Isoniazid Pharmacokinetics-Pharmacodynamics in an Aerosol Infection Model of Tuberculosis

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Received 3 March 2004/Accepted 14 April 2004

Limited data exist on the pharmacokinetic-pharmacodynamic (PK-PD) parameters of the bactericidal activities of the available antimycobacterial drugs. We report on the PK-PD relationships for isoniazid. Isoniazid exhibited concentration (C)-dependent killing of Mycobacterium tuberculosis H37Rv in vitro, with a maximum reduction of 4 log_{10} CFU/ml. In these studies, 50% of the maximum effect was achieved at a C/MIC ratio of 0.5, and the maximum effect did not increase with exposure times of up to 21 days. Conversely, isoniazid produced less than a 0.5-log_{10} CFU/ml reduction in two different intracellular infection models (J774A.1 murine macrophages and whole human blood). In a murine model of aerosol infection, isoniazid therapy for 6 days produced a reduction of 1.4 log_{10} CFU/lung. Dose fractionation studies demonstrated that the 24-h area under the concentration-time curve/MIC (r^2 = 0.83) correlated best with the bactericidal efficacy, followed by the maximum concentration of drug in serum/MIC (r^2 = 0.73).

No new drugs for the treatment of tuberculosis have been registered in the last 40 years. Discovery of new antimycobacterial agents is in part limited by the laborious and slow nature of the in vitro and in vivo studies required. Knowledge of the pharmacokinetic (PK)-pharmacodynamic (PD) properties of candidate drugs could be used to facilitate drug discovery and evaluation of the effects of combinations of agents. As a step toward such a strategy, we have recently identified the PK-PD parameter that correlated with the in vivo efficacy of rifampin in a murine aerosol model of tuberculosis (7). In the present study, we have extended this work to include isoniazid.

MATERIALS AND METHODS

Reagents. Isoniazid (lot 36H1179) and carboxymethyl cellulose (lot 77H1077) were purchased from Sigma, St. Louis, Mo. Isoniazid stock solutions were prepared in 100% dimethyl sulfoxide (DMSO; Sigma) and diluted in normal saline prior to final use. ETDA (lot 5-4514) was purchased from Hi-Media Labs, Mumbai, India. Acetonitrile (high-pressure liquid chromatography [HPLC] grade) and triehloroacetic acid (TCA) were obtained from Spectrochem Pvt. Ltd., Mumbai, India. Cinnamaldehyde (lot 96320) was obtained from Fluka Biochemika, Buchs, Switzerland.

Microbial cultures and cell lines. Mycobacterium tuberculosis H37Rv (ATCC 27294) and J774A.1 macrophages were prepared for in vitro and in vivo studies required. Knowledge of the pharmacokinetic (PK)-pharmacodynamic (PD) properties of candidate drugs could be used to facilitate drug discovery and evaluation of the effects of combinations of agents. As a step toward such a strategy, we have recently identified the PK-PD parameter that correlated with the in vivo efficacy of rifampin in a murine aerosol model of tuberculosis (7). In the present study, we have extended this work to include isoniazid.

Animals. The Institutional Animal Ethics Committee, registered with the Government of India (registration no. CPCSEA 1999/5), approved all experimental protocols with animals and the use of animals. Ethical practices recommend the use of equal numbers of animals of both sexes wherever possible, and since preliminary studies indicated that sex did not influence the outcome of either the PKs or the efficacy of isoniazid, male and female BALB/c mice were used for the PK studies and the efficacy studies, respectively. Six to 8-week-old mice purchased from National Institute of Nutrition, Hyderabad, India, were randomly assigned to cages with the restriction that the weights of all cage members be within a 1 to 2 g each other. They were allowed 2 weeks of acclimation before intake into experiments. Feed and water were given ad libitum.

MICs in broth and serum. By using previously described methods (7), the MIC of isoniazid was determined with BACTEC 7H12B medium (broth MIC) or Middlebrook 7H9 medium supplemented with 50% fetal calf serum (serum MIC).

Protein binding. Protein binding was measured by equilibrium dialysis by previously published procedures (7). The quantification of the isoniazid concentrations in these studies is described as part of the PK methods (see below).

Killing kinetics in vitro. The kinetics of killing by isoniazid were measured in BACTEC 7H12B broth as described previously (7), followed by plating for CFU enumeration on Middlebrook 7H11 agar plates.

Intracellular killing kinetics. Killing in J774A.1 macrophages was measured as described previously (7). Studies of killing in whole blood were done by the protocol reported by Wallis et al. (19). In brief, 0.25 ml of human blood that had been collected in citrate phosphate dextrose anticoagulant was combined with an equal volume of a thawed seed lot culture of 10^5 CFU M. tuberculosis per ml and incubated at 37°C in 4 ml Corning tubes (Medi-Spec Instruments Pvt. Ltd., Mumbai, India) sealed with screw caps. Twenty-four hours after infection, the 0.5 ml of isoniazid-containing solutions in 4% DMSO (final DMSO concentration, 2%) was added and the tubes were further incubated at 37°C. Samples were drawn for plating at the time of drug addition and 48 h after drug addition. The experiment was done in duplicate.

Stability of isoniazid in macrophage cultures. The stability of isoniazid in uninfected macrophage cultures was determined by estimating the total drug concentration over a 4-day period by HPLC methods at 3 times the MIC (1.6 mg/liter) and 512 times the MIC (25.6 mg/liter) in duplicate flasks containing 4 ml of Dulbecco modified Eagle medium (Gibco-BRL Life Technologies, Gaithersburg, Md.) The total concentration of isoniazid in the macrophage cultures was estimated at time zero (immediately after addition) and at days 2 and 4 after drug addition. For estimation of the concentration, the medium containing the drug was collected and the monolayers were directly lysed with 1 ml of 0.04% sodium dodecyl sulfate for 3 min to release the intracellular drug. The cell lysate and the medium (extracellular drug) were pooled and extracted by precipitation.
A noncompartmental analysis program (model 200, noncompartmental analysis for extravascular administration) was used to calculate the values for the PK parameters.

In vivo dose-response studies. We used an aerosol infection model in which drugs are evaluated following a respiratory infection with low numbers of tubercle bacilli (7, 8). Mice were infected via the inhalation route in an aerosol infection chamber designed and constructed in the Mechanical Engineering Shop, University of Wisconsin—Madison. Four weeks after infection, the mice were dosed daily by mouth with isoniazid at 0, 3, 10, 30, or 90 mg/kg, given 6 days a week for 1 or 2 weeks. At the onset and 24 h after the completion of treatment, groups of mice were killed by exposure to CO2 and the lungs were aseptically removed for homogenization in a final volume of 2.0 ml by use of Teflon-glass tissue grinders (catalogue no. W012576; Wheaton). Each suspension was serially diluted in 10-fold steps, and at least three dilutions were plated on Middlebrook 7H11 agar supplemented with 10% albumin-dextrose-catalase and incubated at 37°C with 5% CO2 for 3 weeks.

Dose-fractionation studies. Doses were selected for the dose-fractionation study on the basis of the results of the dose-ranging study and the observed linearity of the PK parameters with dose. The total doses selected were 1.8, 6, 18, 36, 54, 72, 126, 180, 360, 540, 900, 1,140, and 2,160 mg/kg. Each total dose was given as 6, 12, or 18 equally divided doses, and at least three dilutions were plated on Middlebrook 7H11 agar supplemented with 10% albumin-dextrose-catalase and incubated at 37°C with 5% CO2 for 3 weeks.
calculated to be present in a given sample. Nonlinear regression (curve-fitting) analysis by use of an inhibitory sigmoid E\textsubscript{max} response model with or without constants was performed with the in vitro and in vivo killing data. Prism software (version 3; GraphPad Software, Inc., San Diego, Calif.) was used for all the calculations described above. A 1-log\textsubscript{10} CFU killing effect (E\textsubscript{max}) was calculated from the dose-response curves by use of the following equation: 
\[
E\textsubscript{max}\left(\frac{C}{MIC}\right) = \frac{\log_{10} E\textsubscript{0}}{N} \left[\frac{E\textsubscript{max} \left(\frac{x}{N}\right)^N}{EC_{50} \left(\frac{x}{N}\right)^N}\right],
\]
where E\textsubscript{0} is the log\textsubscript{10} numbers of CFU at any given concentration, E\textsubscript{max} is the lowest log\textsubscript{10} numbers of CFU achieved following treatment, N is the Hill slope, and x is the C/MIC ratio or the AUC/MIC ratio.

**RESULTS**

**MIC in serum and serum protein binding.** The MIC of isoniazid in both BACTEC 7H12B broth and serum was 0.05 mg/liter. The levels of plasma protein binding by isoniazid were 48 and 42% at 5 and 10 times the MIC in broth, respectively.

**In vitro killing kinetics.** Isoniazid exhibited concentration-dependent killing of extracellular *M. tuberculosis*, with a maximum reduction of 4 log\textsubscript{10} CFU/ml. The E\textsubscript{max} and the C/MIC at which 50% of E\textsubscript{max} was achieved remained constant at 4 log\textsubscript{10} CFU/ml and 0.4, respectively, from day 1 to day 22 (Fig. 1). In vitro killing of *M. tuberculosis* was described by the equation 
\[
E = \left(7.43 \log_{10} \text{CFU/ml} - \left\{\left(4 \log_{10} \text{CFU/ml}\right) \left(C\text{MIC}\right)\right\}\right) + 0.4 + (C/MIC).
\]

**Intracellular killing kinetics.** (i) J774.A macrophage assay. Although the growth of *M. tuberculosis* in J774.A macrophages was inhibited by isoniazid at 0.05 mg/liter, isoniazid did not exhibit significant killing of *M. tuberculosis* even at a concentration of 32 mg/liter (640-fold above the inhibitory concentration) (Fig. 2). In this assay, a maximum reduction of 0.5 log\textsubscript{10} CFU/ml was achieved on day 4.

(ii) Whole-blood assay. In the assay with whole blood, isoniazid showed no bactericidal activity when it was tested at concentrations up to 128 mg/liter (Fig. 3).

**Stability of isoniazid in J774A.1 cells.** On the basis of the percentage of isoniazid recovered in relation to the amount estimated to be present immediately after drug addition to an uninfected macrophage monolayer, isoniazid was stable over a 4-day period (Table 1).

**Single-dose PKs of isoniazid in uninfected male BALB/c mice.** Isoniazid displayed linear PKs at single doses between 0.1 and 120 mg/kg. The time to C\textsubscript{max} of isoniazid ranged from 0.16 to 0.5 h, and the terminal elimination half-life ranged from 0.4 and 1.6 h (Fig. 4).

**Dose-response studies.** On the basis of our previous work (7), dosing was initiated 4 weeks after infection, which is the time that coincides with late log phase in vivo, in which the bacterial load reaches 10\textsuperscript{6} CFU/lung. Figure 5 shows the effects observed over the entire dose range. The maximum effect of a reduction of approximately 1.0 log\textsubscript{10} CFU/lung was observed at 90 mg/kg. In addition, the CFU reductions seen after dosing for 12 days were not statistically different from those seen after 6 days (P > 0.05 for each dose for the two durations).

**Dose-fractionation studies.** Since the difference in the maximum effect observed between 6 and 12 doses was not significant (P > 0.05), the duration of the dose-fractionation experiment was fixed at 6 days. Figure 6 shows the relationships between log\textsubscript{10} CFU per lung and the three PD parameters. AUC\textsubscript{24}/MIC showed the highest correlation with bactericidal...
activity ($r^2 = 0.83$; best-fit equation of $E = 6.37 \log_{10} \text{CFU/lung} - [1.3 \log_{10} \text{CFU/lung (AUC/MIC)}]/63 + (\text{AUC/MIC})$) (Fig. 6A). The fit for $C/MIC$ was less ($r^2 = 0.73$; Fig. 6B), and percent $T > MIC$ showed a poor correlation ($r^2 = 0.01$; Fig. 6C). The maximum bactericidal effect of isoniazid on $M. tuberculosis$ observed in this model was $1.4 \log_{10} \text{CFU/lung}$.

**DISCUSSION**

Whereas the PK-PD parameters for antibacterial agents are reasonably well characterized (2), the PK-PD relationships for antimycobacterial agents are only now beginning to be fully characterized (7). Several studies have been conducted with isoniazid to evaluate its bactericidal and sterilizing efficacies in mice (3, 5, 9) and guinea pigs (17). However, it is difficult to identify from those studies the PD parameter that best describes its efficacy. Our objectives were to identify the PD parameter(s) for isoniazid that describes its bactericidal efficacy in an aerosol infection model of tuberculosis in mice.

In our experiments, isoniazid displayed concentration-dependent killing of extracellular $M. tuberculosis$ that was independent of the duration of exposure. Although prior work by Armstrong (1) reported that killing was related to the product of concentration and time, that study used a qualitative assess-
ment of killing rather than the quantitative measures used in the present study.

We observed that the maximal effect (reduction, approximately 4 log$_{10}$ CFU/ml) and the concentration required for 50% of the maximal effect (C/MIC, 0.5) remained unchanged even when the C/MIC was increased to 5,120. In addition, all of the observed effect accrued during the first 2 days of drug exposure. Subsequently, the effect was bacteriostatic and independent of an increase in the concentration. One explanation for this could be that only the actively growing bacilli were killed very rapidly within the first 48 h and the residual bacterial population was nonreplicating and thus was unaffected by isoniazid (6, 11). These results are different from the bactericidal effect of rifampin, in which there was complete eradication (reduction, >5 log$_{10}$ CFU/ml) within the first 2 days, although the 50% maximal effect required a C/MIC ratio up to 100-fold higher than that for isoniazid (7). Our in vitro killing data for isoniazid are consistent with the observed early bactericidal activity of isoniazid in patients with strongly positive sputum smears (4): the bactericidal effect seen during days 2 to 14 was not as profound as that seen during the first 2 days of therapy.

In contrast to its effect on extracellular bacilli, the activity of isoniazid against bacilli actively replicating in the macrophage was drastically diminished. Although stasis was seen at a drug concentration equal to the MIC in broth, the maximum killing achieved was a reduction of approximately 0.5 ml log$_{10}$ CFU/ml even when the external concentration was maintained at 32 mg/liter for 4 days. The rates of killing were the same between C/MICs of 10 and 640, indicating that isoniazid produced only a bacteriostatic effect on the intracellular bacteria.

The fact that isoniazid was bacteriostatic and yet not completely ineffective in the intracellular models is intriguing, since it indicated that isoniazid did come into contact with the bacilli without producing killing. It is possible that at the phagosomal location of M. tuberculosis in the macrophage the pH is not optimal for the bactericidal action of isoniazid (15). Although it is possible that the bacilli were not rapidly dividing within the macrophage and thus were refractory to the bactericidal mechanisms of isoniazid, our growth curve experiments (Fig. 2) show that in the absence of isoniazid there was a 0.7 log increase in CFU over a 3-day period, which is a greater increase than that observed in the BACTEC 7H12B broth-based killing experiments, in which drug exposure was started at the late log or early stationary phase. We have also ruled out the possibility that the bacteriostatic effect of isoniazid is due to instability of the drug. Our findings are in agreement with those reported by Rastogi et al. (13) but are in sharp contrast to the data reported by Orme and colleagues (16), in which a reduction of 3 log$_{10}$ CFU/ml over a narrow concentration range between 0 and 1 mg of isoniazid per liter was observed with intracellular M. tuberculosis Erdman in murine macrophages.
The whole-blood system has advantages over a macrophage monolayer system; for example, plasma protein binding and immune components can be factored in, thereby mimicking the in vivo situation closely (18). Furthermore, exposures up to 2,560-fold higher than the concentration producing stasis can be studied in comparison to the exposures possible in the macrophage monolayer system (640-fold higher). Despite the higher exposures achieved in the whole-blood system, isoniazid remained bacteriostatic with increasing concentrations over a 2-day period. This is in contrast to the 2-log₁₀ CFU/ml reduction reported by Wallis et al. (19). This difference could be due to differences in the measure of killing. Whereas our analysis was based on a direct measure of the numbers of surviving CFU, Wallis et al. (19) used a surrogate measure for CFU that was based on the metabolism of radiolabeled palmitate. Such an indirect approach may make a bacteriostatic effect appear to be cidal since the bacteria may not be metabolizing, even though they remain alive.

AUC₂₄/MIC was the PK-PD parameter that best described the bactericidal activity of isoniazid in the mouse model, with a correlation of 0.83. The maximal effect of a 1.3-log₁₀ CFU/lung reduction was seen at an AUC₂₄/MIC of approximately 500. Stated differently, the effect of isoniazid was the same when the total dose was given as 6, 12, or 18 equally divided doses over a period of 1 week. Consistent with our data, Mitchison (12) observed that the efficacy of a fixed total dose of isoniazid in infected guinea pigs was similar whether it was given daily, every 2 days, or every 4 days over a period of 6 weeks. Thus, the efficacy of isoniazid is dependent only on the dose size and not the regimen.

While the killing kinetics in broth suggested the PK-PD driver, the intracellular infection models better predicted the magnitude of the effect in vivo (Fig. 7). This is consistent with the relationships observed for rifampin as well, in which a significant bactericidal effect in macrophages correlated with the bactericidal effect seen in mice (7).

In summary, we have identified the PD parameter that dictates the bactericidal efficacy of isoniazid in the murine model. This study further provides a PK-PD basis for progressing lead compounds in the drug discovery process.

REFERENCES