Review

Clinical Cancer Research

Genetic and Modifiable Risk Factors Contributing to Cisplatin-induced Toxicities

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Abstract

Effective administration of traditional cytotoxic chemotherapy is often limited by off-target toxicities. This clinical dilemma is epitomized by cisplatin, a platinating agent, which has potent antineoplastic activity due to its affinity for DNA and other intracellular nucleophiles. Despite its efficacy against many adult-onset and pediatric malignancies, cisplatin elicits multiple off-target toxicities that can not only severely impact a patient's quality of life but also lead to dose reductions or the selection of alternative therapies that can ultimately affect outcomes. Without an effective therapeutic measure by which to successfully mitigate many of these symptoms, there have been attempts to identify *a priori* those individuals who are more susceptible to developing these sequelae through studies of genetic and nongenetic risk factors. Older age is associated with cisplatin-induced ototoxicity, neurotoxicity, and nephrotoxicity. Traditional genome-wide association studies have identified single-nucleotide polymorphisms in *ACYP2* and *WFS1* associated with cisplatin-induced hearing loss. However, validating associations between specific genotypes and cisplatin-induced toxicities with enough stringency to warrant clinical application remains challenging. This review summarizes the current state of knowledge with regard to specific adverse sequelae following cisplatin-based therapy, with a focus on ototoxicity, neurotoxicity, nephrotoxicity, myelosuppression, and nausea/emesis. We discuss variables (genetic and nongenetic) contributing to these detrimental toxicities and currently available means to prevent or treat their occurrence.

Introduction

Cisplatin and the platinating agents represent one of the most widely used and successful groups of cytotoxic drugs worldwide. Each year, more than 5.8 million patients are diagnosed with cancers for which first-line therapy potentially includes platinating agents (colon, rectum, cervix, endometrium, bladder, stomach, head and neck, lung, esophagus, pancreas, osteosarcoma, ovary, testis, and childhood cancers; ref. 1). Although cisplatin elicits potent antineoplastic activity through the formation of DNA cross-links (2), the agent also triggers several severe off-target toxicities (Table 1), some of which affect patients acutely and resolve after treatment, and others that display little reversibility (2, 3). Although not the focus of this review, mechanisms by which cisplatin elicits these toxicities are listed in Table 1. For a more comprehensive description, refer to previous reviews for ototoxicity (4–7), neurotoxicity (8, 9), nephrotoxicity (10–12), myelosuppression (13), and nausea/emesis (14, 15).

Because of improved survival rates, most notably in testicular cancer and in pediatric malignancies, there are a significant number of survivors living with these severe adverse sequelae that affect quality of life. The nonuniformity of these toxicities in patient populations has been the subject of much research in efforts to circumvent their occurrence. Figure 1 provides an overview of nongenetic risk factors contributing to cisplatin-induced toxicities. Of particular interest is the association between older age and an increased susceptibility to several cisplatin-induced toxicities. Although the exact mechanisms of this association have not been explicitly studied, it is known that drug clearance can decrease with age, particularly when elimination is mediated by renal clearance (16). As cisplatin is eliminated predominantly through the kidney, and is also known to be highly nephrotoxic, the agent ultimately reduces the ability for platinum to be excreted from the body (10), thereby increasing the likelihood of developing cisplatin-induced toxicities. Furthermore, it is not surprising that older adults are associated with cisplatin-induced ototoxicity and neurotoxicity because these individuals often experience age-related hearing loss/tinnitus (17, 18) and paresthesias/neuropathies (19, 20), and the addition of cisplatin will likely exacerbate symptoms.

Variability in patient response can also be explained in part by pharmacogenomics, which aims to provide the foundation for genetically guided treatment regimens that maximize efficacy and minimize toxicity. Initially developed from candidate gene approaches, advances in genomic sequencing technologies over the past decade have enabled agnostic genome-wide analyses of patient populations characterized for specific drug response phenotypes. Thus, pharmacogenomics has elucidated genetic variability as a key determinant in both therapeutic benefit and potential toxicities likely to be experienced during cisplatin-based chemotherapy. One of the challenges in pharmacogenomics is that most cancers are treated with a multidrug regimen making it difficult to ascertain the genetic variants

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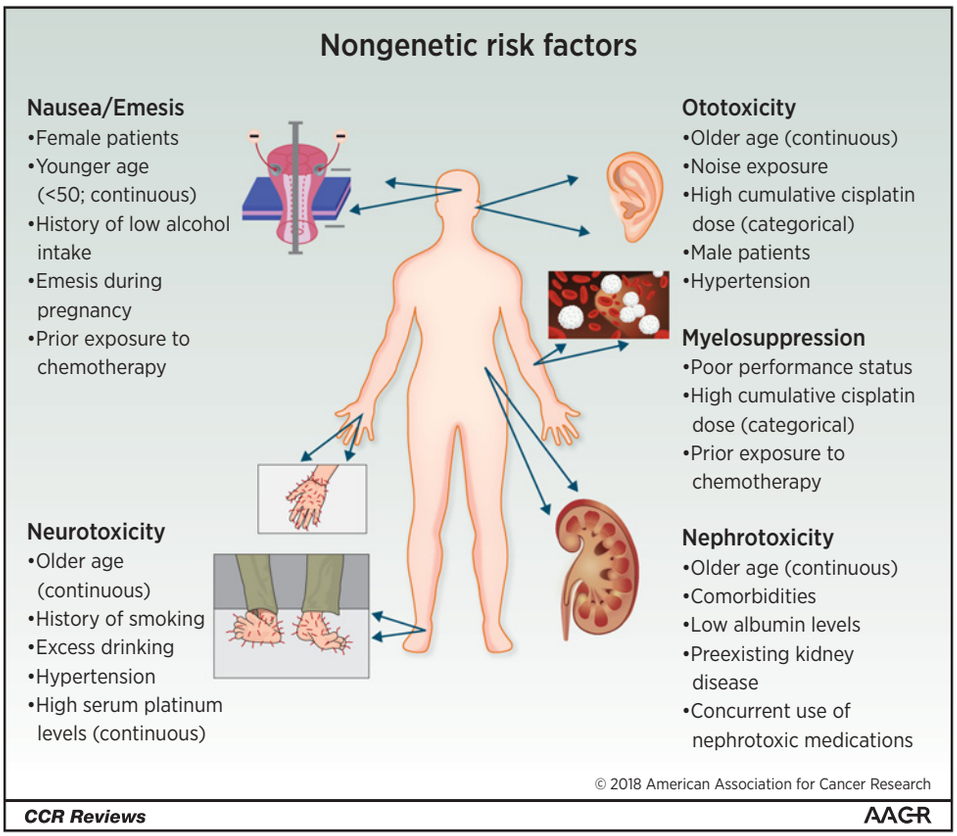

Figure 1.
Nongenetic risk factors that may predispose patients to developing adverse events following cisplatin-based therapy. Where relevant, risk factors are denoted as being either continuous or categorical variables based on how they were examined for association with the given toxicity.

associated with a specific chemotherapeutic toxicity. This is the case for cisplatin; however, some toxicities (i.e., ototoxicity and nephrotoxicity) are primarily due to cisplatin; therefore, the genetic variants identified are most likely associated with cisplatin exposure. However, understanding both the functional significance and clinical application of these findings remains elusive. Therefore, this review will highlight nongenetic and genetic risk factors contributing to cisplatin-induced toxicities, and provide recent data on novel therapeutic strategies by which to reduce adverse effects.

Ototoxicity

Cisplatin is associated with irreversible, bilateral sensorineural hearing loss that occurs at a much higher rate than other ototoxic drugs. Reports indicate that up to 75%–80% of patients may experience some degree of hearing loss and 13%–18% may develop severe-to-profound hearing loss (21–23). In addition, approximately 40% of cisplatin-treated patients (23) experience some degree of tinnitus, which occurs at a significantly higher rate than either the general population (15%; ref. 24), or in comparable cancer patients not given cisplatin-based chemotherapy (12%; ref. 25). The frequency of severe tinnitus is also markedly increased in cisplatin-treated patients (13%–22%; refs. 23, 25) with one study noting that 42% of patients report tinnitus as a major symptom after dose-intensive cisplatin chemotherapy (25). In contrast, severe tinnitus occurs in only 1%–2% of the general population (24). Furthermore, cancer survivors with hearing loss, tinnitus, and neuropathy are more likely to report poorer quality of life than those with neuropathy only (26). Another investigation reported worse perceived stress among cancer survivors with tinnitus (27).

Although nongenetic risk factors for cisplatin-associated ototoxicity (CAO) have been identified (Fig. 1), previous studies have focused almost exclusively on hearing loss susceptibility. Furthermore, there have been conflicting results with regard to the importance of noise exposure and cumulative cisplatin dose on hearing loss (23, 28, 29). However, in pediatric cancer patients, males appear to be more susceptible to cisplatin-induced hearing loss than females ($P = 0.005$; ref. 29). Hypertension has also been identified as a potential risk factor for hearing loss in patients with testicular cancer, with the association remaining significant when controlling for age and cisplatin dose ($P = 0.0066$; ref. 23).

Recently, the FDA granted sodium thiosulfate "fast-track designation" to prevent cisplatin-related hearing loss in pediatric patients diagnosed with hepatoblastoma based on the results of a clinical trial of 109 pediatric hepatoblastoma patients in which 20 g/m^2 sodium thiosulfate was administered intravenously 6 hours after the discontinuation of cisplatin for four preoperative and two postoperative courses. Not only did sodium thiosulfate treatment reduce grade 1 or higher hearing loss incidence by 48% [18 of 55 children (33%) in the cisplatin-sodium thiosulfate group experienced hearing loss compared with 29 of 46 (63%) in the cisplatin-alone group; relative risk, 0.52; 95% confidence interval (CI): 0.33–0.81; $P = 0.002$], but cisplatin–sodium thiosulfate conferred overall and event-free survival rates comparable with those who did not receive the protective agent (30). However, of the 16 serious adverse reactions experienced by

Table 1. Frequently reported cisplatin-induced adverse sequelae

Toxicity	Acute and chronic complications	Frequency (%)	Pathophysiology
Nausea/emesis	• Therapy-related anxiety • Anticipatory chemotherapy-induced nausea/vomiting • Fatigue and weakness • Weight loss, dehydration, and loss of appetite • Bone fractures and tears to the throat	Acute symptoms occur in >90% of patients when antiemetic prophylaxis is not administered (14). Delayed symptoms occur in 60%–90% of patients under the same conditions (77).	Perturbs the lining of the gastrointestinal tract, which subsequently promotes Ca^{2+}-dependent exocytic release of serotonin from enterochromaffin cells (15). Successful binding of serotonin to its receptors on the vagal afferent neurons activates the chemoreceptor trigger zone and vomiting center that promote the initiation of the emetogenic response.
Ototoxicity	• Irreversible sensorineural hearing loss • Tinnitus	Some degree of hearing loss occurs in 75%–80% of patients (5, 23), while 13%–18% develop severe-to-profound hearing loss (4–6). Symptoms of tinnitus occur in approximately 40% of patients (6), with 13%–22% experiencing severe tinnitus (6, 8).	Increases reactive oxygen species concentrations and depletes antioxidants used for detoxification (90–92). Cisplatin also activates big conductance potassium channels in spiral ligament fibrocytes (SLF), which adversely disrupt the electrochemical gradient within cells and trigger apoptosis (93). The cochlea retains cisplatin for months to years after treatment, with accumulation being particularly high in the stria vascularis, the SLF-containing region vital for the maintenance of endolymph ionic composition (94). Platinum–DNA adducts have been detected in the hair cells of the cochlea and the marginal cells of the stria vascularis. Because these cells do not proliferate, platination of mitochondrial DNA (mtDNA) is considered responsible for toxicity (4, 9).
Neurotoxicity (peripheral neuropathy)	• Persistent peripheral sensory neuropathy • Reduced physical activity and weight gain	Peripheral sensory neuropathy occurs in 36%–38% of patients (48, 49). Almost all patients who receive a cumulative dose of 500–600 mg/m^2 experience nerve damage (33).	Accumulates in the dorsal root ganglia of the spinal cord and peripheral neurons via passive diffusion or metal transporters. Forms DNA adducts and inhibits DNA repair pathways that ultimately induce p53-mediated apoptosis via Bax activation (95). The affinity of cisplatin for mtDNA may help explain the clinical quandary of coasting, as the absence of the nucleotide excision repair (NER) in the mitochondria could potentiate a gradual attrition of mitochondria, subsequently reducing ATP levels that neurons require to maintain their functional activity (96).
Myelosuppression	• Cytopenias • Residual bone marrow injury and reduction in hematopoietic stem cell reserves • Potential susceptibility to secondary leukemia	Between 25%–30% of patients develop symptoms of myelosuppression, while 5%–6% (66) are diagnosed with severe myelosuppression.	Elicits both genotoxic effects and oxidative stress to deplete blood counts (68). Patients may also develop residual bone marrow injury in which there is a sustained reduction in hematopoietic stem cell reserves due to self-renewal impairment (69, 70).
Nephrotoxicity	• Acute kidney injury • Hypomagnesemia • Permanent kidney damage	Acute kidney injury occurs in 20%–30% of patients (12). Hypomagnesemia manifests in 40%–100% of patients.	Active transport through Oct2 and Ctr1 (97, 98) induces toxicity primarily in the renal proximal tubules (11). Mechanisms of damage include endoplasmic reticulum stress and mitochondrial dysfunction leading to oxidative stress, as well as inflammation mediated by TNF and other chemokines (11, 12).

patients, 8 were likely attributed to sodium thiosulfate, including two grade 3 infections, two grade 3 neutropenias, one grade 3 anemia leading to transfusion, and two tumor progressions. In addition, the otoprotective effect of sodium thiosulfate was associated with a large sodium load that must be considered in planning therapy. The investigators also cautioned that, despite the use of prophylactic antiemetic agents, sodium thiosulfate remained emetogenic. These adverse events are in accord with prior experiences that note the frequency and severity of sodium thiosulfate toxicities (31), and the agent must be administered with considerable caution. Although sodium thiosulfate has demonstrated potential in the pediatric setting among a small subgroup of patients with cancer, there has yet to be a large, multi-institutional study in adult patients, thereby limiting the potential applicability of the agent. Consequently, there remains no FDA-approved agent to reduce ototoxicity for the vast majority of patients who receive cisplatin.

A number of pharmacogenetics studies have been conducted to identify CAO risk-conferring genotypes (summarized in Supplementary Table S1). In a study (32) that utilized a platform containing primarily single-nucleotide polymorphisms (SNP) in metabolizing genes, genetic variants in *TPMT* (rs12201199) and *COMT* (rs9332377) were identified that prompted the FDA to revise their label recommendations in 2012 for pediatric patients given cisplatin. However, the modification was rescinded in 2015 due to conflicting evidence of association between *TPMT* genetic variants and cisplatin-induced hearing loss provided by two replication studies and a meta-analysis (33–35). The lack of reproducibility in pharmacogenomic studies related to cisplatin is likely due to genetic heterogeneity as well as heterogeneity in

treatment protocols and population substructures, small sample sizes, and the use of cranial radiation in combination with cisplatin, which could substantially increase the likelihood of CAO due to its ototoxic effects (36). Specimen type, handling, sequencing method, gene calling, as well as the method of assessment of the particular toxicity being studied could also contribute to the lack of reproducibility. This points to the importance of replication of these pharmacogenomic studies.

Technological advances have enabled agnostic, genome-wide study designs to identify contributing SNPs associated with a selected trait. Contrary to candidate gene studies, such alleles are not limited by *a priori* hypotheses of loci that generally reside in exonic genomic regions. In fact, the majority (90%) of disease-associated variants identified from genome-wide association studies (GWAS) reside in intergenic regions associated with transcriptional regulatory mechanisms including expression quantitative trait loci (eQTL) known to influence gene expression (37, 38). Chemotherapeutic drug susceptibility-associated SNPs, including those for cisplatin-induced cytotoxicity, are more likely to be eQTLs and be associated with the expression levels of multiple genes (39).

The first GWAS of CAO in 238 pediatric brain tumor patients identified an association with a genetic variant in *ACYP2* (rs1872328, HR = 4.5; 95% CI, 2.63–7.69; $P = 3.9 \times 10^{-8}$), and results were replicated in a second cohort of 68 pediatric patients (40). Furthermore, increased *ACYP2* expression highly correlated with cisplatin sensitivity in lymphoblastoid cell lines *in vitro* ($P = 6.5 \times 10^{-5}$), but the genotype at the SNP rs1872328 position was not associated with cisplatin sensitivity *in vitro*, nor was it related to expression of *ACYP2* and other genes 300 kb within this index SNP. Nevertheless, three studies have replicated this association with cisplatin-induced hearing loss in 156 osteosarcoma patients (41), 149 pediatric cancer patients (42), and 229 testicular cancer patients (43). *ACYP2* encodes for an enzyme that catalyzes phosphate hydrolysis in membrane pumps, most notably the Ca^{2+}/Mg^{2+} ATPase from the sarcoplasmic reticulum of skeletal muscle (44). Importantly, *ACYP2* is expressed in the cochlea for ATP-dependent Ca^{2+} signaling that is critical for hair cell development and has been directly implicated in hair cell damage (45, 46), providing a rationale for its association with CAO.

The first GWAS of CAO in adult-onset cancer in 511 testicular cancer survivors identified a genome-wide significant SNP (rs62283056; $P = 1.4 \times 10^{-8}$) in the first intron of Mendelian deafness gene *WFS1* (wolframin ER transmembrane glycoprotein; ref. 47). This finding was replicated in a Canadian study of 229 testicular cancer patients when evaluating the same phenotype, that is, the geometric mean of hearing thresholds at 4–12 kHz ($P = 5.67 \times 10^{-3}$, OR = 3.2), although it was not replicated using a phenotype of audiologist-defined hearing loss (43). This difference in statistical significance based on the definition of hearing loss is important to note because it indicates that the same genotype can having varying levels of statistical association with a phenotype of interest based on how the trait is defined by the investigators. Nevertheless, the SNP is an eQTL for *WFS1* based on the Genotype-Tissue Expression (GTEx) project, with the risk (and minor) allele being associated with lower gene expression in several human tissues. Using an independent cohort from BioVU (a large, de-identified DNA biobank linked to a clinical data warehouse), *WFS1* was associated with ICD-9 derived codes for hearing loss. In a meta-analysis of this GWAS and the GWAS that initially identified *ACYP2* (40), rs62283056 in *WFS1* remained the top signal. However, the meta-analysis did not support the *ACYP2* variant rs1872328 as being significantly associated with adult-onset cancer CAO. Thus, functional validation studies of both *WFS1* and *ACYP2* using experimental methods are warranted.

Neurotoxicity

Cisplatin-based therapy is associated with peripheral neuropathy (manifested as tingling, numbness, weakness, or burning pain) that occurs in about 36%–38% of patients (48, 49). Predominantly affecting sensory nerves, cisplatin-induced peripheral neuropathy (CisIPN) has been described as a dose-dependent phenomenon, as most cases do not occur until a threshold cumulative dose of 300 mg/m^2 is reached (50), and almost all patients receiving a cumulative dose of 500–600 mg/m^2 have objective evidence of nerve damage (51). In addition, patients may also experience coasting, which is a persistent worsening of symptoms several months after treatment completion (52). The severity of neurotoxicity may also be correlated with serum platinum levels, as shown by Sprauten and colleagues (53) who demonstrated that long-term serum platinum levels are significantly associated with the severity of neurotoxicity 5 to 20 years after cisplatin treatment, and the relationship remains significant after adjustment for initial cisplatin dose.

Depending on neuropathy severity, patients can experience a significant reduction in overall quality of life, with a strong negative correlation between CisIPN and self-reported health (OR = 0.56; $P = 2.6 \times 10^{-9}$) demonstrated in 680 cisplatin-treated testicular cancer survivors (48). There was also a strong negative correlation of CisIPN with physical activity (OR = 0.72; $P = 0.02$), and a strong positive correlation with weight gain since therapy (OR per Δkg/m^2 = 1.05; $P = 0.004$). Because this investigation was cross-sectional, causal inferences could not be made, and a longitudinal design would help determine whether neuropathy deters from physical activity, and thus promotes weight gain. In a multivariate model, variables significantly related to cisplatin-induced neuropathy included age at diagnosis (OR/yr = 1.06, $P = 2 \times 10^{-9}$), smoking (OR = 1.54, $P = 0.004$), excess drinking (OR = 1.83, $P = 0.007$), and hypertension (OR = 1.61, $P = 0.03$; Fig. 1). Currently, there are no effective treatments to prevent or reduce the severity of neuropathy induced by cisplatin or other antineoplastic agents, but duloxetine is moderately recommended for associated pain (54).

Within the few studies that have investigated genetic susceptibility to long-term cisplatin neurotoxicity, there have been several reported associations involving glutathione-S-transferases (GST), in particular, *GSTP1* (55, 56) as well as *XPC* and *ERCC1* (57). None of these were found to be significant when evaluated through a GWAS (ref. 48; Supplementary Table S2).

In contrast to hearing loss (a quantitative phenotype), peripheral neuropathy is either physician-graded or patient-reported using questionnaires. Using the validated EORTC QLQ-CIPN20 questionnaire with 680 cisplatin-treated testicular cancer survivors, there were no genome-wide significant associations (48). However, using PrediXcan (58), a gene-based computational method that uses reference transcriptome (genotype-gene expression) data to generate models to "impute" gene expression levels from genotype data and associate the predicted gene expression with phenotypes of interest, lower expression of *RPRD1B* was identified as significantly associated with CisIPN. An evaluation of

18,620 genotyped patients from BioVU demonstrated a relationship between *RPRD1B* gene expression and polyneuropathy due to drugs. *RPRD1B* is of particular interest because defects in its expression or knockdown have been shown to inhibit DNA repair mechanisms that resolve cisplatin-induced lesions (59). Furthermore, *RPRD1B* knockdown in human breast carcinoma cells potentiates cisplatin sensitivity (60). As illustrated in this example, the advantage of PrediXcan analysis is that it substantially reduces multiple corrections in comparison with SNP-based GWAS, while also providing a directionality of effect between gene expression and phenotype.

Nephrotoxicity

The kidneys are particularly susceptible to toxicity because cisplatin is eliminated predominantly through renal clearance (11). Consequently, impaired renal function is found in approximately 25%–35% of patients after a single cisplatin dose (61). In spite of preventive measures (i.e., intense intravenous hydration during cisplatin administration), successive treatment courses can potentiate a progressive nephrotoxicity that can lead to permanent damage (12). Furthermore, cisplatin induces acute kidney injury in approximately 20%–30% of patients, while hypomagnesemia manifests in 40%–100% (12).

In addition to known risk factors for cisplatin-induced renal toxicity such as older age, comorbidities, low albumin levels, preexisting kidney disease, and concurrent use of nephrotoxic medications (Fig. 1; ref. 12), an increasing number of studies have investigated the importance of genetic contributions, albeit only in candidate gene studies (Supplementary Table S2). A SNP in *ERCC1* (8092C>A/rs3212986) has been shown to be significantly associated with a reduced risk of cisplatin-induced nephrotoxicity in two separate candidate gene studies (62, 63), as well as rs1051740 in *EPHX1* (64). In addition, two cation transporters vital for cisplatin renal uptake (*OCT2*/*SLC22A2* and *CTR1*/*SLC31A1*; Table 1) have SNPs associated with renoprotection and maintenance of estimated glomerular filtration rate [rs596881 (*OCT2*); rs12686377 and rs7851395 (*CTR1*); ref. 65].

Myelosuppression

Like many antineoplastic agents, cisplatin can profoundly impact hematopoiesis. Myelosuppression occurs in 25%–30% of patients, particularly when cisplatin doses exceed 50 mg/m^2 (66), and severe myelosuppression develops in approximately 5%–6% (13). Cisplatin-based therapy often has a disproportionate effect on erythrocyte production in comparison with other blood cells, resulting in a cumulative, clinically significant anemia (67). The increase in oxidative stress that induces other cisplatin-induced adverse sequelae (Table 1) also appears to contribute to bone marrow toxicity (68). While acute myelosuppression is an immediate clinical concern, many patients receiving chemotherapy and/or radiotherapy also develop residual bone marrow injury, as evidenced by a sustained reduction in hematopoietic stem cell reserves that can potentiate long-term hematologic complications (69, 70). Indeed, two studies have shown statistically significant associations between cumulative cisplatin dose and the subsequent development of leukemia (71, 72). In addition, patients who have a poor performance status and have had prior chemotherapy exposure are at increased risk of hematologic complications (Fig. 1; refs. 73, 74).

Although the analysis of genetic contributions to cisplatin-induced myelosuppression has been limited, a GWAS was undertaken in non–small cell lung carcinoma (NSCLC) patients of Han Chinese descent. Two SNPs (rs13014982 and rs9909179) exhibited associations with myelosuppression in the discovery and replication sets, but did not reach genome-wide significance in the discovery set. Nevertheless, these SNPs retained plausible associations in the subsequent meta-analysis of both patient cohorts (rs13014982: $P = 1.36 \times 10^{-5}$; rs9909179: $P = 0.001$ (75). rs13014982 is located in a gene desert at 2q24.3 (within 500 kb of *FIGN*), limiting its potential genetic significance, but rs9909179 was determined via GTEx to be a plausible eQTL for *HS3ST3A1* in blood ($P = 0.03$), an enzyme involved in heparan sulfate biosynthesis, which may be important in hematopoiesis (76).

Nausea and Emesis

Nausea and emesis are frequently cited as among the most feared complications of chemotherapy (14, 77). Although the development of antiemetics has reduced the incidence of these toxicities, many patients still experience either acute (within 24 hours), or delayed nausea and/or emesis. This is epitomized by cisplatin treatment, as doses of 50 mg/m^2 or more induce acute nausea and vomiting in >90% of patients not administered antiemetic prophylaxis (14), with 60%–90% experiencing delayed nausea/emesis (77). Women have a higher susceptibility to developing emesis following cisplatin treatment than men, as shown in two separate studies in patients with NSCLC (78, 79). Other risk factors for chemotherapy-induced nausea and vomiting include younger age, history of low alcohol intake, experience of emesis during pregnancy, impaired quality of life, and prior chemotherapy exposure (Fig. 1; refs. 77, 80).

Variation in the susceptibility of patients experiencing emesis following cisplatin administration based on genetic ancestry has been noted by Khrunin and colleagues (81) in which Yakuts (North Asians) had a borderline statistically significant difference in developing severe emesis compared with Russians of Eastern European descent (38% vs. 25%; $P = 0.061$). Importantly, severe emesis in Yakuts was independently associated with two polymorphisms in the *CYP2E1* gene, but was only associated with the *GSTT1*-null genotype in Eastern European Russians.

Trends in Relevant Pharmacogenomic Studies

Although analyses of genetic predisposition to cisplatin-induced toxicities are relatively novel with most studies published within the last decade, several important trends have emerged that may guide future investigations. Of the 36 genetic studies analyzed in the present review, an overwhelming majority investigated ototoxicity ($n = 26$), with neurotoxicity the next most common toxicity ($n = 5$). Thus, ototoxicity was the only toxicity to have genetic associations investigated for validity through multiple independent replication studies, and many analyses failed to confirm previously identified SNPs (Supplementary Table S1). Although ototoxicity is a prominent cisplatin-related adverse event, other toxicities also occur in a relatively high proportion of patients (Table 1) and can result in the administration of doses that are suboptimal for antineoplastic efficacy. Furthermore, most investigations have relied on a candidate gene approach, and only four GWAS have been performed (40, 47,

59, 75). GWAS have the potential to identify causal SNPs in genes agnostically, but require large cohorts of patients treated with the same regimen and uniformly phenotyped for toxicity.

In addition to the disproportionate number of studies that have used candidate gene approaches to probe cisplatin-induced toxicities, few investigations have evaluated these adverse sequelae in cohorts not predominantly/exclusively of European ancestry. This observation mirrors the lack of ancestral diversity represented in GWAS of chemotherapeutic toxicities despite known differences in allele frequencies and effect sizes among individuals of differing ancestries (82). One reason for this is that several GWAS were performed in testicular cancer survivors, a disease that disproportionately affects white males (83). As such, genetic variants that are associated with varying levels of cisplatin sensitivity in European-based studies may not be relevant in patients of other genetic ancestries, thereby promoting a gap in health disparities. Although these slight genetic variations may appear to be subtle nuances among heterogeneous patient populations, finding causal associations of adverse sequelae is a hallmark paradigm of precision medicine, and may eventually enable treatment regimens and doses to be tailored specifically to the individual patient to maximize treatment efficacy while limiting toxicities.

Future Directions

On the basis of the analysis of previous pharmacogenomic studies of cisplatin-induced toxicities, it is apparent that investigators should expand the search of relevant genetic variants beyond ototoxicity and patient populations of European ancestry. Furthermore, the lack of reproducibility found in candidate gene studies of ototoxicity underscores the importance of genome-wide studies with large cohorts of uniformly treated patients to comprehensively examine the entire genome for potential associations with other cisplatin-induced toxicities. Regardless of the *in silico* approach used to identify genetic variants of potential interest, it is paramount that associations are functionally validated *in vitro* and/or *in vivo* (84). Through this critical step, the biological significance of the identified genetic variants can be definitively ascertained. Moreover, physiologic validation of the genetic architecture underlying different cisplatin-induced toxicities may potentiate the discovery of novel drug targets that can mitigate the adverse effects, thereby reducing its overall morbidity. These mechanistically based therapeutic strategies may ultimately be leveraged to identify novel drug targets that can reduce selected toxicities without inhibiting antineoplastic efficacy.

The Platinum Study examines the long-term effects of cisplatin treatment in cured testicular cancer survivors to comprehensively evaluate the toxicities associated with cisplatin (1). Because testicular cancer generally affects men of European descent, it is inherently limited in its ability to examine cisplatin toxicities in different genetic ancestries. Current plausible alternative cohorts include the St. Jude LIFE study and the multi-institutional Childhood Cancer Survivor Study, initiatives designed to examine the long-term effects of radiotherapy and chemotherapy in pediatric cancer survivors (85, 86). However, in both endeavors, only a small subset of patients received cisplatin. Therefore, the development of patient cohorts of varying genetic backgrounds and cancer diagnoses is required to fully characterize the genetic architecture of cisplatin-induced toxicities.

Once viable predictive biomarkers of cisplatin-induced toxicities have been established, additional preclinical and clinical studies will be required to determine how to optimally apply this information to minimize cisplatin-induced toxicities while maintaining therapeutic efficacy. In addition to establishing *a priori* which patients may likely require either dose reductions or alternative therapy, these patients may also serve as an ideal cohort to examine novel platinum analogues with a reduced toxicity profile (87), provided comparable antineoplastic efficacy has been established.

Conclusions

Cisplatin-induced toxicities are numerous and high in frequency, making identification of patients likely to experience adverse events critical for optimizing clinical care. Understanding nongenetic risk factors for off-target toxicities is informative for physicians because this knowledge can be used to educate patients on their likelihood of experiencing adverse events during and after cisplatin-based therapy. Because cisplatin is a highly used antineoplastic agent, such information is relevant for the treatment of multiple adult-onset and pediatric malignancies. Furthermore, it is important to emphasize that a growing number of patients treated with cisplatin-based chemotherapy are being cured of their disease (i.e., hepatoblastoma, human papillomavirus–positive (HPV^+) oropharyngeal cancer, medulloblastoma, osteosarcoma, and testicular cancer). Cisplatin is also finding use in the neoadjuvant setting for multiple tumor types, particularly bladder cancer (88, 89), indicating that there will be an increasing number of patients exposed to cisplatin who will live many years after their initial cancer diagnosis. Consequently, understanding the underlying basis for cisplatin toxicity has an emerging role in the management of this growing patient population. Given that many patients' tumors and germline DNA are now being sequenced, understanding genetic predisposition to cisplatin toxicity will provide a basis for a personalized medicine approach to managing its toxicity.

Although cisplatin-induced toxicities have been well-characterized, the importance of genetic variation in the occurrence of adverse reactions is only now becoming appreciated through modern pharmacogenomic approaches. Nevertheless, a diversification of studies in regards to toxicity types and patient cohorts is needed, with greater emphasis on implementing genome-wide analyses followed by independent replication and functional validation. Only then can these associations be considered plausible biomarkers of cisplatin-induced toxicity that can be harnessed to tailor treatment regimens to individual patients.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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