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Edited by Nancy Hopkins, Massachusetts Institute of Technology, Cambridge, MA, and approved August 19, 2010 (received for review June 14, 2010)

Acetaminophen (APAP) toxicity is the most common drug-induced cause of acute liver failure in the United States. The only available treatment, N-acetylcysteine (NAC), has a limited time window of efficacy, indicating a need for additional therapeutic options. Zebrafish have emerged as a powerful tool for drug discovery. Here, we developed a clinically relevant zebrafish model of APAP toxicity. APAP depleted glutathione stores, elevated aminotransferase levels, increased apoptosis, and caused dose-dependent hepatocyte necrosis. These outcomes were limited by NAC and conserved in zebrafish embryos. In a targeted embryonic chemical screen, prostaglandin E2 (PGE2) was identified as a potential therapeutic agent; in the adult, PGE2 similarly decreased APAP-associated toxicity. Significantly, when combined with NAC, PGE2 extended the time window for a successful intervention, synergistically reducing apoptosis, improving liver enzymes, and preventing death. Use of a wnt reporter zebrafish line and chemical genetic epistasis showed that the effects of PGE2 are mediated through the wnt signaling pathway. Zebrafish can be used as a clinically relevant toxicological model amenable to the identification of additional therapeutics and biomarkers of APAP injury; our data suggest combinatorial PGE2 and NAC treatment would be beneficial for patients with APAP-induced liver damage.

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Acetaminophen (N-acetyl-p-aminophenol; APAP) is a commonly used analgesic and antipyretic. Although safe at therapeutic doses, accidental or suicidal drug overdose can cause dose-dependent liver damage. APAP is the most common cause for liver transplantation for toxin-induced fulminant hepatic failure and results in more than 300 deaths annually in the United States (1). The only antidote in clinical use is N-acetylcysteine (NAC), which reduces mortality by ~20–28% (2); however, the time interval of effective intervention after ingestion is typically <12 h, and delayed or prolonged treatment can negatively impact clinical outcome and survival (3). Therapeutic options for hepatic failure are limited to best supportive care and liver transplantation.

APAP toxicity results from a hepatotoxic metabolite, N-acetyl-p-benzoquinone imine (NAQPI), produced by the cytochrome P450 enzymes CYP1A2, 2E1, and 3A4 (4). At therapeutic doses, NAQPI is efficiently inactivated in the liver by glutathione (GSH) conjugation (5). At toxic doses, excess production of NAQPI depletes hepatic GSH. Unconjugated NAQPI causes dysfunction of critical liver proteins, oxidative stress, and mitochondrial damage (6–8). NAC is a true antidote and limits damage by repleting GSH. Clinical efficacy of NAC treatment was shown for patients presenting after APAP ingestion; however, no conclusive clinical trials were conducted to elucidate its efficacy and optimal treatment window. Therapeutic benefits have been shown in mammalian models for other antioxidants (9, 10) that function to restore GSH levels. Compounds that support liver recovery from APAP injury rather than antagonizing the mechanism of toxicity are lacking. Chemical inhibitors of mitochondrial damage have been tested in mouse models (11); however, in vivo screens for novel compounds to act synergistically with NAC have not been performed.

Fish have been used to assess water quality and detect toxins. Genetic conservation between zebrafish and mammals was documented in liver development, regeneration, and carcinogenesis (12); however, the functional conservation of toxic–metabolic effects on the liver has not been evaluated. Proteomic analysis of the zebrafish liver has revealed potential indicators of xenobiotic response (13), implying the suitability for translational toxicological studies. Zebrafish embryos are uniquely amenable to chemical screening approaches for the identification of novel compounds. Recently, we have shown that findings in embryonic screens can be extended to adult zebrafish physiology and translated into therapeutic applications (14).

Here, we characterize a zebrafish model for APAP liver toxicity and identify therapeutics that work cooperatively with NAC. APAP was found to decrease zebrafish liver GSH content and elevate serum alanine aminotransferase (ALT) levels. Survival and histological evidence of liver injury were dose-dependent. Progressive APAP injury was inhibited by NAC, making this an excellent preclinical model. Liver-specific APAP toxicity was conserved in zebrafish embryos, enabling a targeted chemical genetic evaluation for hepatoprotectants, which identified prostaglandin E2 (PGE2) as a potential therapeutic; in the adult, it worked synergistically with NAC to limit hepatic APAP injury and enhance survival, extending the therapeutic window for chemical intervention. PGE2 increased wnt pathway activity, a known regulator of liver regeneration, after APAP injury to improve outcomes in embryos and adults. These results show the therapeutic relevance of modeling organ-specific toxicity in zebrafish and point to clinical strategies to reduce APAP-mediated liver damage.

Results

APAP Causes Liver Toxicity in Adult Zebrafish. APAP exposure in mammals leads to the rapid depletion of GSH stores (15). Similarly, in the adult zebrafish liver, GSH was significantly reduced...
by 75% in liver homogenates 24 h postexposure (hpe) to APAP (10 mM; 513.4 ± 18.0 vs. 130.5 ± 13.6 nmols/liver; t test, \( P \leq 0.001, n = 5 \)) (Fig. 1A). Baseline ALT levels, used to detect liver injury clinically, were higher in zebrafish than in mice and humans, consistent with prior reports (16) (Fig. 1B); within 6 hpe, ALT levels were elevated in a dose-dependent fashion and continued to rise over the first 24 h (Fig. 1B Inset). To establish toxicity thresholds, we recorded survival after exposure to increasing doses of APAP (Fig. 2A). Doses up to 5 mM had no impact on survival, whereas 10 mM APAP caused progressive death in ∼50% of fish, beginning by 20 hpe. Exposure to 25 mM APAP caused rapid death in almost all fish by 10 hpe. Bolus treatment with 50 mM APAP for 3 h, to mimic suicidal overdose, resulted in liver toxicity comparable with extended 10-mM exposure. Histological evaluation revealed minimal effects with 1 mM APAP (Fig. 1C); 5 mM APAP did not affect gross liver morphology at 24 hpe but by 48 hpe, caused increased hepatocyte necrosis and areas of focal hemorrhage. Widespread necrosis and sinusoidal hemorrhage were seen as early as 12 hpe after exposure to 10 mM APAP. To visualize the extent of liver damage in vivo, we used the transgenic liver fatty acid binding-protein reporter \( Tg(-2.8\text{labp}10\text{EGFP})^{as3} \) (referred to as \( \text{Iflabp: GFP} \) (Fig. S1A) (17); APAP caused a time-dependent reduction in fluorescence, suggestive of hepatocyte death and corresponding with the histological analysis.

**NAC Prevents Liver Toxicity.** To document the applicability of the zebrafish model to human physiology, we exposed APAP-treated fish concurrently to NAC. Zebrafish survival and ALT levels after 10 mM APAP exposure were markedly improved by NAC (10 \( \mu \)M) compared with APAP-treated controls (Fig. 2A and B; \( P < 0.05 \)). NAC could not improve survival after higher APAP doses (25 mM) (Fig. 2A); these results are consistent with clinical observations. In vivo fluorescence microscopy of \( \text{Iflabp: GFP} \) fish showed dramatic improvement in liver morphology after immediate NAC treatment (Fig. S1B), which was confirmed histologically (Fig. 2C). Ethanol (EtOH) exposure worsened outcome after APAP injury (Fig. S2A and B) and antagonized NAC efficacy.

**Proteomic Analysis of Zebrafish Plasma.** To show changes in liver function in response to APAP, serum protein concentrations were assessed by MS. After generation of a partial 2D-gel map of the plasma proteome (Fig. S3A), comprehensive protein coverage was obtained by 2D-liquid chromatography MS/MS, resulting in the identification of 223 high-confidence proteins. Most were highly evolutionarily conserved and present in human serum (Table S1). Relative changes in serum protein concentration over time were quantified by isobaric tag for relative and absolute quantitation (iTRAQ), revealing four differential protein response patterns (Fig. 3A and Fig. S3B). One group (71 proteins) steadily decreased over time (Fig. 3B); this cluster contained proteins associated with liver function, such as transferrin and thrombin, suggesting impaired synthetic capacity. Cluster 2 (46 proteins) exhibited a biphasic pattern, where protein concentration initially declined and then rose; several of these, such as GST and carbonic anhydrase, were previously shown to be regulated by APAP treatment (18). Cluster 3 (33 proteins) was characterized...
by the reverse response; this cluster included structural and remodeling proteins. Cluster 4 (73 proteins) showed continuously increasing protein levels indicative of cellular damage. Several representative genes displayed quantitative PCR (qPCR) expression patterns consistent with iTRAQ protein responses (Fig. S3C). Although direct comparisons across model systems are difficult because of variation in experimental design, the results presented are broadly comparable with prior observations in murine models of APAP toxicity (7, 18–22), indicating conservation of the xenobiotic response.

**Conserved Effects of APAP in Zebrafish Embryos.** Zebrafish embryos are amenable to unbiased chemical genetic screens (14). To discern whether APAP produced similar effects on embryonic and larval hepatocytes, ifabp:GFP embryos were exposed to increasing doses of APAP. Liver size diminished in a dose- and time-dependent fashion after APAP treatment (Fig. S4A–D). The effect of NAC was also conserved, as evidenced by the larger liver in more than 50% of APAP-treated embryos (Fig. S5 A and B). This analysis was confirmed by ifabp in situ hybridization and replicated in larve.

**Embryonic APAP Chemical Modifier Screen Identifies PGE2.** Given the conserved embryonic effects of APAP, a targeted chemical screen for modifiers of xenobiotic-induced toxicity was performed. Ifabp:GFP embryos were exposed to APAP from 48 to 96 hours postfertilization (hpf) concurrently with individual compounds with known embryonic liver-specific bioactivity (Fig. S6 A and B). APAP toxicity over this time frame resulted in substantial death (>90%) and dramatically reduced liver size. PGE2 mitigated the APAP effects in a significant fraction of embryos (screen: 6 normal/11 scored; retest: 26/54). Exposure to a long-acting derivative, 16,16-dimethyl-PGE2 (dmPGE2, 10 μM), substantially increased liver size at 96 hpf (screen: 10 increased/12; retest: 59/66) (Fig. 4A) and partially corrected the APAP phenotype (screen: 8 normal/12; retest: 37/58); these results were confirmed by qPCR (Fig. 4B). To determine how PGE2 mitigated APAP-induced hepatotoxicity, we examined proliferation and apoptosis by BrdU and TUNEL staining, respectively. dmPGE2 rescued liver size (729) and embryo survival (25%) in a modest proportion of embryos (Fig. 5A and B); the combination of NAC and dmPGE2, after delay, caused marked improvement in survival (45%) and ifabp expression (26/48). Caspase analysis confirmed that the effects of combinatorial treatment were mediated, in part, by a reduction in apoptosis (Fig. 5C).

**PGE2 and NAC Improve Clinical Parameters of APAP Injury.** To show applicability, we exposed adult zebrafish to single agent or combinatorial therapy concomitantly with APAP or 18-h delay and combinations and assessed for alterations in ifabp expression. APAP inhibited liver growth (47 decreased/48), whereas dmPGE2 increased liver size at 96 hpf (56 increased/59) (Fig. S4). dmPGE2 (42 normal/66) and NAC (37 normal/61) each partially rescued the negative effects of APAP with synchronous exposure. In combination, NAC and dmPGE2 had synergistic protective effects, where the majority of embryos did not exhibit signs of any APAP-mediated hepatocyte loss (52 normal/63). Immediate combinatorial treatment affected embryonic survival (Fig. 5B) (85%) and apoptosis, as measured by combined caspase 3/7 activity (Fig. 5C) (P < 0.001). In clinical practice, NAC is typically administered with some delay after APAP ingestion. Although NAC alone had minimal effects on survival when given with 12-h delay (del), dmPGE2 rescued liver size (729) and embryo survival (25%) in a modest proportion of embryos (Fig. 5A and B); the combination of NAC and dmPGE2, after delay, caused marked improvement in survival (45%) and ifabp expression (26/48). Caspase analysis confirmed that the effects of combinatorial treatment were mediated, in part, by a reduction in apoptosis (Fig. 5C).
recorded clinical parameters of liver injury (Fig. 6 A–D). Hepatic GSH was significantly diminished by APAP treatment and corrected by immediate administration of NAC or combinatorial therapeutics. dmPGE2 alone improved caspase and ALT levels, but not hepatic GSH, indicating it limited hepatotoxicity primarily through reducing apoptosis. Biochemical parameters of injury and cell death were unchanged between the APAP-exposed group and fish treated with significant delay (18 hpe) by NAC or dmPGE2 alone. Despite delay, combinatorial dmPGE2 and NAC treatment vastly improved liver parameters, cell death, survival, and histology (Fig. 6 A–E). These results indicate the potential synergistic therapeutic benefit of dmPGE2 and NAC as standard treatment for liver APAP toxicity.

PGE2 Enhances wnt Activity to Improve APAP Liver Toxicity. We have previously shown that PGE2 regulates wnt activity during liver regeneration (23). Wnt activation has been observed after both surgical and toxic liver injury (12, 24, 25). To document hepatic wnt activation in zebrafish, Tg(TOP:GFP) embryos (referred to as TOP:GFP) were exposed to APAP at 48 hpf; markedly increased fluorescence was found in livers of treated fish at 72 hpf (Fig. S8A) (34 increased/48). To show that wnt signaling induced by APAP injury functioned to improve outcome, inducible wnt8a [Tg(hsp70l:wnt8a-GFP)] embryos (27) were heat-shocked and exposed to APAP at 48 hpf. wnt8a overexpression was hepatoprotective and rescued liver-specific fluorescence (Fig. S8B) (wt APAP: 49 decreased/51; wnt8a: 49 increased/55; wnt8a-APAP: 53 rescued/67) (Fig. S8C). To corroborate that dmPGE2 treatment worked at least in part by enhancing wnt activation after adult APAP toxicity, TOP:GFP expression was analyzed. wnt activity was increased in response to APAP injury, consistent with recent results (25), and was further enhanced by dmPGE2 treatment (Fig. S8D). To determine whether pharmacologically elevating wnt signals could produce a biologically similar correlate to PGE2, adults were treated with APAP and exposed to the wnt-activator 6-bromoindirubin-3′-oxime (BIO) (0.5 μM). Gross morphological examination revealed that APAP-induced hemorrhage in the liver was greatly limited by BIO. As seen with PGE2, wnt activation dramatically improved liver appearance synergistically with NAC, even with delay (Fig. 7A). Inhibition of PGE2 production by indomethacin had detrimental effects on both morphology and survival (Fig. 7B), implying a role for PGE2 beyond the initiation of inflammatory responses in the setting of toxic injury. These effects were equilibrated by BIO treatment, highlighting the functional interaction between PGE2 and the wnt pathway in the nascent regenerative process after APAP liver injury.

Discussion
APAP liver toxicity remains a significant medical problem with multiple unmet clinical needs. NAC, the single available therapeutic option, is effective at preventing toxicity when given early after ingestion; however, it has a limited window of efficacy: patients who receive NAC with significant delay (>12 h) do not derive the same benefit from treatment and exhibit up to 15-fold increased death rates (28). The molecular mechanisms of APAP

Fig. 5. PGE2 acts synergistically with NAC to improve APAP toxicity. (A) Zebrafish embryos were treated with APAP at 48 hpf and with dmPGE2 and/or NAC, either concomitantly or with 12-h delay (del). Combined NAC and PGE2 treatment improved liver morphology, assessed by in situ hybridization for ifabp at 96 hpf, even after delayed exposure. (B) Embryo survival is dependent on treatment parameter and is improved by NAC and PGE2 exposure. (C) Caspase 3/7 activity, as indicator of apoptosis, was measured in a luminometric assay and normalized to controls. *ANOVA, n = 10/treatment for three replicates, P < 0.001.

Fig. 6. Synergy between NAC and PGE2 limits toxicity and extends the therapeutic window in adult zebrafish after APAP. Adult zebrafish were exposed to APAP and NAC, dmPGE2, or a combination either concomitantly or with 12 h delay. (A) GSH (mole/whole liver) was improved by combined exposure to NAC and dmPGE2. *ANOVA, n = 3–4, P < 0.01. (B) Relative caspase 3/7 levels were elevated after APAP and improved with immediate NAC and/or dmPGE2; delayed combinatorial therapy was still beneficial. *ANOVA, n = 4–5, P < 0.001. (C) Serum ALT levels (n = 10–20 fish/treatment at 24 hpe) show that combined NAC and dmPGE2 prevented hepatocyte damage by APAP, even after delay. (D) Combined NAC and dmPGE2 treatment led to improved adult zebrafish survival (n = 9–10/treatment) at 48 hpe. (E) Effect of delayed treatment on zebrafish liver histology at 24 hpe; sinusoidal hemorrhage and necrosis in APAP-treated adults could not be reversed with NAC or dmPGE2 alone but only with combined treatment.
The repletion of GSH
Survival after APAP exposure is affected by wnt and PGE2 modulation. PNAS | vol. 107

To show conservation of the injury process, only reliable parameters to provide therapeutic guidance are evaluate the effectiveness of therapeutic strategies in zebra fish. APAP-metabolizing enzyme in humans, CYP3A4, is present in zebra fish. The utility of in vivo animal models for human liver toxicity depends greatly on applicable assays to measure toxin-specific effects. Here, we use a variety of biochemical, histological, and clinical outcome measures to show the overall relevance of the zebrafish APAP toxicity model to human physiology. APAP significantly lowers hepatic GSH, which improves with NAC. Our findings are consistent with reports that an ortholog of the major APAP-metabolizing enzyme in humans, CYP3A4, is present in zebrafish. ALT levels, a standard test in clinical practice, were measured here to detect and quantify liver-specific toxicity and evaluate the effectiveness of therapeutic strategies in zebrafish. Histological parameters, especially hepatocyte necrosis, and survival are also consistent with clinical experiences.

For patients presenting with APAP-induced liver failure, the only reliable parameters to provide therapeutic guidance are APAP serum levels. To show conservation of the injury process across vertebrate species and discover potential biomarkers indicative of outcome, we performed the first analysis of the zebrafish serum proteome. Prior proteomic studies in the zebrafish have focused on the embryo and adult liver. Our analysis revealed an absence of albumin, the major mammalian serum transport protein, consistent with recent genome analyses; apolipoproteins and vitellogenin may serve as alternative carriers for hydrophobic compounds in zebrafish blood. We found distinct serum protein patterns of response to APAP and concordant transcriptional gene regulation. A subset of the proteins found to be regulated in our studies was also identified in mammalian models after APAP injury; many, such as catalase, aldehyde dehydrogenase, heat-shock proteins, complement, and transferrin, are involved in oxidative processes or inflammatory responses. These conserved reactions confirm the value of zebrafish as a relevant toxicological model for mammalian biology.

The feasibility of performing in vivo chemical screens in an intact vertebrate organism is a unique feature of the zebrafish. We used the conservation of hepatic metabolic function and gene expression to conduct a chemical toxicity modifier screen with direct clinical applicability. No prior in vivo studies have explored the potential to extend and enhance the therapeutic effects of NAC for APAP injury. Here, we showed that the combined use of dmPGE2 and NAC led to a significantly improved outcome in both embryos and adults after delayed treatment, whereas single agents had no impact. Previous investigations of the relationship between PGE2 and APAP in liver injury are controversial; some studies suggest that PAP directly impacts cyclooxygenase-2 function, whereas the majority of research indicates that APAP does not work as a nonsteroidal antiinflammatory drug. Recently, both PGE2 and prostacyclin (PGI2) were found to be hepatoprotective when given before or shortly after APAP exposure in the mouse. Our work suggests that the greatly improved therapeutic outcome from combinatorial NAC and PGE2 administration after APAP injury, even after delay, results from the modulation of two different mechanisms of liver damage—the repletion of GSH mediated by NAC combined with a proproliferative, antiapoptotic signal from PGE2; it is unlikely, particularly with delayed treatment and given the failure of PGE2 alone to restore GSH levels, that exogenous PGE2 acts as an antidote to potential cyclooxygenase inhibition mediated by APAP or that it simply increases the pool of cells available to survive toxic injury.

Wnt activation is involved in many instances of organ repair, including liver regeneration after surgical resection or in the setting of mitochondrial dysfunction. Wnt signaling was found to be activated after APAP injury in murine livers, consistent with our work. Here, we showed that wnt activation can improve outcome from APAP toxicity in zebrafish, indicating that the proproliferative antiapoptotic effect of both PGE2 and wnt is not restricted to regeneration after mechanical injury. Modulation of wnt signaling may provide another therapeutic option for improving outcome of APAP poisoning; however, the current spectrum of wnt pathway activators is not easily tolerated and tends to have pleiotropic effects on organs such as the intestine and skin, where tissue turnover is regulated by wnt. In contrast, chemical modulation of PGE2 production and signaling is established and clinically well-tolerated. Additionally, the upcoming generation of therapeutics targeting PGE2 receptors should provide the necessary organ specificity to eliminate the majority of unwanted side effects associated with prolonged systemic use of these compounds.

The conservation of indicators of liver injury in zebrafish could lead to more universal applications of this model to assess drug-induced liver damage. The occurrence of liver toxicity, as a serious side effect, is a major problem for many candidate therapeutics in development, preventing them from reaching late clinical trial stages. Recently, complex in vitro assays have been developed to detect or predict hepatocyte toxicity; however, these may not completely replicate the interactions of the various liver cell types or physiologically mimic the metabolites produced in vivo. Our approach highlights the feasibility of performing whole-organism toxicity assays in a small, vertebrate model system that allows for the rapid and cost-effective development of potential therapeutic agents.

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Materials and Methods

Zebrafish. Fish were maintained according to Institutional Animal Care and Use Committee protocols. Tg(2.8abfp:10:GFPP2), Tg(sp6:70:wt1na- GFP)z44 and Tg(TOP:GFP)z25 transgenic lines were described previously (17, 26, 27).

Drug Exposure and Chemical Screen. Embryos and adult zebrafish were exposed to APAP, NAC, ETOH, dmPGEx2, indomethacin, and BSO at doses and times as described. After exposure, fish were transferred to fresh fish water until analysis. For the chemical screen, Tg(2.8abfp:10:GFPP2) zebrafish embryos were arrayed in multiwell plates (10 embryos/well) and contemporaneously exposed to 10 mM APAP and each test compound (~10 μM) at 48 hpf; compounds were subseted from a prior screen for modifiers of Ifabp+ liver development (Fig. S6 A and B). At 96 hpf, alterations in liver formation were qualitatively assessed by fluorescent microscopy compared with controls.

qPCR. qPCR (60 °C annealing) was performed with cDNA from pooled embryos (n = 20) or dissected adult liver using the iQ5 Multicolor RTPCR Detection System (BioRad).

In Situ Hybridization and Whole-Mount Staining. Paraformaldehyde (PFA)-fixed embryos were processed for Ifabp in situ hybridization (http://zfin.org/ZFIN/Methods/ThiSeProtocol.html). Expression changes are reported as the number of altered per number of scored per treatment (10 per treatment/3 replicates). Immunostaining for BrdU and TUNEL was performed as described (23).

GSH Assay. Total liver GSH content was determined in dissected livers after exposure of adult fish to either DMSO or APAP for 24 h, according to manufacturer’s protocols (Sigma).

Capase 3/7 Assay. Caspase 3/7 was measured on homogenized tissue (96 hpf zebrafish embryos (10 per treatment) or adult livers at 24 hpf) in 0.9% PBS, according to manufacturer’s protocols (Promega).

Serum ALT Measurements. Zebrafish blood (poled from 10 to 20 fish) was obtained by cardiac puncture. Serum was separated by centrifugation (2,000 g for 10 min) and subjected to enzyme diagnosis in the clinical laboratory.

Histology. Adult fish (5 per treatment/2 replicates) were fixed with PFA, paraffin embedded, cut for histological analysis, and stained with H&E using standard techniques.

Fluorescence Microscopy. Microscopy was performed on fish (10 per treatment/3 replicates) anesthetized with 0.04 mg/mL Tricaine-S.

Proteomic Analysis. Detailed experimental methods for the proteomic analysis are described in SI Materials and Methods.

ACKNOWLEDGMENTS. This research was supported by a Friends of Dana-Farber fellowship (to W.G.), Harvard Digestive Diseases Center (W.G.), a Mount Desert Island Biological Laboratory Junior Investigator Award (to W.G.), American Cancer Society (T.E.N.), Harvard Stem Cell Institute (T.E.N. and W.G.), National Institutes of Health National Institute of Diabetes and Digestive and Kidney Diseases (T.E.N., L.I.Z., and W.G.), National Cancer Institute (I.R.D. and S.R.T.), and The John A. Hartford Foundation (to L.I.Z.). Described methods were supported by grants from the American Cancer Society (R.G., T.E.N., and L.I.Z.) and the National Institutes of Health (T.E.N., K. Pollard, and L.I.Z.).

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