Methyliosothiazolinone, A Neurotoxic Biocide, Disrupts the Association of Src Family Tyrosine Kinases with Focal Adhesion Kinase in Developing Cortical Neurons

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ABSTRACT

Methyliosothiazolinone (MIT) is a biocide widely used in industrial and cosmetic products with potential as a neurotoxicant. We previously reported that short acute exposures to relatively high concentrations of MIT (100 μM) lead to widespread and selective neuronal death in vitro. To evaluate the biological properties of chronic exposures to MIT, freshly dissociated rat cortical neurons were continuously exposed to low concentrations (0.1–3 μM) of the biocide in serum-containing media. Although we observed minimal effects on cell viability, MIT induced a dramatic inhibition of neurite outgrowth. Immunoblotting and immunoprecipitation experiments revealed that focal adhesion kinase (FAK) phosphorylation was primarily affected by the MIT treatment. The phosphorylation level at tyrosines 576 and 861 of FAK was significantly decreased and likely contributed to the overall reduction of tyrosine phosphorylation of this protein. MIT inhibited Src family kinases (SFKs) in cell-free assays and led to the physical dissociation of FAK from the signaling complexes that it normally forms with c-Src and Fyn in developing neurons. High-density neuronal cultures were then employed to increase cell-to-cell contact. This approach resulted in an overall enhancement of SFKs and FAK phosphorylation and could overcome the deficits induced by MIT. This study suggests that a disruption of FAK-SFK complexes due to SFK inhibition leads to FAK dysfunction, with detrimental effects to immature neurons. Prolonged exposure to low levels of MIT and related compounds may have damaging consequences to the developing nervous system.

Isothiazolone and its derivatives are a class of common chemical biocides used as preservatives to control microbial growth in a very large number of industrial applications and in household products. These compounds have an active sulfur moiety that can react with and oxidize thiol-containing residues, thereby effectively killing most aerobic and anaerobic bacteria as well as fungi and other microorganisms (Collier et al., 1990). In addition, isothiazolone derivatives can inhibit human immunodeficiency virus replication in vitro (Rice et al., 1995) and can reduce tumor mass in a mouse model of human breast cancer (Wang et al., 2004).

Two widely used isothiazolone biocides are 5-chloro-2-methyl-4-isothiazolin-3-one (CMIT) and 2-methyl-4-isothiazolin-3-one (MIT), which are the active ingredients in a biocide mixture sold commercially as Kathon. They are supplied either as a single chemical solution or in combination at a wide range of concentrations (1.5–50%). As the use of these compounds has risen dramatically in recent years, there is increased concern about their potential risks to humans through inhalation and skin contact. Previous in vitro studies have shown that CMIT and MIT are profoundly cytotoxic to different types of cell lines (Ettorre et al., 2003). In addition, our group has reported that MIT is a highly selective neurotoxin, largely sparing glia, following a short acute exposure in established, mature rat cerebrocortical cultures (Du et al., 2002). MIT, under these conditions, triggered noncaspase-dependent cell death following the liberation of intracellular zinc and sequential activation of 12-lipoxygenase, extracellular signal-regulated kinase (ERK), and NADPH oxidase, leading to reactive oxygen species production, DNA damage, and overactivation of poly(ADP-ribose) polymerase (Du et al., 2002).

In the present study, we sought to investigate the neurotoxic consequences of prolonged applications of MIT at much lower concentrations than those utilized previously. Here, we...
present evidence that MIT can inhibit Src family kinases (SFKs) and describe a MIT-induced disruption of the functional interaction between focal adhesion kinase (FAK) and SFKs. This results in a reduced level of tyrosine phosphorylation on FAK that is probably responsible for MIT’s neurotoxic actions on developing cortical neurons in vitro.

Materials and Methods

Materials. Antibodies used in this study were from the following sources: mouse anti-FAK monoclonal antibody (clone 4G4) and anti-phosphotyrosine antibody (clone 4G10), Upstate Biotechnology (Lake Placid, NY); mouse anti-FAK monoclonal antibody, MBL International (Woburn, MA); rabbit anti-Src monoclonal antibody (36D10), rabbit anti-ERK1/2, and anti-phospho-ERK1/2 polyclonal antibodies, Cell Signaling (Beverly, MA); mouse anti-PYK2/2 cell adhesion kinase β monoclonal antibody, BD Biosciences/Transduction Laboratories (San Diego, CA); rabbit anti-Fyn antibody, mouse anti-Src monoclonal antibody (B-12), and protein A/G plus-agarose, Santa Cruz Biotechnology (Santa Cruz, CA); horseradish peroxidase-conjugated goat secondary antibodies against either mouse or rabbit IgG, Bio-Rad (Hercules, CA); and mouse anti-neuronal class III β-tubulin (TuJ1) monoclonal antibody, Covance (Berkeley, CA). Rabbit anti-Src pY418 and pY529 phosphospecific antibodies and rabbit phosphorilation site-specific anti-FAK antibodies were purchased from Biosource International, Inc. (Camarillo, CA). Enolase and fluorescein isothiocyanate-labeled anti-mouse IgG secondary antibody were from Sigma (St. Louis, MO). Partially purified, active c-Src, and Fyn kinases were from Upstate Biotechnology. Recombinant active FAK kinase was from Biosource. PD98059 and U0126 were from Calbiochem (La Jolla, CA). Alexa Fluor 546 phalloidin for labeling F-actin was from Molecular Probes (Eugene, OR). Mouse monoclonal antibody against tubulin was a generous gift from Dr. Willi Halfter (University of Pittsburgh). Bicinchoninic acid-based Protein A/G plus-agarose, Santa Cruz Biotechnology (Santa Cruz, CA); horseradish peroxidase-conjugated goat secondary antibodies against either mouse or rabbit IgG, Bio-Rad (Hercules, CA); and mouse anti-neuronal class III β-tubulin (TuJ1) monoclonal antibody, Covance (Berkeley, CA). Rabbit anti-Src pY418 and pY529 phosphospecific antibodies and rabbit phosphorilation site-specific anti-FAK antibodies were purchased from Biosource International, Inc. (Camarillo, CA). Enolase and fluorescein isothiocyanate-labeled anti-mouse IgG secondary antibody were from Sigma (St. Louis, MO). Partially purified, active c-Src, and Fyn kinases were from Upstate Biotechnology. Recombinant active FAK kinase was from Biosource. PD98059 and U0126 were from Calbiochem (La Jolla, CA). Alexa Fluor 546 phalloidin for labeling F-actin was from Molecular Probes (Eugene, OR). Mouse monoclonal antibody against tubulin was a generous gift from Dr. Willi Halfter (University of Pittsburgh). Bicinchoninic acid-based

Cell Culture. Cultures were prepared from the cerebral cortex of embryonic day 17 Sprague-Dawley rat fetuses (Hartnett et al., 1997). In brief, dissociated cells were suspended in plating medium composed of 80% Dulbecco’s modified Eagle’s medium (Invitrogen, Gaithersburg, MD), 10% Ham’s F-12 nutrients, and 10% heat-inactivated bovine calf serum with iron supplement (Hyclone, Logan, UT), with 104 cells/ml, were added to each PLL-coated well of a 24-well plate to produce a low-cell density culture (5.21 × 103 cells/ml) for 1 h. To harvest protein, cell-containing dishes were briefly rinsed twice with ice-cold PBS, and cells were then gently scraped off the dishes on ice after addition of lysis buffer (50 mM HEPES, pH 7.5, 1% Triton X-100, 0.1% SDS, 0.25% sodium deoxycholate, 150 mM NaCl, 1 mM phenylmethylsulfonyl fluoride, 1 mM sodium vanadate, 10 mM sodium fluoride, 10 mM sodium pyrophosphate, 25 mM β-glycerophosphate, 5 μg/ml leupeptin, 5 μg/ml aprotinin, and 2 mM benzamidine). Debris was pelleted by centrifugation for 10 min, and the remaining lysate was used immediately or stored at −20°C. The protein concentrations of the samples were measured with the bicinchoninic acid method according to the manufacturer’s protocol.

Immunoprecipitation. Equal amounts of total proteins from MIT-treated cell extract or control were mixed with 2 to 3 μg of either mouse anti-FAK or anti-PYK2 monoclonal antibody and incubated at 4°C overnight with gentle agitation. The immune complex of specific protein and mouse antibody was then mixed in a rotary rotator with 100 μl of 50% (v/v) affinity gel coupled with rabbit anti-mouse IgG antibody at 4°C for an additional 2 h. For SFK protein binding assays, cells were lysed following inactivation of MIT, and samples were precleared with protein A/G plus-agarose for 3 h at 4°C before incubation with 10 μl of rabbit antibody against Src or Fyn overnight at 4°C. Antibody-protein complexes were precipitated with 40 μl of protein A/G plus-agarose for 3 h at 4°C. All beads were then washed and dissolved in 2× reducing electrophoresis sample buffer and boiled at 100°C for 5 min. With brief centrifugation, the supernatants of protein samples were collected and later subjected to gel electrophoresis.

Electrophoresis and Immunoblotting. SDS-polyacrylamide gel electrophoresis (PAGE) was carried out by standard procedures using the Mini Protein 3 System (Bio-Rad). Before electrophoresis, protein samples, with the exception of those samples prepared by immunoprecipitation, were treated with the reducing electrophoresis sample buffer from Pierce and boiled at 100°C for 5 min. Samples with equal amount of protein and a broad-range molecular weight protein marker from Bio-Rad were run in parallel on 10% SDS-PAGE gel. For immunoblotting analysis, separated protein bands were transferred onto a 0.2 μm-nitrocellulose membrane (Bio-Rad).
Protein transfer was confirmed by staining with Ponceau S solution (0.1% Ponceau S in 5% acetic acid). The membranes were then blocked with 1% nonfat milk powder in PBS with 0.05% Tween 20 (PBST) at room temperature for 1 h and probed with appropriately labeled primary antibodies diluted in PBST. After washing (three times) in PBST, blots were incubated with goat secondary antibody conjugated to horseradish peroxidase at room temperature for 1 h. Blots were then visualized using SuperSignal CL-HRP Substrate System (Pierce) and exposed to BioMax films (Eastman Kodak, Rochester, NY). Equal protein loading was evaluated using two approaches. Generally, the blots were stripped [100 mM 2-mercaptoethanol, 2% (w/v) SDS, and 62.5 mM Tris-HCl, pH 6.7] for 30 min at 50°C and then reprobed with primary and secondary antibodies as described above. Alternatively, an identical gel was run in parallel, and the additional blot was used to check protein loading. This method was employed in cases of low levels of protein, in which the stripping method could not provide accurate detection. The developed films were scanned and analyzed using Scion Image software (version 4.02; Scion Corporation, Frederick, MD).

**Statistical Analysis.** Data are expressed as the mean ± S.E.M. Experimental data were analyzed by one-way analysis of variance (ANOVA) with post hoc comparisons or by pair-wise comparisons (Student’s t test).

**Results**

**Neurotoxic Consequences of MIT Exposure to Developing Cortical Neurons.** To assess the toxicity of MIT on developing neurons, cells were plated at a density of 5.21 × 10⁴ cells/cm², allowed to adhere for 3 h (time 0 h in Fig. 3 and subsequent figures), and then treated with varying concentrations of the biocide (0.1, 0.3, 1, and 3 μM) for 14 h. The viability of neurons was determined by measuring total cytoplasmic LDH activity in the remaining cells. Under these conditions, we observed a modest level (~35%) of MIT-induced cell death, but only when the concentration of the biocide reached 3 μM (Fig. 1). At 1 μM MIT or below, no significant cell loss could be detected. Strikingly, however, we observed a profound inhibition of process outgrowth by these low concentrations of MIT (Fig. 2). Therefore, we turned our attention to investigate this phenomenon further. After overnight incubation with 0 to 1 μM MIT, neurons were fixed and stained with a monoclonal antibody against neuronal class III β-tubulin. Comparing the morphological changes between control and treated neurons (Fig. 2, A–C), we found a significant inhibition of process outgrowth by 1 μM MIT (Fig. 2G), although at 0.3 μM, there was an observable trend to shorter neurites as well. In subsequent studies, the medium containing MIT was removed from sister culture plates after the 14-h treatment, and cells were washed, refed with normal growth medium, and maintained for an additional 4 days. Under these conditions, many MIT-pretreated neurons showed shorter and less elaborate processes as they appeared to experience slow growth and decreased cell-to-cell contact, perhaps due to a decrease in neuronal mobility (Fig. 2, compare D with E and F). These results suggest that chronic exposures to low concentrations of MIT had toxic effects on immature cortical neurons in culture, which were manifested primarily by a pronounced inhibition of process outgrowth.

**Characterization of FAK as a Signaling Protein Regulated by MIT.** We next investigated the biochemical pathways involved in this neurotoxicity by searching for potential MIT-sensitive signaling proteins. We first examined the overall level of protein tyrosine phosphorylation in treated and untreated cultures. Embryonic rat cortical neurons were plated and allowed to adhere to tissue culture plates for 3 h. Cells were then treated with either vehicle or 2 μM MIT for an additional 4 h. Protein samples were then harvested, separated by SDS-PAGE, transferred onto nitrocellulose membranes, and immunoblotted with a phosphotyrosine-specific monoclonal antibody (4G10). Proteins bearing phospho-tyrosines exhibited a wide range of molecular weights (Fig. 3A), and there was a basal level of tyrosine-phosphorylated proteins in control cultures (Fig. 3A, 0 h). Interestingly, we found that the level of tyrosine phosphorylation of one single major protein with an approximate molecular mass of ~125 kDa had been substantially affected by MIT treatment (Fig. 3A, arrow). To identify this 125-kDa protein, we first tested if its tyrosine phosphorylation levels were affected upon cell adhesion. We observed that the phosphorylation of this protein was barely detectable in cell extracts generated from cell suspensions (data not shown). In contrast, extracts harvested from cells plated onto PLL-coated dishes had substantial levels of tyrosine phosphorylation, suggestive of an adhesion-related process. This unknown protein thus had a number of characteristic attributes, including a high level of tyrosine phosphorylation upon cell adhesion, seemingly associated with neurite outgrowth, and a molecular mass of approximately 125 kDa. With this information, we hypothesized this protein to be FAK. Indeed, a monoclonal antibody specific for FAK detected a major protein band of 125 kDa in samples treated with or without MIT, which comigrated with the antiphosphotyrosine antibody-reacting band (Fig. 3B). To confirm the identity of this protein as FAK, we performed immunoprecipitation with an anti-FAK antibody. Cell extracts were prepared from MIT or vehicle-treated cultures. Proteins were immunoprecipitated and then immunoblotted.
Fig. 2. MIT impairs neurite outgrowth. Freshly dissociated embryonic rat cortical neurons \((5.21 \times 10^4 \text{ cells/cm}^2)\) were plated on poly-L-lysine-coated glass coverslips for 3 h and then treated with vehicle (A and D) or 0.3 (B and E) or 1 (C and F) \(\mu\text{M}\) MIT. A to C, neurons were cultured overnight in the presence or absence of MIT. D to F, neurons were cultured with or without MIT overnight and then returned to normal growth medium without MIT for an additional 4 days. Neurons were fixed and immunocytochemically stained with mouse antibody specific for neuronal class III \(\beta\)-tubulin. Immunofluorescent labeling of cells was done using a fluorescein isothiocyanate-conjugated anti-mouse IgG secondary antibody. Representative photographs show morphological changes on neurons as a result of MIT treatment. G, quantification of the concentration-dependent inhibition of neurite outgrowth induced by MIT. Values represent mean \(\pm\) S.E.M. of five independent experiments (**, \(p < 0.01\), compared with control; ANOVA/Dunnett).

Fig. 3. Deficits in FAK phosphorylation as a result of MIT treatment. Freshly dissociated embryonic (E17) cortical neurons were plated at low-cell density as described in Materials and Methods. A, after 3 h in culture (designated as 0 h, before MIT treatment), cells were treated with MIT (2 \(\mu\text{M}\)) or vehicle for 4 h. Protein samples were collected, and equal amounts of proteins were separated by 10% reducing SDS-PAGE and transferred to a nitrocellulose membrane. The resulting blot was probed with a mouse monoclonal antibody specific for phosphotyrosine. Compared with control (0 h), proteins showed an increasing level of tyrosine phosphorylation with time in culture (4 h). The arrow points to a protein band with a substantial reduction of tyrosine phosphorylation in the presence of MIT. Protein loading for all samples was identical as judged by Coomassie Blue-stained SDS-PAGE gels (data not shown). B, samples were prepared after incubation with either vehicle or MIT (2 \(\mu\text{M}\)) for 45 min. Two identical protein-bound nitrocellulose membranes were blotted with antibodies against either phosphotyrosine (P-Tyr) or FAK. Arrow, position is the same for the band with decreased phosphotyrosine levels after MIT treatment. C, immunoprecipitation of FAK from cortical neurons. Anti-FAK immunoprecipitated proteins were probed with anti-phosphotyrosine monoclonal antibody (P-Tyr) indicated by arrow (top). After stripping this antibody, blot was reprobed with anti-FAK monoclonal antibody (FAK) to demonstrate equal protein loading (bottom). These data are a representative of results from three independent experiments. D, early and persistent impairment of FAK phosphorylation by MIT. Cells plated at low density as mentioned above were cultured for 3 h (0-h time point) and then treated with MIT (2 \(\mu\text{M}\)) or vehicle for 0.5, 2, or 8 h and harvested. Two identical protein-bound nitrocellulose membranes were blotted with antibodies, either anti-phosphotyrosine antibody (P-Tyr) or anti-FAK antibody (FAK), the latter serving as a loading control. Data shown are representative of two independent experiments.
with anti-phosphotyrosine antibody. Figure 3C shows that the level of phosphotyrosine on immunopurified FAK was substantially decreased when compared with control. These data indicate that the MIT-sensitive 125-kDa protein is indeed FAK.

The deficits in tyrosine phosphorylation of FAK could be detected as early as 30 min following MIT treatment, and this inhibitory effect was still present as late as 8 h (Fig. 3D). In contrast, tyrosine phosphorylation of FAK in vehicle-treated cultures continued to increase with time in culture. Hence, the inhibitory actions of MIT on FAK phosphorylation were both rapid and persistent. FAK is a multiple tyrosine-containing enzyme with as many as six tyrosine residues that have been identified as phosphorylation targets. As such, we analyzed the level of phosphorylation at four tyrosine residues of FAK with phosphorylation site-specific antibodies (Fig. 4A). We observed a 60% decrease in the phosphorylation state of Tyr576 within the kinase domain of FAK and approximately a 40% decrease at Tyr861 in MIT-treated neurons (Fig. 4B). In contrast, the phosphorylation levels of tyrosine 407 were not significantly altered when compared with vehicle-treated cultures. We also noted an abundant level of autophosphorylation at tyrosine 397 in samples obtained from MIT-treated cultures.

**Direct Inhibition of MIT on c-Src Kinase Activity in Cell-Free Assays.** Earlier studies have demonstrated that phosphorylation of FAK at Tyr576, Tyr577, and Tyr861 is primarily regulated by the nonreceptor protein tyrosine kinase c-Src and other SFKs (Calalb et al., 1995). We thus tested whether MIT inhibited FAK phosphorylation directly or via SFK inhibition. First, the effects of this biocide on c-Src activity were evaluated using a commercially available, purified recombinant kinase. Changes of tyrosine kinase activity of c-Src after MIT treatment were measured by detecting the level of autophosphorylation at tyrosine 418, as well as the level of tyrosine phosphorylation of the exogenous substrate enolase using a cell-free assay. As shown in Fig. 5A, using a phosphospecific antibody against Src Tyr418, we found that the autophosphorylation of c-Src was decreased by MIT (50 μM), indicating that the biocide probably directly inhibited c-Src. Consistent with this observation, the tyrosine phosphorylation of enolase was also inhibited at the same concentration of MIT (Fig. 5B). However, no change of the phosphorylation at (Tyr529) on the inhibitory domain of c-Src could be detected (data not shown), suggesting at least a certain degree of specificity to MIT’s inhibitory actions on c-Src kinase activity. We also employed purified recombinant Fyn kinase, another SFKs member, and tested it in a similar fashion. We found that MIT had similar inhibitory effects on this kinase as well (data not shown). The concentrations of MIT required to produce inhibition of c-Src and Fyn were much higher than those needed to observe its deleterious actions in neurons. This is probably due to the need to overcome the high concentration of dithiothreitol present in these commercially available active enzymes. Finally, we proceeded to test any possible direct inhibitory effects of MIT on FAK. However, we found no change in the levels of tyrosine phosphorylation of enolase catalyzed by FAK in the presence of MIT at concentrations as high as 100 μM (data not shown). These results strongly suggest that MIT can inhibit the kinase activity of SFKs and not FAK.

**MIT Induces Physical Disassociation of c-Src and Fyn from FAK in Developing Cortical Neurons.** It is well documented that c-Src and Fyn are highly expressed in the developing nervous system. Previous studies have shown that the autophosphorylation site of FAK at Tyr397 participates in a binding site for c-Src or Fyn to form a functional signaling complex (Cobb et al., 1994), facilitating SFK-induced phosphorylation of other tyrosine residues on FAK (Calalb et al., 1995). We thus tested whether the association between FAK with c-Src or Fyn could be altered in cultured neurons following MIT treatment. Immunoprecipitation experiments were performed using antibodies specific for c-Src and Fyn. Immune complexes containing endogenous c-Src or...
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Enhanced Cellular SFK Activity and FAK Phosphorylation by High-Density Culture in MIT-Exposed Neurons. Cell density can influence the phosphorylation state of c-Src and FAK in cultured cells by facilitating cell-to-cell contact and cell adhesion molecule-dependent signaling (Batt and Roberts, 1998). In preliminary studies, we observed that neurons plated on L1 or neural cell adhesion molecule (NCAM) could partially overcome the deleterious actions of MIT on neurite outgrowth. We thus investigated if neurons grown at various cell densities responded differently to the toxic actions of MIT. Two different methods to increasing cell density were employed and examined the degree of SFKs and FAK tyrosine phosphorylation in the presence or absence of MIT. First, cells were plated in increasing numbers in tissue culture plates of the same size (100 mm). Under these conditions, we observed a higher level of autophosphorylation (Tyr418) on endogenous SFKs (the phospho-specific antibody is nonselective for SFKs) in control cells with increasing cell density, although phosphorylation level of Tyr529 remained unchanged (Fig. 7). The inhibitory actions of MIT seen at low-cell density culture could be reversed by the high-density growth conditions (Fig. 7, top). Likewise, the phosphorylation level of FAK increased with higher cell density, with MIT unable to inhibit the phosphorylation of this kinase under these circumstances (Fig. 8A). In the second set of experiments (Fig. 8B), we plated the same number of cells in tissue culture plates of various sizes (35, 60, and 100 mm). This strategy also resulted in different cell densities, but the total number of cells in the culture remained the same. Both the level of FAK tyrosine phosphorylation and the inhibitory actions of MIT essentially reproduced what had been observed using the first strategy. The evidence presented in this series of studies indicates that increased cell-to-cell contact resulting in increased kinase activity of SFKs as well as tyrosine phosphorylation of FAK can overcome the actions of MIT in cultured neurons. Whether higher concentrations of MIT could reverse this effect could not be tested because the previously reported cell death pathway is then rapidly triggered (Du et al., 2002).

Phosphorylation ERK1/2 and PYK2 Are Not Affected by MIT Treatment. FAK can act as an adapter protein, integrating signals to alter cell function via several signaling pathways, including ERK. In our previous study, we reported that the acute toxicity induced by high concentrations of MIT was mediated via ERK activation (Du et al., 2002). We thus sought to determine whether the neurite growth-inhibiting effects of MIT could reverse this effect could not be tested because the previously reported cell death pathway is then rapidly triggered (Du et al., 2002).

Cell density modulates the kinase activity of SFKs in cultured neurons. Freshly dissociated cells (18.5 ml) were plated at different densities to control cell-to-cell contact (low, 2.51 × 10^5; medium, 5.01 × 10^5; high, 1 × 10^6 cells/ml) onto 100-mm culture dishes, allowed to adhere for 3 h, and then treated with either vehicle or MIT (2 μM) for an additional 1 h. Cells were then lysed, and proteins were harvested. The immunoblot (top) was performed with a rabbit phosphospecific antibody to Src (pY418), reflective of SFK activity. An identical blot was also probed with a rabbit phosphospecific antibody to Src (pY529), which served as a loading control. This result also suggests that MIT does not interfere with the inhibitory domain of SFKs. Data shown are representative of three independent experiments.

Materials and Methods. In this study, we sought to determine whether the neurite growth-inhibiting effects of MIT could reverse this effect. Neurons were isolated from rat embryos at E18.5, plated onto 100-mm culture dishes for 3 h. They were then treated with MIT (4 μM) or vehicle for 1 h. Samples were harvested, and immunoprecipitation was performed with rabbit anti-Fyn (FYN3) or anti-Src (36D10) antibodies. The amount of FAK in either Fyn or Src-related immunoprecipitate was detected using a mouse anti-FAK monoclonal antibody, and the levels of immunoprecipitated Fyn and Src were also probed using a mouse antibody. Data shown are representative of three independent experiments.

Fig. 5. MIT inhibits autophosphorylation of Src kinase and Src-dependent enolase tyrosine phosphorylation. Protein samples were prepared as described under Materials and Methods using recombinant active Src. In the top panels of A and B, Src autophosphorylation was detected using a rabbit phosphospecific antibody to Src(pY418), whereas the level of phosphorylated enolase was probed using an anti-phosphotyrosine antibody. Background protein loading was checked on respective membranes after stripping, using anti-Src antibody or anti-enolase antibody (A and B, bottom). Data shown are representative of three independent experiments.

Fig. 6. MIT causes cellular FAK dissociation from the signaling complex with SFKs. Freshly dissociated neurons (18.5 ml, 5 × 10^5 cells/ml) were plated on 100-mm culture dishes for 3 h. They were then treated with MET (4 μM) or vehicle for 1 h. Samples were harvested, and immunoprecipitation was performed with rabbit anti-Fyn (FYN3) or anti-Src (36D10) antibodies. The amount of FAK in either Fyn or Src-related immunoprecipitate was detected using a mouse anti-FAK monoclonal antibody, and the levels of immunoprecipitated Fyn and Src were also probed using a mouse antibody. Data shown are representative of three independent experiments.

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actions of MIT involved changes in the level of activation of this mitogen-activated protein kinase. Cell lysates harvested from neuronal cultures treated with vehicle or MIT (2 μM) for either 30 min or 2 h were probed with an anti-phosphorylated ERK1/2 polyclonal antibody. In contrast to the results obtained with FAK, we observed no changes in the level of ERK phosphorylation with either plating time or MIT treatment (Fig. 9A). Finally, we observed that U0126 and PD98059 failed to inhibit neurite outgrowth in our cultures (Fig. 9B). These data indicate that the ERK pathway is

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**Fig. 8.** Enhanced cell density prevents MIT-induced impairment of FAK phosphorylation. A, samples from freshly dissociated cells were prepared as same as described in Fig. 7. Two identical immunoblots (top) were performed with anti-phosphotyrosine antibody (P-Tyr) and anti-FAK antibody (FAK), respectively, the latter serving as a loading control. In the bottom, blots were quantified and normalized to control. Values represent the means ± S.E.M. (n = 3). A one-way ANOVA revealed a significant effect of cell density on FAK phosphorylation in MIT-treated cultures (p < 0.001). B, alternative approach to increase cell density. An equal number of cells (7.74 × 10^5 cells/ml; 6 ml) were plated onto culture dishes of different diameters (low, 100 mm; medium, 60 mm; high, 35 mm). Cells were then lysed, and proteins were harvested. Two identical immunoblots (top) were performed with anti-phosphotyrosine antibody (P-Tyr) and anti-FAK antibody (FAK), respectively, the latter serving as a loading control. In the bottom, blots were quantified and normalized to control. Values represent the means ± S.E.M. (n = 3). A one-way ANOVA revealed a significant effect of cell density on FAK phosphorylation in MIT-treated cultures (p < 0.01).

**Fig. 9.** MIT does not interfere with ERK and Pyk2 signaling. Cells were plated at low density the same as described in Fig. 8 and cultured for 3 h. A, following 3-h plating (0-h time point), cells were treated with either vehicle or MIT (2 μM) for 0.5 and 2 h. At each designated time point, cells were harvested and lysed; protein samples were immunoblotted with anti-phosphorylated Erk1/2 antibody (P-ERK1/2) and later reprobed with anti-Erk1/2 antibody (ERK1/2, bottom). No changes in ERK1/2 phosphorylation were noted with MIT treatment. B, cells were treated with either vehicle or the ERK activation inhibitors U0126 (10 μM) and PD98059 (38.7 μM) overnight. Representative phase-contrast photographs show that inhibitors of ERK activation do not interfere with neurite outgrowth in our system. C, following the treatment with either vehicle or MIT (2 μM) for 1 h, cells were lysed, and Pyk2 was immunoprecipitated using an anti-Pyk2 monoclonal antibody. Proteins were separated by 10% reducing SDS-PAGE and transferred onto nitrocellulose membranes. Two identical membranes were immunoblotted with anti-phosphotyrosine antibody (P-Tyr, top) and anti-Pyk2 antibody (Pyk2, bottom).
probably not involved in the neurodevelopmental toxic actions of low concentration of MIT.

In our final set of experiments, we were keen to explore PYK2-related adhesion focal tyrosine kinase/cell adhesion kinase \( \beta \) as a potential downstream target in our developmental MIT toxicity paradigm. PYK2, like FAK, is a non-receptor tyrosine kinase highly expressed in neuronal cells (Girault et al., 1999). It shares a high degree of sequence similarity and biochemical properties with FAK, in addition to possessing multiple sites of tyrosine phosphorylation (Girault et al., 1999). PYK2 was immunoprecipitated from MIT-treated sample and vehicle-treated controls using a mouse anti-PYK2 monoclonal antibody and probed with anti-phosphotyrosine antibody. We observed no difference in PYK2 phosphorylation under both conditions (Fig. 9C), suggesting that this protein was not a target of the toxic actions of MIT.

**Discussion**

**Molecular Mechanism of Neurodevelopmental MIT Toxicity.** The regulation and interaction of SFKs with FAK, stimulated by integrins, cell adhesion molecules, and extracellular matrix proteins, is recognized to play an important role in many cellular processes, including neural development. Here, we report a previously unrecognized consequence of SFK inhibition by the thiol-reactive compound MIT, namely a physical dissociation of FAK from the signaling complex, leading to FAK dephosphorylation and probably loss or decrease of function of the signaling cascade. Our results also demonstrate that MIT, at low concentrations, significantly impairs the growth of neurites and can cause neuronal death in freshly dissociated cortical neurons in vitro.

Our studies show that SFKs are sensitive targets for the thiol modification by MIT. In contrast, FAK is not directly inhibited by the biocide, although its phosphorylation level clearly, albeit indirectly, is. The autophosphorylation of Src Tyr418 can be used as an indicator of kinase activity because its phosphorylation level correlates well with enzyme activity (Boerner et al., 1996). MIT decreased the phosphorylation of this tyrosine and impaired its kinase function, whereas the phosphorylation level of another tyrosine in Src, Tyr529, remained unaffected. Our results are highly reminiscent of other studies in which thiol modification on SFKs were reported to affect Tyr418 phosphorylation-associated processes, independently of Tyr529 phosphorylation (Akhand et al., 1999). SFKs have a cluster of cysteine residues in their kinase domains. Of these, cysteine 487 and cysteine 498 are highly conserved and are critical for enzymatic activity (Senga et al., 2000); modification of these sulfhydryl groups can abolish the kinase activities of both Src and Lck (Üehara et al., 1989; Veillette et al., 1993; Senga et al., 2000; Oo et al., 2003). Interestingly, it has been reported that an isothiazole-derived compound can inhibit Lck activity via precisely this mechanism (Trevillyan et al., 1999). Related to this, we have recently observed that herbimycin A, an SFK inhibitor also possessing thiol reactivity, inhibits neurite outgrowth in cortical neurons. Herbimycin A has been shown to inhibit neuronal migration, differentiation, and FAK tyrosine phosphorylation in rat cortical neurons (Maeda and Noda, 1998).

It is generally believed that after cell adhesion-stimulated autophosphorylation of FAK Tyr397, SFKs are recruited to form a complex via their SH2 binding domain. This results in the activation of SFKs and subsequent phosphorylation of other tyrosines on FAK, including Tyr576 and Tyr677 on the kinase domain, as well as Tyr861 in the C-terminal domain (Calalb et al., 1995). Our data suggest that, as a result of MIT exposure, SFKs dissociate from the complex and fail to phosphorylate FAK. The fact that phosphorylation of FAK Tyr397 was unaltered in MIT-treated cultures suggests that the initial cell adhesion process after plating is sufficient for autophosphorylation to occur. SFKs have an additional pair of highly conserved cysteines (Cys238 and Cys245) in the SH2 domain (Oo et al., 2003). Thus, it is also plausible that MIT also interacts with these thiol to promote the dissociation of the signaling complex.

**Effects of Plating Density.** Increased cell plating densities reversed the effects of MIT on FAK phosphorylation. When cells are plated at a high density, increased cell-to-cell contact may initiate multiple cellular signaling pathways by cell adhesion molecules such as integrins, cadherins, and the Ig superfamily. The effects of these possibly nonoverlapping signaling pathways may then be sufficient to compensate for the detrimental actions of MIT. For instance, NCAM can stimulate neurite outgrowth via a signaling pathway requiring the Src family kinase Fyn (Beggs et al., 1994), and immunoprecipitation studies have demonstrated the association of NCAM with Fyn and FAK, leading to the increased tyrosine phosphorylation of both kinases (Beggs et al., 1997). In contrast, the adhesion molecule L1 stimulates neurite outgrowth via a homophilic binding mechanism involving Src but independently of FAK activation (Iguelzi et al., 1994; Schmid et al., 2000). In preliminary studies, when we used L1 and NCAM as coating substrates, we found they could partially reverse the deleterious actions of MIT on neurite outgrowth. Therefore, cross-talk between signaling pathways triggered by cell contact may be sufficient to overcome the actions of MIT, at least at the low concentrations tested. We could not properly evaluate whether higher concentrations of MIT could overcome the high-density plating effect as the biocide then becomes highly lethal via a different pathway (Du et al., 2002).

**ERK Activation Is Not Involved in Neurite Outgrowth in Cortical Neurons.** In addition to its kinase activity, FAK has been suggested to work as a scaffolding protein to integrate multiple signaling pathways in response to extracellular stimuli (Sieg et al., 2000; Parsons, 2003). One of these downstream signaling pathways from FAK is the mitogen-activated protein kinase ERK (Schaller, 2001). We were not able, however, to detect any changes in the phosphorylation levels of ERK upon MIT exposure, nor did ERK activation inhibitors prevent neurite outgrowth. Since our exposure conditions were performed in the presence of serum, it is likely that trophic factors present in the plating media were sufficient to trigger ERK activation. The fact that ERK activation inhibitors were unable to inhibit neurite outgrowth suggests that, under our plating conditions, the phosphorylation levels of FAK, and not its role in ERK activation via protein scaffolding, are more immediate predictors of its physiological function, vis-à-vis neurite outgrowth. In fact, it has been shown by others that the inhibition of FAK activation has no effect on ERK1/2 phosphorylation (Yang et
suggest that the potential neurodevelopmental consequences of occupational or environmental exposure to isothiazoline derivatives should be closely scrutinized.

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