Dissection of mechanisms of Chinese medicinal formula Realgar-Indigo naturalis as an effective treatment for promyelocytic leukemia

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To enhance therapeutic efficacy and reduce adverse effects, practitioners of traditional Chinese medicine (TCM) prescribe a combination of plant species/minerals, called formulae, based on clinical experience. Nearly 100,000 formulae have been recorded, but the working mechanisms of most remain unknown. In trying to address these gaps in the formulae with current biomedical approaches, we use Realgar-Indigo naturalis formula (RIF), which has been proven to be very effective in treating human acute promyelocytic leukemia (APL) as a model. The main components of RIF are realgar, Indigo naturalis, and Salvia miltiorrhiza, with tetraseranic tetrarsufide (A), indirubin (I), and tanshinone IIA (T) as major active ingredients, respectively. Here, we report that the ATI combination yields synergy in the treatment of a murine APL model in vivo and in the induction of APL cell differentiation in vitro. ATI causes intensified ubiquitination/degradation of promyelocytic leukemia (PML)-retinoic acid receptor α (RARα) oncproteins, stronger reprogramming of myeloid differentiation regulators, and enhanced G1/S arrest in APL cells through hitting multiple targets compared with the mono- or biagents. Furthermore, ATI intensifies the expression of Aquaglyceroporin 9 and facilitates the transportation of A into APL cells, which in turn enhances A-mediated PML-RARα degradation and therapeutic efficacy. Our data also indicate A as the principal component of the formula, whereas T and I serve as adjuvant ingredients. We therefore suggest that dissecting the mode of action of clinically effective formulae at the molecular, cellular, and organism levels may be a good strategy in exploring the value of traditional medicine.

The complexity of medicine suggests that treatment protocols should be carefully designed, and the construction of a prescription is an art in fighting disease. Increasing evidence demonstrates that, in treating illnesses, including cancer and HIV/AIDS, treatment regimens containing multiple drugs with distinct but related mechanisms can usually amplify the therapeutic efficacies of each agent, leading to maximal therapeutic efficacy with minimal adverse effects. Interestingly, the therapeutic efficacies of each agent, leading to maximal therapeutic efficacies (3, 4). However, essential compounds have not been identified in most formulae, whereas precise mechanisms of formulae remain to be addressed by using molecular approaches, thus hampering the modernization of TCM.

Acute promyelocytic leukemia (APL), the M3 type of acute myeloid leukemia (AML), is characterized by the accumulation of immature promyelocytes in bone marrow (BM) and the presence of a specific chromosome translocation t(15;17) (q22;q21), which generates the leukemogenic PML-RARα fusion gene in a vast majority of patients. APL is uniquely sensitive to the differentiation inducer all-trans retinoic acid (ATRA), which causes the modulation and catabolism of PML-RARα oncoprotein (5, 6). Interestingly, arsenic trioxide (ATO) (7, 8), an ancient remedy in both TCM and Western medicine, has been proven effective in treating APL, and the key molecular mechanism has been revealed to be related to the degradation of promyelocytic leukemia (PML)-retinoic acid receptor α (RARα) (9). A recent report on the ATRA/ATO combination yields the 4-year disease-free survival of >90% of APL patients (10). Of note, in parallel to this advancement in the understanding and treatment of APL, accomplished mainly by the hematology/oncology community in China and other countries, a group of TCM doctors in China designed a Realgar-Indigo naturalis formula (RIF) in the 1980s (11) entirely based on TCM theories, in which mined ore, realgar, is the principal element, whereas Indigo naturalis, Salvia miltiorrhiza, and Radix psusostellariae are adjuvant components to assist the effects of realgar.

Intriguingly, recent multicenter clinical trials showed that a complete remission rate of 96.7% (12) to 98% (11) and a 5-year overall survival rate of 86.88% (13) were achieved in APL patients receiving RIF, with moderate adverse effects such as gastrointestinal discomfort and rash. Realgar, in combination with Indigo naturalis, also showed anti-APL activity (14). The literature documents the antitumor activity of Salvia miltiorrhiza (15), whereas R. psusostellariae is believed to be able to strengthen immune activity and seems not to be essential for RIF. Studies showed that tetraseranic tetrarsufide (As₄S₄, A) (8), indirubin (I) (16), and tanshinone IIA (T) (17) are the major active ingredients of realgar, Indigo naturalis, and S. miltiorrhiza, respectively (18). These results not only demonstrate the clinical efficacy of, but also suggest the possible synergistic effects


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Among, the three components of RIF, warranting the mechanistic exploration of this formula.

In trying to approach the rationale of formula design in TCM, here we use the treatment of APL with RIF as a working model. A, I, and T were used as active compounds of realgar, Indigo naturalis, and S. miltiorrhiza, respectively, and the efficacies and mechanisms of ATI combination on APL were tested in vivo and in vitro.

**Results**

**In Vivo Therapeutic Efficacies of ATI on a Murine APL Model.** In FVB/NJ mice injected with $1 \times 10^5$ cells expressing PML-RARα (19, 20), a statistically significant prolongation of median overall survival was observed in mice treated with ATI combination compared with animals treated with vehicle control or mono- or bitreatment of A, T, and I ($p < 0.0001$). (B) ATI does not cause loss of body weight, suggesting that ATI might probably not cause serious toxicity. (C) Treatment with ATI results in cell maturation revealed by an accumulation of Gr-1 and Mac-1-positive cells in BM and peripheral blood (PB). (Dosage of agents used: A, 10 mg/kg; T, 50 mg/kg; I, 50 mg/kg. A is administered by i.v. injection, whereas T and I are given orally.)

**ATI Causes Enhanced Ubiquitination and Degradation of PML-RARα Oncoprotein.** Like ATO, As₂S₃ is able to trigger the degradation of the PML-RARα oncoprotein (Fig. 3A). Interestingly, T or I augmented A-triggered catabolism of PML-RARα, whereas the ATI combination further enhanced this effect (Fig. 3A). Previous studies showed that ATO shifts PML/PML-RARα from the nucleoplasm onto the nuclear matrix and induces their degradation via the proteasome pathway (24). By Western blot analysis of the PML-RARα contents of RIPA (the cytoplasm and most of the nucleoplasm) and pellet (the nuclear matrix and some chromatin components) fractions (24) in PML-RARα expressing 293 cells pretreated with proteasome inhibitor MG-132, we found that A, but not T and/or I, induced a clear shift from the nucleoplasm to the nuclear matrix and an apparent ubiquitination of PML-RARα (Fig. 3B), whereas T increased A-triggered relocation and ubiquitination of the oncoprotein (Fig. 3B). Immunofluorescence staining using an anti-PML antibody showed that untreated NB4 and NB4-R2 cells exhibited hundreds of micropunctuates in the nuclei and cytoplasm, whereas A down-regulated PML-RARα and restored the normal PML speckles (SI Fig. 9). Although T, I, or a TI combination did not affect the staining pattern, these compounds enhanced the effects of A (SI Fig. 9), suggesting that degradation of PML-RARα by A can be synergized by T and I. That MG-132 could induce a significant accumulation of PML-RARα (Fig. 3B) provided strong evidence that the synergistic effect of A, T, and I occurred at the level of protein ubiquitination. These data, together with the in vivo and cell biology data, suggest that A is the principal ingredient in this formula, whereas T and I could serve as adjuvant components.

**ATI Triggers Relief of Transcription Suppression.** Transcription factors, e.g., CCAAT/enhancer-binding proteins (C/EBPs) and PU.1, are critical for normal myelopoiesis and granulocytic maturation and are suppressed in APL. We found that in NB4 cells treated with the ATI combination, C/EBPα at protein level was up-regulated on day 2 and subsequently decreased, whereas C/EBPβ1/2 and C/EBPe were up-regulated (Fig. 3 C and D). Further analysis showed that A or T alone modulated these proteins, and combined use of ATI intensified the effect (Fig. 3C). The oncogene C-Myc blocks myeloid differentiation, and its down-regulation is critical for myeloid cell differentiation (25). Interestingly, down-regulation of C-Myc at both the protein and mRNA levels was detected in cells treated with ATI compared with cells treated with mono- or biagents (Fig. 3 C and D). RARβ2 is an RAR target gene that contains the strongest natural RA response element so far (pRARE) in its promoter (26, 27). We found that both T and A up-regulated RARβ2 at the mRNA level, whereas the ATI combination significantly intensified RARβ2 up-regulation (Fig. 3E Upper). Using the ChIP assay, we identified the dissociation of RARβ2 from histone deacetylase 1 (HDAC1) (Fig. 3E Lower), which might contribute to the activation of RARβ2 transcription. Suppression of transcription factors by the dominant-negative effect of PML-RARα is involved in APL pathogenesis, and the ATI combination might relieve the repression of the normal function of transcription
machinery in APL cells, suggesting the rationality of RIF in treating APL.

**ATI Induces G\(_{1}/G_{0}\) Arrest of APL Cells with Effects on Key Regulators of Cell Cycle Progression.** We tested whether ATI treatment could act on cell cycle progression and found that T alone increased cellular compartment in the G\(_{1}/G_{0}\) phase, whereas AT, AI, and TI combinations further caused G\(_{1}/G_{0}\) blockage (Fig. 4\(A\)). Intriguingly, 83.7\% ± 6.7\% of NB4 cells treated with ATI were at the G\(_{1}/G_{0}\) phase, demonstrating an enhanced effect of the compounds in inhibiting the G\(_{1}\) to S transition (Fig. 4\(A\)). Similar results were observed in NB4-R2 cells treated with ATI (Fig. 4\(A\)). It has been shown that I is a potent inhibitor of cyclin-dependent kinase 2 (CDK2), which is critical for cell cycle progression from the G\(_{1}\) to S phase (16). We found that A and I down-regulated CDK2 in NB4 and NB4-R2 cells, whereas the ATI combination further enhanced this effect (Fig. 4\(B\)). CDK2 has been shown to be able to phosphorylate histone H1 (28), whereas phosphorylated H1 is increased during the transition from the G\(_{1}\) to S phase (29). Regimens containing I markedly decreased phosphorylated H1 (Fig. 4\(C\)). P27 is an important CDK inhibitor, which negatively regulates the progression from G\(_{1}\) to S phase. We showed that the protein but not the mRNA level of P27 was dramatically increased during A, T, I, and the combinatory treatment on NB4 cells (Figs. 3\(D\) and 4\(B\)). The ATI combination also up-regulated P27 in NB4-R2 cells (Fig. 4\(B\) Right). Normally, Rb governs cells’ entry into the S phase (30). We found that the expression of the Rb protein was slightly increased in treatment groups containing T (T, AT, TI, and ATI) in NB4 cells, whereas hypophosphorylated Rb (\(^{\text{hypoP}}\)Rb, the functional form of Rb as a tumor suppressor in blocking the cell cycle) was significantly up-regulated in the ATI treatment group (Fig. 4\(B\)). These observations indicated that A, T, and I had a synergistic/additive effect on inducing G\(_{0}/G_{1}\) arrest of APL cells.

T and I Increase Cellular Uptake of Arsenic Through Cooperating with A in Inducing Up-Regulation of the Transmembrane Protein Aquaglyceroporin 9 (AQP9). It has been shown that AQP9 serves as the transmembrane transporter of arsenic compounds (31). A question can thus be raised: could T and/or I exert any effect on the transportation of A through AQP9? To address this, NB4 cells were pretreated with different protocols for 4 days, washed, and then incubated with 2.5 \(\mu\)M A for 4 h. The intracellular arsenic concentration ([As]\(_{i}\)) was carefully evaluated by an atomic absorption spectrometer system. Intriguingly, cells treated with ATI had the highest [As], whereas [As] in cells treated with AT and AI but not TI was higher than in cells treated with A (Fig. 5\(A\)), demonstrating that T and/or I assist arsenic uptake. It has been reported that MRP-1 is involved in arsenic efflux (32), and recently, AQP9 has been shown to mediate arsenic uptake by leukemic cells and determine arsenic sensitivity (31). We found that expression of MRP-1 was not changed in NB4 cells treated with these compounds (data not shown). Interestingly, ATI treatment induced strong expression of AQP9 after 24–96 h (Fig. 5\(B\) and \(C\)). Further analysis revealed T, I, or Indirubin-3’-monoxime (3m), an analog of I, cooperated with A in up-regulating AQP9 at both the mRNA (Fig. 5\(B\)) and/or protein (Fig. 5\(C\)) levels, whereas TI or T3m moderately caused the elevation of AQP9. The immunofluorescence assay confirmed the cooperation of T and I with A in up-regulating AQP9 expression, whereas the strongest effect was seen in the ATI combination (Fig. 5\(D\)).

To validate the importance of AQP9 in arsenic uptake, RNA interference (RNAi) was used to suppress AQP9 gene expres-
Transfection of the AQP9 siRNA expression vector into NB4 cells resulted in a decrease of AQP9 by approximately one-half (Fig. 5E). Consequently, AQP9 silencing led to a decrease of [As]i of cells treated with A, AT, AI, or the ATI combination (Fig. 5F). Moreover, AQP9 knockdown inhibited cell maturation induced by ATI, as revealed by CD11b expression (Fig. 5G). These results suggest that AQP9 is critical to arsenic transportation, and T and I facilitate arsenic uptake through up-regulation of AQP9.

**Discussion**

In the past few years, the pharmaceutical industry has seen a shift from the search for “magic bullets” that specifically target a single disease-causing molecule to the pursuit of combination therapies that comprise more than one active ingredient (33). Interestingly, TCM has advocated combinatory therapeutic strategies for over 2,500 years. Based on the symptoms and characteristics of patients and guided by the theories of TCM, formulae are designed to contain a combination of different kinds of plants or minerals to improve clinical efficacy. One example is RIF, whose efficacies in treating APL have been well established recently (12, 13).

In this study, we find that, in a murine APL model, combined use of the active components of RIF, namely A, T, and I, significantly prolongs the life span of mice bearing PML-RARα-positive leukemic cells. At the cellular level, the ATI induced the terminal differentiation of APL cells in vivo and in vitro and overcame ATRA resistance. Assessment of the CI value by the median-effect method directly demonstrates the synergic effect of A, T, and I on NB4 and NB4-R2 cells. These results clearly show that components of RIF exert effects of mutual reinforcement. However, ATI does not show an intensified adverse effect in the APL murine model, as revealed by change in body weight, consistent with the safety of RIF.
Treatment with AQP9-specific siRNA inhibits differentiation of NB4 cells on up-regulation of AQP9. (Fig. 5. T and I facilitate arsenic uptake by malignant promyelocytes via up-regulation of AQP9. (A) Combinatory use of T and/or I increases intracellular arsenic concentration ([As]) in NB4 cells (*, P = 0.002; #, P = 0.004; **, P = 0.002). (B and C) T and/or I in combination with A up-regulate AQP9 expression at both the mRNA (B) and protein (C) levels (Coom, stained with Coomassie blue). (D) Immunofluorescence analysis of AQP9 expression in NB4 cells treated with the ATI combination. (E) AQP9-specific siRNA down-regulates AQP9 expression by approximately one-half in NB4 cells (NB4-AQP9-Si) compared with cells treated with nonsilencing siRNA control (NC). (F) Treatment with AQP9-specific siRNA reduces [As] in NB4-AQP9-Si cells upon ATI compared with NB4-NC cells (*, P = 0.018; #, P = 0.037; **, P = 0.009). (G) Treatment with AQP9-specific siRNA inhibits differentiation of NB4 cells on ATI, revealed by analysis of CD11b expression.

observed in the clinic. These observations are in agreement with the rationality of the formula: mutual reinforcement of the compounds and reduction of adverse effects.

A large body of evidence indicates that PML-RARα is the causative oncoprotein of APL. Interestingly, A, which exhibits the strongest therapeutic effects in the murine APL model, has also been shown to be the principal agent of RIF in targeting PML-RARα. Furthermore, the TI combination enhances A-induced ubiquitination and degradation of PML-RARα, augmenting the effects of A. Thus, the RIF formula, although designed by TCM doctors in the premolecular era of APL, proves its rationality of the formula: mutual reinforcement of the compounds and reduction of adverse effects.

In summary, we show that the dissection of the mode of action of clinically well established TCM formulae such as RIF should be possible by combined application of both analytical and synthetic research approaches at the molecular, cellular, and organism levels. This study may be considered a useful pilot trial in exploring the value of traditional formulae on a larger scale and in helping to bridge Western and the Eastern medicines in the era of systems biology.

Materials and Methods

Reagents. Details on A, I, T, and other materials used can be found in SI Materials and Methods.

Animals. Mice were bred and maintained in a specific pathogen-free environment. Six- to eight-week-old FVB/NJ mice were i.v. injected with 1 × 10^5 cells expressing PML-RARα (20) via the tail vein. When they became moribund, the mice were killed, and splenic cells were isolated and inoculated into secondary recipients for passage (19). Five days after leukemic cell transplantation, the mice were treated with A and/or T and/or I at the doses indicated in the legend for Fig. 1.

Cell Culture, Cell Viability, Cell Differentiation, and Cell Cycle. NB4 and NB4-R2 cells lines were kindly provided by M. Lanotte from Hôpital Saint-Louis, Paris, France. Fresh leukemia cells were obtained from four APL patients with informed consent. Cells were cultured, and their major biological features were assayed as described (19). The dose–effect curves of single or combined drug treatment were analyzed by the median-effect method (23) by using CalcuSyn Software (Biosoft).

Semiquantitative RT-PCR. Semiquantitative RT-PCR was performed by using the primers listed in SI Table 1, according to a method described in ref. 19.
Immunofluorescence, Western Blot Assays, and ChIP. Immunofluorescence and Western blot assays were performed as described (9) by using the antibodies indicated. ChIP was conducted as described (19). Semiquantitative RT-PCR was performed by using the primers listed in SI Table 1.

Immunoprecipitation (IP) and CDK2 Kinase Assay. Cells were lysed and proteins purified for IP and kinase assay of CDK2 according to protocols provided by the reagent manufacturer (Santa Cruz Biotechnology).

Measurement of Arsenic Concentration. Cells were pretreated with A, T, and I alone or in combination, as indicated, for 4 days. After being washed with PBS, cells were resuspended in RPMI medium 1640 supplemented with 10% FBS and 2.5 μM As2O3 for 4 h. After being washed with PBS, cell samples were broken by ultrasonic wave, and total inorganic trivalent As(III) were determined as described (9).