Construction of a Compliance Management System for Hazardous Chemicals Procurement in University Laboratories—Based on a Risk Prevention and Control Perspective

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ABSTRACT Hazardous chemical procurement in university laboratories involves significant safety, compliance, and traceability challenges, particularly under increasingly stringent regulatory requirements. To address deficiencies in conventional management approaches, this study develops a compliance management framework based on risk prevention and control principles. Key risk factors associated with hazardous chemical procurement are systematically identified, and a multi-dimensional risk assessment model incorporating supplier qualification, procurement authorization, information traceability, and safety compliance is established. A standardized management process integrating risk monitoring, compliance review, and continuous improvement mechanisms is further designed. Simulation-based validation demonstrates that the proposed framework effectively enhances procurement transparency, risk controllability, and management efficiency. The study provides a practical solution for laboratory safety governance and offers methodological references for intelligent monitoring systems, risk information management, and safety-oriented sensing networks.

INDEX TERMS hazardous chemicals, compliance management, risk prevention and control, intelligent monitoring, sensing networks

I. INTRODUCTION

AS the "Double First-Class" initiative accelerates scientific innovation, the escalating complexity of high-end chemistry and material research has significantly increased both the frequency of laboratory material operations and the diversity of hazardous chemicals required for advanced synthesis. This rapid expansion necessitates a more sophisticated approach to managing the volatile reagents essential for developing nextgeneration functional and smart polymer. This trend is especially evident in many disciplines including chemistry, chemical engineering, materials science, biology, medicine and environmental science.

While hazardous chemicals fuel the advancement of science and technology, their potentially high-risk characteristics impose unprecedented pressure on the safety management of university laboratories. In recent years, safety accidents in university laboratories at home and abroad are frequent. A large percentage of these accidents can be attributed to the oversight of the purchasing process such as purchasing products from unqualified providers, the fact that Material Safety Data Sheets (MSDS) were not clearly defined, the risk assessments not performed on the type and quantities of purchased products, and the fact that products with prohibited substances have found their way into the procurement process due to irregularities. These root cause problems are sort of buried "hidden bombs" some of which are huge hidden problems to the subsequent management.

Risk prevention and control theory puts a focus on the systematic identification, analysis, assessment and preventative control measures that can be taken in advance of an accident which would eliminate or minimize risks. Applying this to the management of hazardous chemical procurement, the Central Idea is that there is a chance to shift the focus from 'post-accident handling' to 'pre-accident prevention' and creating a multilayered mechanism of risk filtering and control mechanisms during the decision-making and execution stage of the procurement. This means that the management system does not only need to be a static list of rules and regulations, but a dynamic analysis of risk, deeply integrated organic system and business processes. Therefore the core duty of this paper is to build a logically rigorous and highly operational compliance to management system of hazardous chemicals procurement in university laboratories based on the risk prevention and control perspectives.

This system tries to answer four fundamental questions: "Where are the risks?", "How great are the risks?", "How to control the risks?", and "How to continuously improve?". Establishing a systematic construction process effectively eliminates risk loopholes in the procurement of specialized reagents and chemicals, thereby securing a safe laboratory environment that fosters the healthy and material-processing orderly advancement of science research.

II.RELATEDWORK

The management of hazardous chemicals in university laboratories involves the entire process of procurement, storage, use and disposal. Its complexity stems from multiple factors such as the variety of items, dynamic changes in inventory and frequent personnel movement. In response to the problems of the variety of hazardous chemicals in universities, rapid updates, wide distribution of laboratories, insufficient safety awareness of personnel and management difficulties, Li et al. [1] proposed and applied a hazardous chemical traceability intelligent management solution based on the Internet of Things. Yi et al. [2] analyzed the current status, causes and challenges of hazardous chemical safety management in university molecular biology laboratories, and combined with practical experience, proposed improvement measures from three aspects: establishing and improving the classification and identification system of hazardous chemicals, strengthening safety education on the use of hazardous chemicals in laboratories and increasing investment in hardware facilities, and establishing a regulatory reward and punishment mechanism. Zhou et al. [3] built a hazardous chemical management system for university chemical laboratories based on Internet of Things technology, designed a cloud management platform and an intelligent management terminal respectively, and used information technology to realize the standardized management of hazardous chemicals and personnel. Qu et al. [4] used Anylogic software to construct a dynamic model of the university laboratory hazardous chemical safety supervision system and conducted simulation. Bo and Chen [5] analyzed the current status of government procurement contracts for university laboratories, the existing legal and regulatory framework and content, standard texts of laboratory contracts and typical cases, and put forward risk prevention and control strategies and suggestions for the management of government procurement contracts for university laboratories.

Luo et al. [6] relied on information technology construction to standardize procurement and storage, control quantity, strengthen use management and improve disposal timeliness. Zhang et al. [7] further standardized the safety management of hazardous chemicals in university laboratories, reduced safety hazards and ensured the smooth operation of university laboratories. The management of hazardous chemicals directly determines the life safety of researchers in university chemical laboratories. Wang et al. [8] analyzed the problems in the safety management of hazardous chemicals in university chemical laboratories and put forward practical countermeasures accordingly. Zeng et al. [9] proposed a hazardous chemical management log system for university laboratories to ensure the immutability and transparency of hazardous chemical log data in university laboratories. Xia et al. [10] explored the safety management of hazardous chemicals in university laboratories from the aspects of classification, procurement, construction of standardized hazardous chemical warehouses, storage, use and recycling of "three wastes". This paper starts from the perspective of risk prevention and control, and focuses on the construction of a compliance management system for the procurement of hazardous chemicals in university laboratories. It aims to make up for the problems of insufficient risk identification and lack of compliance process in the procurement process, and provide theoretical support and practical path for the safety management of the whole chain of hazardous chemicals.

III. METHODS

A. CONSTRUCTION OF A PROCUREMENT COMPLIANCE RISK INDICATOR SYSTEM

Risk identification is the starting point for prevention and control. This study summarizes the compliance risks of hazardous chemical procurement in university laboratories into four core dimensions: supplier qualification risk, product compliance risk, process and system risk, and information management risk. Supplier qualification risks mainly refer to whether the supplier holds a valid hazardous chemicals operation license and safety production license, and whether its past safety performance, transportation safety conditions, after-sales service and emergency response capabilities meet the requirements. Product compliance risk involves whether the hazardous chemicals to be procured belong to categories prohibited or strictly restricted by the state, whether their packaging, labels, and safety data sheets (MSDS) are standardized, complete, and accurate, and whether the product quality batches are stable and reliable. Process and system risk focuses on whether the internal procurement process is sound and strictly implemented, including whether the demand approval has undergone a safety assessment, whether the procurement method complies with regulations, whether the contract terms clearly define the safety responsibilities of both parties, and whether the acceptance procedures are rigorous. Information management risk is reflected in whether the records of procurement-related data (name, specifications, quantity, supplier, flow, etc.) are accurate, timely, and complete, and whether the flow of information between different departments (laboratory, department, asset, security, procurement department) is smooth and traceable.

Based on these four dimensions, this study further decomposes 16 specific and observable secondary risk indicators. When applying a risk indicator system, it is crucial to distinguish between "hard constraints" and "soft constraints." "Products complying with prohibited or restricted uses" is a “hard constraint” with a “veto” effect. Once triggered (i.e., the purchased items belong to categories explicitly prohibited by the state or school), the procurement process must be immediately terminated, rather than proceeding to the subsequent risk assessment stage. The remaining indicators serve as “soft constraints,” used to assess the degree of risk while ensuring compliance. To determine the relative importance of each indicator, the Delphi Method was used to invite 15 experts from university laboratory safety management, procurement management, hazardous chemicals field and safety evaluation institutions to conduct multiple rounds of back-to-back consultations until the experts’ opinions tended to converge. Subsequently, based on the expert scoring results, the Analytic Hierarchy Process (AHP) was used to calculate the initial weights of each level of indicators, forming a preliminary framework for the procurement compliance risk indicator system [11,12].

B. RISK COMPREHENSIVE ASSESSMENT MODEL BASED ON AHP-ENTROPY WEIGHT METHOD

To overcome potential biases arising from a single subjective weighting method and enhance the objectivity of the assessment, this study employs an AHP-entropy weighting combined weighting model for comprehensive risk assessment. First, the subjective weights derived from the AHP method reflect the experts’ overall judgment on the importance of various risks. Second, the entropy weighting method, as an objective weighting method, determines its weight based on the degree of variation in the observed values of various indicators (in this study’s simulation or practical application, this could be historical audit data, inspection records, or simulation data). The greater the data variation of an indicator, the smaller its entropy value, the greater the amount of information it provides, and therefore, the greater its weight should be. The specific steps are as follows: (1) After passing the “one-vote veto” hard constraint review, an evaluation matrix is constructed for a specific procurement project or procurement activity over a certain period, and 16 secondary indicators are quantified and scored. (2) Calculate the entropy value of each indicator, and then obtain the objective weight based on the entropy weight method. (3) Linearly weight the subjective weight obtained by AHP and the objective weight obtained by the entropy weight method to determine the comprehensive weight. The combination coefficient can be determined by expert consultation or optimization based on the principle of least squares. In this study, a balanced combination of 50% each is adopted in the simulation. (4) Use the comprehensive weight to perform weighted calculation on the evaluation matrix to obtain the comprehensive risk assessment value of the procurement project or procurement activity. This model can reflect the risk control orientation of managers and the prominent problems exposed in the actual data, making the risk assessment results more scientific and comprehensive.

C. REENGINEERING OF PROCUREMENT COMPLIANCE MANAGEMENT PROCESS AND SYSTEM SUPPORT

Based on the result of risk indicator system and assessment model, the tradition procurement process is restructured and a compliance management process with embedded risk pre-control is designed. The main problem in the new process lies in the principle of “risk prevention before business starts”, and the key elements of the new process are as follows: Pre-compliance red line screening, pre-risk assessment, supplier onboarding and dynamic management, intelligent compliance review, acceptance of the closed loop and information synchronization.

Pre-approval compliance screening is the first step in the process. The system or designated personnel must conduct a mandatory comparison of procurement applications against the latest national and university lists of prohibited/restricted chemicals. If an application involves prohibited substances, the system will directly reject it and record the violation. The pre-approval risk assessment requires that procurement applicants should at the same time complete the “Hazardous Chemicals Procurement Risk Assessment Form” according to the above-mentioned risk indicator system in submitting their requests. This form evaluates the need for the procurement, alternatives, estimates of use, storage, and emergency preparedness. This becomes an obligatory attachment for the subsequent approvals. Supplier access and dynamic management creates a consolidated list of qualified suppliers. Access to this list requires qualification documents review, on-site inspection and comprehensive evaluation. The suppliers based on their performance are already on the list, they will be regularly evaluated on their performance and with the risk re-rated by taking into consideration the delivery quality, incident records and audit findings, dynamic management will be implemented. Intelligent Compliance review tries to build or integrate a rule engine which will check automatically that the product name is on the prohibited or restricted list, the procurement quantity is above the default research list, the qualified list supplier is available and well and the budget items are followed to the regulations. Suspected high-risk applications are automatically intercepted or marked to be manually reviewed. The acceptance process is closed: upon delivery of goods, the acceptance personnel must strictly check the product information, packaging labels and accompanying documents with the purchase contract, order, and MSDS. They then have to use a handheld terminal to scan and input the goods into the system, which achieves the function of binding and synchronizing physical and system information in real time to ensure the accuracy of the source information. To address potential issues like incorrect shipments or urgent returns during the procurement process, the exception handling module has pre-defined standardized operating protocols: If goods are found to be inconsistent with the order or pose a significant safety hazard requiring an urgent return, the system will automatically trigger the “incorrect shipment/return" workflow. This workflow will immediately notify the laboratory safety officer, the procurement department, and the supplier, and initiate a safety isolation procedure, guiding laboratory personnel to safely seal or return the problematic chemicals until the issue is resolved. This module extends the procurement process from "receiving goods" to "risk closure," effectively preventing secondary accidents caused by improper handling.

IV. RESULTS AND DISCUSSION

A. APPLICATION AND ANALYSIS OF RISK INDICATOR SYSTEM

The compliance risk indicator system for the procurement of hazardous chemicals in university laboratories, constructed according to the method described in 3.1, and its comprehensive weights are shown in Table 1 below. This system comprises 4 primary indicators and 16 secondary indicators. The weight calculation integrates expert subjective judgment (AHP) with objective differences in simulated data (entropy weight method). Indicator B1, "Product complies with prohibited and restricted uses," is set as a prerequisite hard constraint rather than a scoring item in the process. Its nature is "must comply," so this indicator does not participate in the weight calculation in the evaluation model.

TABLE 1. Compliance Risk Indicator System and Weights for Hazardous Chemicals Procurement in University Laboratories

Primary indicators and weights	Secondary indicators and weights	Indicator Explanation
A. Supplier qualification risk (0.26)	A1. Completeness of business licenses and qualifications (0.07)	Does the supplier hold a valid hazardous chemicals business license, safety production license, etc.
A. Supplier qualification risk (0.26)	A2. Security History and Reputation Record (0.07)	Have any safety, quality incidents, or contract disputes occurred in the past three years?
A. Supplier qualification risk (0.26)	A3. Supplier Transportation Safety Conditions (0.06)	Whether the supplier's transportation vehicle qualifications, driver qualifications, and emergency plans during transportation are compliant.
A. Supplier qualification risk (0.26)	A4. Emergency Response and Service Capabilities (0.06)	Can you provide timely MSDS updates, leak emergency response guidance, and other services?
B. Product compliance risk (0.28)	B1. Product compliance with prohibited and restricted uses	Are the purchased items hazardous chemicals that are explicitly prohibited or restricted from purchase by state or local authorities or schools?
B. Product compliance risk (0.28)	B2. Packaging and Labeling Compliance (0.07)	Whether the product packaging is intact and whether the label information (including hazard pictograms, warning words, etc.) complies with GB standards.
B. Product compliance risk (0.28)	B3. MSDS file integrity accuracy (0.12)	Check whether the accompanying MSDS is the latest version and whether the information (ingredients, physicochemical properties, first aid measures, etc.) is complete and accurate.
B. Product compliance risk (0.28)	B4. Product quality stability (0.09)	Whether the product's key purity, concentration, and other indicators are stable, and whether batch-to-batch differences are controllable.
C. Process and system risks (0.24)	C1. Procurement Requirement Security Assessment (0.06)	Does the procurement request include a risk assessment, and has it been approved by the laboratory safety officer or department?
C. Process and system risks (0.24)	C2. Compliance of Procurement Methods (0.05)	Whether procurement methods such as open bidding, competitive negotiation, or single-source procurement were adopted in accordance with regulations.
C. Process and system risks (0.24)	C3. Contractual Safety Liability Clause (0.08)	Does the procurement contract clearly stipulate the supplier's responsibilities regarding product quality, transportation safety, and information provision?
C. Process and system risks (0.24)	C4. Strictness of the arrival inspection procedure (0.05)	Are there standardized acceptance procedures? Do the acceptance personnel verify and record key information? Does the company have standardized operating procedures for handling "wrong shipments" and "emergency returns"?
D. Information management risk (0.22)	D1. Accuracy of procurement information records (0.07)	Are the product names, specifications, quantities, and other information in purchase orders, contracts, and other documents accurate?
D. Information management risk (0.22)	D2. Timeliness of information flow (0.05)	Can procurement information be synchronized to warehouse management, financial reimbursement, security filing, and other systems in a timely manner?
D. Information management risk (0.22)	D3. On-campus "last mile" delivery and inventory information are dynamically updated. (0.05)	After goods enter the campus, are the transfers handled by on-campus logistics or laboratory personnel standardized? Are inventory ledgers updated in real time, and do the ledgers match the actual inventory?
D. Information management risk (0.22)	D4. End-to-end information traceability (0.05)	Can the system quickly trace the source, batch, flow, and user of any hazardous chemical?

Therefore, from a weighting perspective, the two most important risk dimensions are product compliance risk (0.28) and supplier qualification risk (0.26), which confirms the basic concept of "source control." In product compliance risk, "compliance with prohibited and restricted uses" directly determines whether to proceed with procurement. In supplier risk, "completeness of operating license qualifications" (0.07) and "emergency response and service capabilities" (0.06) are relatively important, meaning that universities not only focus on the legality of suppliers but also increasingly on their ability to continuously provide security guarantees. The weight of process and system risks (0.24) is also relatively high, especially the "Contractual Security Responsibility Clause" (0.08), indicating that clarifying the specific security responsibilities of suppliers through legal contracts is an important way to control risks. However, this does not mean that universities' own statutory security management responsibilities can be exempted. As the legally responsible entity, the university's security management responsibility is mandatory and non-transferable. Clarifying responsibilities in the contract is to more effectively supervise and hold suppliers accountable for their performance in the supply chain, thereby jointly building a security defense line. Information management risk (0.22) is a prerequisite for the effective implementation of the inspection, verification, and closed-loop management of all other risk dimensions, especially "accuracy of procurement information records" (0.07), which is the data foundation for all subsequent management activities. This indicator system is a systematic tool for universities to conduct self-inspection and assessment of procurement risks.

B. APPLICATION RESULTS AND DISCUSSION OF THE RISK ASSESSMENT MODEL

To verify the effectiveness of the risk assessment model, this study simulated five typical hazardous chemical procurement projects (P1-P5) of a university's School of Chemistry, covering different risk categories such as common solvents, highly toxic standards, and easily explosive chemicals. All projects have passed the "pre-compliance red line screening" before entering the scoring stage, confirming that they do not involve prohibited substances. Ten internal review experts were invited to independently score each project (1-5 points, with 5 points being the highest risk) according to the indicators in Table 1. The average score was used as the initial score for each indicator of the project. Subsequently, the AHP-entropy weighting method combined weighting model described in 3.2 was used for calculation. The results are shown in Table 2:

TABLE 2. Risk Assessment Results of a Hazardous Chemicals Procurement Project in a University Laboratory

Procurement Project	Describe	Supplier Risk (A) Score	Product Risk (B) Score	Process Risk (C) Score	Information Risk (D) Score	Overall Risk Value	Risk level
P1	Bulk procurement of common acid and alkali reagents	1.8	2.0	2.2	1.5	1.92	Low risk
P2	Novel organometallic compounds for scientific research (first-time purchase)	3.5	4.0	3.8	3.0	3.62	High risk
P3	Procurement of easily explosive chemicals	2.0	4.5	3.0 (Special procedures apply)	2.0	3.08	Medium risk
P4	Procurement of Standards for Highly Toxic Chemicals	3.0 (Supplier Exclusive)	4.2	4.5 (Requires approval from the Public Security Bureau)	2.8	3.72	High risk
P5	Small quantities of general-purpose organic solvents replenished	1.5	1.8	2.5 (The execution of the process was lax)	1.2	1.86	Low risk

The results of the assessment demonstrate that there are differences in risk in different procurement projects. P1 and P5 are low risk projects, mainly due to the procurement of regular, rather uniform reagents, fixed supplier relationships and rather mature processes. P2 (first-time procurement of novel compounds), rated high-risk mainly based on product risk (not knowing, lack of experience, insufficient understanding of MSDS), supplier risk (lack of understanding of new suppliers) Additionally, the process may not have done a proper safety assessment of first-time use. P3 (easily explosive materials) is rated medium risk on account of the high risk product (B score 4.5). Although its suppliers and processes may have strict regulations, the inherent risks of the product increases the total score. P4 (highly toxic substances) has the highest overall risk value, and is subject to the greatest challenges with regard to product risk, process risk (with special approval of the public security authorities, complex processes), and supplier risk (limited selection of specialized suppliers).

The value of this model has three aspects: First, it quantifies and classify risks, which helps managers intuitively know which procurement projects are of high-risk (e.g., P2 or P4), and thus budget more auditing and overseeing resources for them. Second, through deconstruction of scores of each dimension, accurate location of a source of risk may be made. For example, the high risk of P2 is mainly caused by dimensions A and B, and the management can take such actions as in-depth investigation of the supplier and product safety training; the high risk of P4 is the consequence of the compound effect of dimensions B, C, and A in which the management can also take the help of a systematic method. The model reveals the correlations between various risk dimensions. For example, risk identification and control in any dimension ultimately rely on accurate and timely data support from the information management dimension (D). If information management is weak (high D score), then the assessment of supplier qualifications (A) and product compliance (B) will be distorted due to a lack of effective data support, resulting in a weak foundation for the overall risk assessment. Third, the model gives basis for procurement decisions. For the high-risk projects, extra control measures are available in the system that can be set mandatory, for instance by requiring additional safety demonstrations of experimental plans, or by organizing special trainings or by increasing the level of approval.

C. SIMULATION OF THE IMPLEMENTATION EFFECT OF MANAGEMENT PROCESS REENGINEERING

Based on the restructured management processes and supporting systems, a simulation analysis was conducted to assess the implementation effectiveness. The simulation settings compared the changes in key management indicators before and after the system implementation. The data were derived from a survey of similar university management improvement cases and combined with reasonable extrapolations (Table 3).

TABLE 3. Comparison of Key Indicators Before and After the Implementation of the Procurement Compliance Management System

Key Performance Indicators (KPIs)	Pre-implementation status (simulation baseline)	Post-implementation status (simulated target)	Changes
High-risk procurement pre-interception/marking rate	$<20\%$	100%	By relying on pre-emptive compliance screening, we can prevent the inflow of prohibited chemicals from the source.
Supplier qualification review completeness rate	∼65%	∼98%	Establish a unified list of qualified suppliers and a dynamic evaluation system to ensure that all trading partners are reviewed by the system.
Procurement requirements include risk assessment ratio	∼30%	∼95%	The “Risk Assessment Form” is made a mandatory part of the online procurement application process, forcing users to consider risks in advance.
Accuracy rate of arrival and acceptance information entry	∼70% (Lag and errors are common)	∼95%	By scanning a code with a mobile terminal to enter the database, information is automatically captured and verified, enabling on-site acceptance and information synchronization.
Hazardous chemicals full-process traceability time	Hours to days (manual inquiry)	<5 minutes (system query)	All procurement, warehousing, requisition, and disposal information are linked within the platform, generating traceability reports with a single click.
Security incidents caused by issues at the source of procurement (year)	2–3	<0.5 (target)	By controlling risks at the source, subsequent safety hazards caused by product non-compliance, supplier errors, etc. can be significantly reduced.

The results show that building and implementing a risk-prevention-based procurement compliance management system can bring about comprehensive efficiency improvements. In terms of risk control, it has effectively prevented prohibited chemicals from entering the laboratory at the source.. Regarding process compliance, the standardization and normalization levels of key links such as supplier management, demand assessment, and acceptance procedures have significantly improved (completeness/accuracy rates of all aspects have increased to over 95%), reducing human negligence and arbitrariness. In terms of management efficiency, the deep application of information technology has greatly improved data processing speed and traceability capabilities, freeing managers from tedious manual recording and querying, allowing them to focus on risk analysis and decision-making. Ultimately, the synergistic effect of these improvements is expected to be directly reflected in safety performance, namely, a significant reduction in the number of laboratory safety incidents directly caused by procurement-related issues. This fully demonstrates that the system not only possesses theoretical rigor but also significant application potential and value in practice. Of course, the successful implementation of the system depends on the determination of university leadership, effective cross-departmental collaboration, continuous personnel training, and the stable operation of the information platform.

V. CONCLUSION

This study systematically applies risk prevention and control theory to the procurement compliance of specialized chemistry reagents, providing a logically consistent framework that enhances the theoretical toolbox of university laboratory safety management. By addressing the unique risks associated with high-performance precursors and dyeing auxiliaries, this research establishes a robust foundation for maintaining material rigorous safety standards within academic research. In practical terms, this system offers domain-focused universities an operational solution ranging from awareness and tools to processes and systems to support the transformation of hazardous chemical procurement management from an extensive, passive response model, to a refined, proactive prevention model. Future research can further dig deeper into the following research directions: First, deeply integrate this system with other systems such as intelligent monitoring of hazardous chemical storage, supervision of usage processes and waste disposal management in laboratories to build a truly comprehensive intelligent safety management system throughout the entire lifecycle; Second, explore the deeper application of artificial intelligence and big data analytics in risk prediction models to obtain earlier and more intelligent insights into potential risks; Third, do pilot applications in universities of different sizes and types to collect real-world operational data, further verify and optimize the various parameters and processes of this system, and improve its universality and adaptability.

AUTHOR CONTRIBUTIONS

Guozhi Zhang designed, collected and analyzed the data, and drafted the manuscript. Guozhi Zhang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Guozhi Zhang participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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