p65 in U87 cells, and displacement of p65 from the nucleus to the cytoplasm. Conclusion: Meisoindigo inhibits proliferation and induces apoptosis of U87 cells, probably through down-regulating the PI3K/Akt pathway and reducing nuclear translocation of NF-κB p65.

Keywords: meisoindigo, glioblastoma, cell proliferation, apoptosis, NF-κB

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Abbreviations: CCK-8, Cell counting kit-8; CML, chronic myeloid leukemia; GBM, glioblastoma multiforme; WHO, World Health Organization; TMZ, temozolomide

INTRODUCTION

There are multiple grades of gliomas – grade II, III and IV, with grade IV being the most malignant. Glioblastoma, sometimes referred to as glioblastoma multiforme (GBM), considered as grade IV tumor according to the World Health Organization (WHO) classification, is believed to be the most frequent and the highest malignant histological subtype glioma (Wirsching et al., 2016). It is well known for its “three-high and one-low” characteristics, which means a high incidence, a high mortality, and a high recurrence rate and a low cure rate, and it serious effects on human health (Nayak & Reardon, 2017). Nowadays, the standard treatment for glioblastoma is surgery followed by chemotherapy based on temozolomide (TMZ) and radiotherapy, which leads to poor patient survival. However, the prognosis for this disease continues to be bleak, with a mean survival of only 15 months after diagnosis (Ohba & Hirose, 2016). Autophagy, cellular senescence, programmed cell death and necrosis are key responses of a cell facing a stress. Autophagy is the key player in TMZ resistance in GBM. TMZ can induce apoptosis due to selective inhibition of autophagy, in which autophagic vehicles accumulate as their fusion with lysosomes is blocked (Pawlowska et al., 2018). GBM cells can be intrinsically resistant to apoptosis, which is one of the most important reasons for GBM treatment failure and high recurrence (Hottinger et al., 2014), and new therapeutic methods that can effectively control glioblastoma are urgently required.

Meisoindigo is one of the most common clinical anti-tumor drugs in clinical practice. It is a structural analogue of the natural ingredient of indirubin, widely used in the treatment of chronic myeloid leukemia (CML) in China since the 1980s (Xiao et al., 2000). Comparative clinical trials showed that meisoindigo was as effective for CML as hydroxyurea in hematological responses, median duration of chronic phase, median survival and blast crisis rate at 60 months from diagnosis. Furthermore, meisoindigo in combination with hydroxyurea prolonged the median duration of chronic phase and median survival while reduced incidence of blast crisis as compared to busulphan, meisoindigo or hydroxyurea alone, suggesting that meisoindigo has a synergistic effect with hydroxyurea (Huang et al., 2014). It inhibits DNA and RNA synthesis and enables assembly of microtubules in vitro. Nowadays, meisoindigo is mainly used in the treatment of leukemia (Huang et al., 2006). It induces not only differentiation of neutrophils via down-regulating c-Myb probably, but also inhibits proliferation and apoptosis of AML cells (Lee et al., 2010) in vitro and in vivo. But now, several studies have shown that the growth of multiple tumor cells is also inhibited by meisoindigo, such as colorectal cancer HT-29 cells and JAK2/V617F heterozygous mutation cell line-SET2 cell line (Mingxin et al., 2008). Meisoindigo can also affect the Wnt signal pathway through inhibiting the GSK-3beta expression and down-regulating the beta-catenin and c-MYC protein expression, which play an important role in the treatment for chronic myeloid leukemia (Zuo et al., 2010). Moreover, its anti-tumor effect is much more...
obvious and adverse reaction is much milder than natu-
ral indirubin (Xiao et al., 2002). Unfortunately, its anti-
glioma effect has not been reported so far.

The PI3K/Akt signaling pathway, one of the crucial 
cellular signal pathways, plays a pivotal role in inhibiting 
apoptosis as well as promoting cellular proliferation (Shi 
et al., 2018; Zhang et al., 2018). It is extremely closely 
related to the occurrence and development of various 
kinds of human cancers (Robbins & Hague, 2015; Span-
gle et al., 2017). PI3K/Akt is characterized by persistent 
phosphorylation in a large number of malignant tumors 
including glioblastoma (Wang et al., 2017). The over-ac-
tivation promotes downstream gene expression, resulting 
in uncontrolled cell growth, inhibition of tumor cell ap-
optosis, promotion of tumor cell proliferation, facilitating 
tumor immune escape, and ultimately leading to the 
occurrence and development of malignant tumors (Li 
et al., 2016). Therefore, the PI3K/Akt pathway is an attrac-
tive potential target for glioblastoma treatment.

Studies have shown that a series of drugs could inhib-
it the growth of tumor cells as well as induce the expres-
sion of apoptosis-related proteins by inhibiting some ac-
tive molecules related to the PI3K/Akt pathway (Huang 
et al., 2017; Zhang et al., 2018). We consequently studied 
the effect of meisoindigo on human astrocytoma cell line 
U87 in vitro and explored its possible mechanism so as 
to provide a pre-clinical basis for extending the applica-
tion of meisoindigo.

MATERIALS AND METHODS

Cell line and agents

Human glioblastoma cell line U87-CL-0238, Procell, 
Wuhan, China, was cultured in RPMI-1640 (G4530, Ser-
vicebio, Wuhan, China) with 10% fetal bovine serum 
(FBS, 11011-8611, Every Green, Hangzhou, China) at 
37°C in an atmosphere containing 5% of CO2 with sat-
urated humidity, and logarithmically growing cells were 
collected for further experiments.

Anti-caspase-3 (# 9662S), anti-Akt (# 9272S), anti-
phospho-Akt (# 4060S), anti-Pi3K (# 4228S), anti-p65 
(# 8242S) and anti-phospho-p65 (# 3031S) antibod-
ies were purchased from Cell Signaling Technology 
(CST, Boston, United States). Anti-caspase-9 antibody 
(ab32539) was obtained from Abcam (Cambridge, Unit-
ed Kingdom). Annexin-V kit was purchased from BD 
Biosciences (556422, Franklin Lakes, United States). Al-
exa 594-conjugated antibody and Alexa 488-conjugated 
antibody were purchased from Millipore (Billerica, MA, 
United States). IRDye-labeled secondary antibody was 
purchased from Li-Cor Biosciences (BIO-RAD Life Science Research, Hercules, CA, USA) after electrophoresis. The membrane 
was firstly incubated in Tris–buffered saline containing 
5% fat-free milk and 0.1% Tween 20 for blocking for 1 
h at room temperature, and then incubated with primary 
antisera at 4°C overnight, followed by incubation with horseradish peroxidase-conjugated secondary antibod-
ies (Santa Cruz Biotechnology). Then, the membrane 
was scanned with Bio-Rad ChemiDoc Imaging System 
(BIO-RAD Life Science Research, Hercules, CA, USA) 
and the gray scale values were measured with the use 
of Quantity One v4.6.2 software (Bio-Rad Laboratories, 
Hercules, CA, United States). The relative level of protein 
expression is: the gray value of the different sample 
protein bands/gray value of the corresponding sample 
actin and GADPH protein band.

Cell viability determination

After rinsing with PBS buffer solution (G4202, Ser-
vicebio, Wuhan, China), U87 cells were seeded in 96-
well plates and cultured for 24 h. Dimethyl sulfoxide 
was used as an organic solvent to dissolve meisoindigo 
and then PBS was used to regulate the concentration. 
Then, U87 cells were exposed to serial concentrations 
of meisoindigo (#1011055-201001, National Institutes 
for Food and Drug Control, Beijing, China) for 24 h. 
Finally, CCK-8 solution was added into each well and 
incubated at 37°C for additional 4 h before spectro-
photometry measurement at 590 nm. The experiment 
was repeated three times independently. The cells were 
stained with trypan blue and counted with a cell count 
plate. The cell growth inhibition rate was calculated by 
the formula: the cell growth inhibition rate (%)=(1 – 
the experimental group/the control group)×100%, and IC50 
was obtained by statistical calculation.

Morphological observation

The cells were treated with serial concentrations 
of meisoindigo for 24 h. The morphological characteristics 
of the cells were observed under the automatic fluores-
cence microscope (BX63, Olympus Optical Ltd, Tokyo, 
Japan).

Determination of apoptosis rate

Logarithmically growing cells were collected and treat-
ed with serial concentrations of meisoindigo for 24 h. 
After wash with cold PBS, labeled and assayed with ref-
erence to antibody instructions, the cells were added to 
FITC labeled RNA enzyme Annexin V and propidium 
iodide pyridine (PI), respectively. The cells were incu-
bated for 1 h in the dark and then detected by flow cy-
tometry (BD, Biosciences, Franklin Lakes, NJ, USA). At 
the same time, the apoptosis rate was calculated. This 
experiment was repeated three times and the average 
was taken.

Western blotting assays

U87 cells from different groups were collected and lys-
ed with RIPA buffer containing protease inhibitors and 
phosphates inhibitors (G2002, Servicebio, Wuhan, Chi-
na). The supernatant was collected after centrifugation 
at 14000 rpm for 20 min at 4°C, and the protein con-
centration was quantified with the use of BCA kit. The 
total protein was separated by electrophoresis in 10% 
polyacrylamide gel loaded at 30 μg/well. Proteins were 
transferred to PVDF membrane (Millipore, Billerica, MA, United States) after electrophoresis. The membrane 
was firstly incubated in Tris–buffered saline containing 
5% fat-free milk and 0.1% Tween 20 for blocking for 1 
h at room temperature, and then incubated with primary 
antibodies at 4°C overnight, followed by incubation with horseradish peroxidase-conjugated secondary antibod-
ies (Santa Cruz Biotechnology). Then, the membrane 
was scanned with Bio-Rad ChemiDoc Imaging System 
(BIO-RAD Life Science Research, Hercules, CA, USA) 
and the gray scale values were measured with the use 
of Quantity One v4.6.2 software (Bio-Rad Laboratories, 
Hercules, CA, United States). The relative level of protein 
expression is: the gray value of the different sample 
protein bands/gray value of the corresponding sample 
actin and GADPH protein band.

Immunofluorescence staining

Cells cultured on 22×22 mm (No. 1.5) coverslips were 
treated with 10, 20 and 30 μmol/L of meisoindigo, left 
to rest for 24 h before fixation with 100% methanol for 
3 minutes at –20°C. Then, the coverslips were washed 
three times with PBS + 1% normal goat serum (NGS, 
54528, CST, Boston, United States), incubated in a hu-
mid chamber with the primary p65 antibody for 1 h at 
a room temperature, washed three times with PBS plus 
1% NGS, each for 10 minutes, and incubated for 1 h at 
a room temperature in a humid chamber with a fluores-
cently labeled secondary antibody diluted to 4 μg/mL. 
Washed four times with PBS, 10 minutes each time. The 
coverslip was sealed on the carrier sheet with a lidding
agent and clean nail polish was used to prevent the coverslip from sliding. It was then immediately observed under an automatic fluorescence microscope (BX63, Olympus Light Ltd, Tokyo, Japan).

Statistical analysis

SPSS 18.0 (SPSS, Chicago, IL, USA) was used for statistical analysis. All data were presented as mean ± S.D. One-way ANOVA was used to compare numerical data in more than 2 groups. P<0.05 was considered statistically significant.

RESULTS

Effect of Meisoindigo on the proliferation of U87 cells

U87 cells were treated with different concentrations (10, 20 and 30 μmol/L) of meisoindigo for 24 h, the proliferation of U87 cells was inhibited by meisoindigo in a dose-dependent manner. The IC50 was 20 μmol/L (P<0.001) (Fig. 1A, B).

Effect of meisoindigo on the morphology of U87 cells

U87 cells were subjected to the same treatment as in 2.1. Then, it was observed that as the drug concentration gradient accelerates, the number of total and adherent cells decreases.

Effect of meisoindigo on the apoptosis rate and expression of apoptosis-related proteins in U87 cells

U87 cells were treated with the same gradients of meisoindigo as in Materials and Methods. The cellular apoptosis rate and the expression of apoptosis-related proteins were measured with the use of flow cytometry and Western blotting assays, respectively. The level of cellular apoptosis induced by meisoindigo was dose-dependent, and the difference was statistically significant.

Figure 1. Inhibitory effects of meisoindigo on the proliferation of U87 cells.

A) Meisoindigo inhibits the proliferation of U87 cells in a dose-dependent manner. The IC50 value is 20μmol/L. B) Relative cell viability of cells in the treatment group was significantly decreased when comparing with the control group. C) The morphological changes of U87 cells are observed under microscope. As the concentration of meisoindigo increases, the number of total and adherent cells decreases. Mean ± S.D., n=5. ***P<0.001 vs 0 μmol/L.

Figure 2. Effect of meisoindigo on U87 cells in inducing apoptosis.

A) Results from flow cytometry. The cells in the lower-left quadrant are normal cells, the cells in upper-right and lower-right quadrant are late and early apoptotic cells, respectively. B–D) Cellular apoptosis induced by meisoindigo is dose-dependent, with statistically significant difference when compared with the control group. Mean ± S.D., n=5. ***P<0.001 vs 6 μmol/L.
compared with the control group ($P<0.001$) (Fig. 2). In addition, contrasting to the control group, caspase-3 and caspase-9, as well-known and reliable apoptosis-related proteins, were also significantly increased after meisoindigo treatment in a dose-dependent manner ($P<0.001$) (Fig. 3).

**Molecular mechanism of meisoindigo on inhibiting proliferation and inducing apoptosis**

Meisoindigo inhibited the phosphorylation of Akt in U87 cells. Meisoindigo at 20 μmol/L significantly inhibited Akt activation in U87 cells. In the meantime, the level of PI3K, the upstream molecule of Akt, was detected. These results indicated that the expression of these two groups of protein was also inhibited and this effect was statistically significant ($P<0.001$) (Fig. 4). The level of nuclear protein p65 and its phosphorylation was also found to be significantly different ($P<0.001$) (Fig. 4).

**Effect of meisoindigo on P65 protein in U87 cells**

NF-κB is a transcriptional factor regulating a wide array of genes mediating numerous cellular processes such as proliferation, differentiation, motility and survival (Hayden & Ghosh, 2012; Perkins, 2007). In addition, aberrant activation of NF-κB is a frequent event in numerous cancers, including glioblastoma (Soubannier & Stifani, 2017). Therefore, we examined the effect of meisoindigo on the activation of NF-κB p65 with immunofluorescence analysis. The result showed that administration of meisoindigo by different concentrations of 10, 20, 30 μmol/L markedly downregulated the protein expressions of NF-κB p65 in dose dependent manners ($P<0.05$) (Fig. 5).

**DISCUSSION**

Nowadays, the main treatment regimen of human glioblastoma includes surgery, chemotherapy, radiotherapy, endocrine therapy and targeted therapy (Ohba & Hirose, 2016; Wirsching et al., 2016). However, it is characterized by uncontrolled cell proliferation, highly diffusive infiltration, resistance to apoptosis, robust angiogenesis, and DNA repair mechanisms contributing to drug resistance. When the extent of DNA damage exceeds DNA repair potential, such as in the case of many anticancer drugs,
a cell can be given, or gives itself, an additional time for that damage repair at the G1/S or G2/M checkpoint of the cell cycle or be directed on a programmed death pathway, usually apoptosis (Lin et al., 2017). However, cancer cells can avoid this scenario and survive treatment with anticancer drugs due to deregulated DNA damage response and apoptosis resistance. Autophagy, a process of removal of damaged or no longer needed cellular products, has two faces in response to TMZ and other anticancer drugs, pro-survival and pro-death, resulting in the opposite effects, TMZ resistance and TMZ enhanced sensitivity, respectively (Klionsky & Schulman, 2014). Autophagy can protect against apoptotic death, but, when too extensive, can lead to self-destruction of a cancer cell. On the other hand, inhibition of autophagy can result in apoptosis activation and cell death, but when a cancer cell is intrinsically resistant to apoptosis, accumulation of toxic waste not cleared by autophagy takes place. Therefore, it is very important to seek more effective drugs against human glioblastoma.

Meisoindigo, an indirubin compound, is an anti-cancer drug developed in China. Clinical and laboratory studies have shown that meisoindigo is effective as an anti-leukemia drug (Huang et al., 2014; Xiao et al., 2002). Both animal models and clinical trials showed that meisoindigo displayed higher antitumor ability than indirubin (Ji & Zhang, 1985). In maintenance treatment, meisoindigo produced less transformation and longer survival in CML patients compared to busulfan, another classic drug for CML treatment. However, further studies of meisoindigo as a treatment of CML became tarnished as imatinib became a better choice for CML treatment. Experimental results on the mouse leukemia L1210 cell cycle showed that meisoindigo induced accumulation of S phase cells. The movement of cells in G2+M phase to G1 phase may also be blocked to some extent (Ji et al., 1991). Another study suggested that the induction of cancer cell differentiation associated with decreased c-myb oncogene expression might also account for the anticancer action and low toxicity of meisoindigo (Liu et al., 1996). In addition, Xiao and his team found that meisoindigo could inhibit an angiogenetic process through reducing the secretion of VEGF in leukemic cells and also through inhibiting the proliferation, adhesion and differentiation of

![Figure 5. Effect of meisoindigo on P65 protein in U87 cells.](image)

The level of nuclear protein P65 and its nuclear translocation is significantly different. A) Representative imaging of for nuclear protein P65, counterstained with DAPI after different dose (0, 10, 20 and 30 μM) of Meisoindigo treatment. B) Quantification of P65-positive cells in U87 cell after different dose of Meisoindigo treatment. Mean ± S.D., n=5. Scale bar=20 mm. *P<0.05 vs. DMSO; #P<0.05 vs. 10 μM Meisoindigo.
endothelial cells, causing the interruption of a reciprocal stimulatory loop between leukemic and endothelial cells (Xiao et al., 2006). Moreover, one research showed that the antileukemic effects of meisoindigo were investigated in four human leukemic cells (NB4, NB4.007/6, HL-60 and U937) including both retinoic acid sensitive and retinoic acid resistant cells, and meisoindigo could effectively inhibit the growth and/or proliferation of these four cell types (Huang et al., 2014). In view of meisoindigo as a lead compound possessing anti-leukemia effect with clinical safety, exploring its novel biological activities is extremely urgent for drug development in other diseases besides CML (Zheng et al., 2017). Moreover, its outstanding anti-cancer effect and mild adverse reactions suggest its potential application for the treatment of solid tumor, for example human glioblastoma (Lee et al., 2010). The present study aimed to fill this gap in knowledge by exploring the in vitro inhibitory effects of meisoindigo in human glioblastoma cell lines and the underlying signaling mechanism.

We studied the effect of meisoindigo on human glioblastoma cell line U87. The results showed that meisoindigo can significantly inhibit the proliferation of U87 cells in a dose dependent manner with an IC50 of 20 μmol/L, which was observed with the use of light microscopy after U87 cells were treated with meisoindigo for 24 h. The apoptosis rate was positively correlated with the concentration of meisoindigo. Flow cytometric results indicated that meisoindigo could inhibit the proliferation of U87 cells by inducing apoptosis as reported before (Mingxin et al., 2008). Furthermore, Western blotting assays showed that the treatment with meisoindigo significantly increased the expression of caspase-3 and -9 in human glioblastoma cell line U87 in a dose-dependent manner. Studies have shown that meisoindigo can regulate the conduction of signaling pathways (Zhang et al., 2013; Zuo et al., 2010), which are closely related to the tumor genesis. The phosphatidylinositol three kinase/protein kinase (PI3K/AKT) signaling pathway is an important regulatory pathway in cell cycle progression (Hawkins & Stephens, 2015), which is closely related to the growth, differentiation and apoptosis of cells (Robbins & Hague, 2015; Spangle et al., 2017). In this study, we found that the expression of Akt, p-Akt, PI3K, p65 and phospho-p65 nuclear protein were down-regulated by meisoindigo, and intracellular content of P65 was also observed with immunofluorescence microscopy, suggesting that the apoptosis of U87 cells induced by meisoindigo may be regulated by the PI3K/AKT pathway and may be associated with nuclear translocation. Furthermore, a study showed that meisoindigo has neuro-protective effect on ischemic brain, the protection attributes to its ability of relieving the brain inflammation by inhibiting the activation of the NLRP3 inflammasome and preventing the microglial/macrophage switch from the pro-inflammatory M1 phenotype to the protective M2 phenotype, which may obtain through the inhibition of TLR4/NF-κB signaling pathway in neurons and microglia (Ye et al., 2019). Due to the synergistic effect of meisoindigo with hydroxyurea in CML, we assumed that meisoindigo might have the same effect with other chemotherapeutics in GBM.

This study demonstrated that meisoindigo could induce apoptosis of U87 cells and inhibit their proliferation, and the preliminary molecular mechanism underlying apoptosis. Our studies suggest that meisoindigo has a significant anti-proliferation effect and induces apoptosis on human glioblastoma cell line U87, which may guide a wider application of meisoindigo in clinical practice. However, further experiments on other glioblastoma cell lines or primary cells from human glioblastoma samples are needed to confirm the effect of meisoindigo on glioblastoma, and further studies are necessary to elucidate the mechanisms and complex molecules involved in this process. To explore late-stage apoptosis and other such delayed effects, it is needed to extend culture time of U87, and in vitro and in vivo validation experiments should be considered as well.

Conflicts of interest
The authors declare that there is no conflict of interests regarding the publication of this paper.

Ethics approval and consent to participate
This study does not contain any studies with human participants or animals performed by any of the authors. All procedures were conducted according to the guidelines of the bioinformatic criteria of China Wuhan University. The study was approved by the ethics Committee of Renmin Hospital of Wuhan University.

Consent for publication
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Availability of data and materials
Not applicable.

REFERENCES

Hawkins PT, Stephens LR (2015) PI3K signalling in inflammation. Biochem Biophys Acta 1851: 882–897. https://doi.org/10.1016/j.bbadip.2014.12.006
Hayden MS, Ghosh S (2012) NF-kappaB, the first quarter-century: remarkable progress and outstanding questions. Genes Dev 26: 203–234. https://doi.org/10.1101/gad.183434.111
Hottinger AF, Stupp R, Homsicko K (2014) Standards of care and novel approaches in the management of glioblastoma multiforme.
Clin J Cancer 33: 32–39. https://doi.org/10.5732/cjc.013.10207
Huang H, Li LJ, Zhang HB, Wei AY (2017) Papaverine selectively inhibits human prostate cancer cell (PC-3) growth by inducing mitochondrial mediated apoptosis, cell cycle arrest and downregulation of NF-κB/PI3K/Akt signalling pathway. J Biochem 158: 112–118. PMID: 28365943
Huang M, Lin HS, Lee YS, Ho PC (2014) Evaluation of meisoindigo, an indirubin derivative: in vitro antileukemic activity and in vivo pharmacokinetics. Int J Oncol 45: 1729–1734. https://doi.org/10.3892/ijo.2014.2548
Ji XJ, Liu XM, Li K, Chen RH, Wang LG (1991) Pharmacological studies of meisoindigo: absorption and mechanism of action. Biomed Environ Sci 4: 332–337. PMID: 1764225
Ji XJ, Zhang FR (1985) Studies on antineoplastic action of indirubin derivatives and analogs and their structure-activity relationships. Yao Xue Xue Bao 20: 137–139. PMID: 4066648 (in Chinese)
Klionsky DJ, Schulman RA (2014) Dynamic regulation of macroautophagy by distinctive ubiquitin-like proteins. Nat Struct Mol Biol 21: 336. https://doi.org/10.1038/nsmb.2787
Lee GC, Lin CP, Lee YL, Wang GC, Cheng YC, Liu HE (2010) Meisoindigo is a promising agent with in vitro and in vivo activity against human acute myeloid leukemia. Leuk Lymphoma 51: 897–905. https://doi.org/10.3109/10428191003672115
Li N, Wu C, Chen N, Gu H, Yen A, Cao J, Wang F, Wang L (2016) PI3K/Akt/mTOR signaling pathway and targeted therapy for glioblastoma. Oncotarget 7: 33440–33450. https://doi.org/10.18632/oncotarget.7961
Lin AB, McNeely SC, Beckmann RP (2017) Achieving precision death with cell-cycle inhibitors that target DNA replication and repair. Clin Cancer Res 23: 3232–3240. https://doi.org/10.1158/1078-0432.CCR-16-0883
Liu XM, Wang LG, Li HY, Ji XJ (1996) Induction of differentiation and down-regulation of c-myb gene expression in ML-1 human myeloblastic leukemia cells by the clinically effective anti-leukemia
agent meisoindigo. Biochem Pharmaco. 51: 1545–1551. https://doi.org/10.1016/0006-2952(96)00098-6
Mingxin Z, Yan L, Hongbo W, Jianhua Z, Hongyan L, He L, Hongqi X, Sen Z, Xiaoguang C (2008) The antitumor activity of meisoindigo against human colorectal cancer HT-29 cells in vitro and in vivo. J Chemother 20: 728–733. https://doi.org/10.1007/s10582-008-0728
Nayak I, Reardon DA (2017) High-grade gliomas. Continuum (Minneap Minn) 23 (6, Neuro-oncology): 1548–1563. https://doi.org/10.1212/CON.0000000000000554
Ohba S, Hirose Y (2016) Current and future drug treatments for glioblastomas. Curr Med Chem 23: 4309–4316. https://doi.org/10.2174/092986732366161014132907
Pawlowska E, Szczepanska J, Szatkowska M, Blasiak J (2018) Induction of autophagy by salidroside through the AMPK-mTOR signalling pathway. Mol Cell Biochem 438: 125–131. https://doi.org/10.1007/s11010-018-3020-9
Shi X, Yang L, Xie J, Zhao Y, Cong J, Li Z, Li H, Cheng X, Fan J (2016) UNBS5162 inhibits proliferation of human melanoma cells by inducing apoptosis via the PI3K/Akt pathway. Mol Med Rep 18: 3382–3388. https://doi.org/10.3892/mmr.2018.9321
Soubanier V, Stifani S (2017) NF-kappaB signalling in glioblastoma. Frontier Cell Neurosci 13: 553. https://doi.org/10.3389/fncel.2019.00553
Zhang B, Liu Y, Li Y, Zhe X, Zhang S, Zhang L (2018) Neuroglobin promotes the proliferation and suppresses the apoptosis of glioma cells by activating the PI3K/AKT pathway. Mol Med Rep 17: 2757–2763. https://doi.org/10.3892/mmr.2017.8132
Zhang HJ, Zhang Y, Jin J, Zhou WQ, Chen XG (2013) Mechanism about therapeutic effect of meisoindigo on psoriasis via down-regulation of the TLR4-TAK-NF-kappaB pathways. Yao Xue Xue Bao 48: 503–507. PMID: 23833936 (in Chinese)
Zhang X, Lan D, Ning S, Ruan L (2018) Anticancer action of lac-tucopicrin in SKMEL-5 human skin cancer cells is mediated via apoptosis induction, G2/M cell cycle arrest and downregulation of mTOR/PI3K/AKT signalling pathway. J Buon 23: 224–228. PMID: 29352788
Zheng XT, Wu ZH, Wei Y, Dai JJ, Yu GF, Yuan F, Ye LC (2017) Induction of autophagy by salidroside through the AMPK-mTOR pathway protects vascular endothelial cells from oxidative stress-induced apoptosis. Mol Cell Biochem 425: 125–138. https://doi.org/10.1007/s11010-016-2868-x
Zuo MX, Li Y, Zhou JH, Wang HB, Chen XG (2010) Effect of Meisoindigo on Wnt signal pathway in K562 and HL-60 cells. Zhongguo Shi Yan Xue Ye Xue Za Zhi 18: 579–582. PMID: 20561405 (in Chinese)