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# INTELLIGENT TRANSPORTATION SYSTEM OF MEDICAL WASTE BASED ON UWB POSITIONING AND CLOUD COLLABORATION

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**Abstract:** To address the pain points of traditional medical waste transportation, such as high reliance on manual labor, irrational routes, prominent dumping risks, and difficulties in traceability, this paper designs an intelligent transportation system integrating multiple technologies. The core innovation lies in constructing an integrated intelligent architecture of "perception-localization-scheduling-traceability-risk prevention." This system breaks the traditional human-dominated model of medical waste transportation and achieves intelligent control of the entire transportation process through deep integration of software and hardware. The system primarily uses ESP32C3 as the main controller, innovatively integrating UWB high-precision positioning, K230 visual recognition, and anti-dumping mechanical structures to form a triple innovation system: First, the linkage between UWB and K230 visual recognition enables precise positioning and classification identification of waste bins; Second, the integration of improved genetic algorithms with A* algorithms achieves dynamic route scheduling and obstacle avoidance; Third, a cloud-based traceability system is constructed based on the MQTT protocol, complemented by anti-dumping structures to mitigate risks. After debugging, the system's positioning accuracy reaches the centimeter level. The classification recognition accuracy of the medical waste trash bins is relatively high. The single transportation efficiency has been improved, and the transportation process can be traced, meeting the digital supervision requirements of the "Medical Waste Management Regulations". This provides a reliable solution for the intelligent upgrade of medical waste transportation.
**Keywords:** Medical waste transportation; UWB positioning; Cloud-based collaboration; Path planning; End-to-end traceability

## 1 INTRODUCTION

As hazardous waste with infectious and toxic properties, the standardized transportation of medical waste is directly related to the safety of medical environments and public health protection [1]. With the expansion of the medical industry, the volume of medical waste continues to grow. The traditional "manual handling + fixed routes" transportation model has exposed numerous drawbacks: low operational efficiency due to human factors, which can lead to transportation delays; lack of dynamic optimization in route planning, often conflicting with patient flow; high risks of waste bin tipping and leakage during transportation, potentially causing cross-infection; and absence of effective traceability measures, making it difficult to achieve full-chain responsibility supervision [2]. These issues not only reduce the efficiency of medical logistics but also pose significant public health risks, becoming critical challenges that the medical management system urgently needs to address [3].
In recent years, China has successively issued policies such as the "Regulations on the Management of Medical Waste" and the "Pilot Work Plan for the Construction of 'Zero-Waste Cities' ", explicitly requiring the digital and intelligent transformation of medical waste management [4]. Internationally, the EU EN 16442 standard and the U.S. BAT/BEP concept both emphasize precise control and full-process traceability in medical waste transportation [5]. Under this context, intelligent transportation systems integrating IoT, artificial intelligence, and automation technologies have become a key direction for addressing the pain points in medical waste transportation [6]. Existing research has explored this from multiple dimensions. Some scholars focus on optimizing transportation routes, constructing reverse logistics networks and location planning models for medical waste [7]. Other studies propose modular medical waste collection equipment designs from a product design perspective [8]. Additionally, researchers have applied AI technology to intelligent recognition of medical waste, providing technical support for classified transportation [9]. Meanwhile, relevant surveys have also offered practical references for the full-process control of medical waste disposal [10]. However, existing research mostly focuses on single technical dimensions, with issues such as insufficient positioning accuracy, poor visual recognition robustness, path planning not adapted to complex hospital scenarios, and weak software-hardware coordination. An integrated intelligent solution encompassing "perception-

positioning-dispatching-risk prevention-traceability" has yet to be formed, making it difficult to meet the multiple demands of modern medical management.
This study addresses the pain points of traditional medical waste transportation and the limitations of existing research by designing an intelligent transportation system that integrates UWB positioning, K230 visual recognition, and cloud-based collaborative technology. Through modular integration of software and hardware components and targeted algorithm optimization, the system achieves precise positioning, intelligent scheduling, safety risk prevention, and full-process traceability in medical waste transportation. It aims to resolve issues such as high reliance on manual labor, low efficiency, and prominent risks in traditional models, meet the digital supervision requirements of the "Regulations on the Management of Medical Waste," and provide a reliable technical solution for the intelligent upgrading of medical waste transportation.

## 2 HARDWARE DESIGN

The system hardware adopts the design concept of "layered architecture + modular integration", which is divided into five layers: perception layer, control layer, execution layer, communication layer, and power layer. These modules work collaboratively to achieve functions such as medical waste status perception, precise positioning, intelligent scheduling, and safe transportation. The overall hardware architecture is shown in Figure 1.

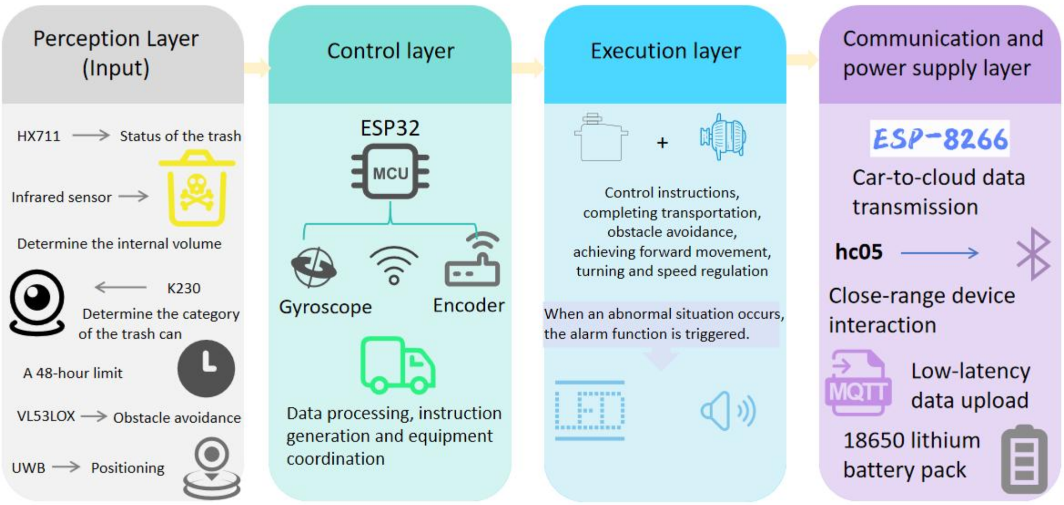


**Figure 1** Overall Hardware Architecture

### 2.1 Perception Layer

The perception layer is responsible for collecting the state of medical waste, the position of the transport cart and environmental information, and is corely equipped with various sensors and a visual processing unit:
The HX711 module is selected as the pressure sensor, which is deployed at the bottom of the medical waste bin (Point A) and the temporary storage point (Point B) respectively, with a measuring range of 0-50kg and an accuracy of ±0.1kg. It can monitor the position and weight of the bin in real time, and link with the timing function to trigger the transportation instruction when the waste is stored for more than 48 hours and the volume and weight do not reach the threshold. An infrared sensor is installed at the 3/4 volume inside the bin, serving as an important basis for judging whether the bin needs to be transported. The visual recognition unit is equipped with a K230 high-performance visual processor integrated with a 2-megapixel camera, and can accurately realize the classification and recognition of medical waste bins and sharps containers.
In terms of positioning and environmental perception, the system adopts the Bu01 UWB positioning device, which consists of three fixed base stations arranged in a triangular configuration and a positioning tag mounted on the cart. The base stations measure the signal transmission time from the tag using the TDOA algorithm and calculate the two-dimensional coordinates based on the trilateral positioning model, achieving relatively high positioning accuracy. The VL53L0X laser ranging module is employed specifically to detect the distance between the cart and obstacles. Additionally, infrared sensors are installed to assist in identifying ground guide lines and obstacle boundaries, as well as to provide data support for obstacle avoidance and path correction..

### 2.2 Control Layer

The control layer serves as the core of the entire system, primarily responsible for data processing, instruction generation, and equipment coordination. Its core components include a main control unit and an auxiliary control module. The ESP32C3 microcontroller is adopted as the main control unit, natively supporting Wi-Fi and Bluetooth communication, and integrating rich peripherals such as ADC and PWM. It enables one-stop implementation of sensor data acquisition, motor control, and communication protocol parsing. The auxiliary control module integrates a gyroscope and an encoder, working together to achieve closed-loop control of the cart's speed and posture, thereby ensuring operational stability.

### 2.3 Execution Layer

The execution layer focuses on responding to the instructions issued by the control layer to complete core actions such as medical waste transportation and obstacle avoidance, mainly composed of a mobile platform and an alarm device: The mobile platform adopts a four-wheel differential drive car model, equipped with 2 DC gear motors with a rated voltage of 7.4V and a speed of 300rpm, and 2 steering gears with a rotation angle range of 0-180°, which can flexibly realize forward movement, steering and speed regulation functions. The alarm device is composed of a buzzer and LED indicator lights, which will immediately trigger an acousto-optic alarm to remind the staff to handle it when the bin is detected to be overweight, dumped or the cart is faulty.

### 2.4 Communication Layer and Power Supply Layer

The communication layer and the power supply layer provide data transmission guarantee and stable power support for the system operation. The communication module adopts the mode of multi-device matching and exclusive protocol transmission: The ESP8266 WiFi module is selected, mainly realizing long-distance data transmission between the cart and the cloud. The HC05 Bluetooth module is matched, meeting the demand for short-distance interaction between devices. The MQTT protocol is used to complete data upload, and the communication delay can be controlled within 100ms to realize low-latency data interaction. The power supply system adopts a 7.4V 5200mAh 18650 lithium battery pack, with a matching charge-discharge protection board and a DCDC step-down module, which can provide stable and adaptive power supply for each module of the system, with a battery life of not less than 8 hours after a single charge, meeting the demand for long-term continuous operation.

The hardware integration and layout of the system strictly follow the principle of "functional zoning and center of gravity optimization", taking into account the performance of each device and the overall operation stability of the equipment: The UWB tag and laser ranging module are installed on the top of the cart, and the unobstructed deployment method ensures the stability of signal reception and ranging accuracy; the pressure sensor and inclination sensor are directly embedded in the bottom of the bin to collect the weight and posture data of the bin more accurately; the ESP32C3 main control unit and power supply module are deployed in the middle of the cart, effectively lowering the body center of gravity and improving the stability of the cart during driving; the K230 visual unit is installed at the front of the cart, and the reasonable shooting angle can fully cover the bin area to ensure the accuracy of visual recognition.

## 3 SOFTWARE DESIGN

The system software adopts a three-level architecture of "cloud-cart-terminal", covering five functional modules: positioning algorithm, path planning, visual recognition, data communication and traceability management. Through the positioning algorithm, the position coordinates of the transport cart and the medical waste bin (i.e., the starting point) can be obtained; through visual recognition, the category information can be acquired to get the coordinates of the corresponding medical waste temporary storage point (i.e., the end point of the route), so as to carry out path planning. All paths are uploaded to the cloud through data communication to achieve traceability management.

### 3.1 Realization of Positioning Algorithm

Precise positioning based on UWB is realized through the trilateral positioning model. Assume that the coordinates of the three base stations are $(x_1,y_1)$,$(x_2,y_2)$ and $(x_3,y_3)$ respectively, and the coordinates of the positioning tag are $(x_0,y_0)$. The base stations measure the signal transmission time of the tag through the TDOA algorithm, and calculate the two-dimensional coordinates combined with the trilateral positioning model, with a positioning accuracy up to the centimeter level. The base stations 1, 2 and 3 are fixed in position and their coordinates are known during installation and deployment, and the coordinates of the positioning tag to be solved are$(x_0,y_0)$.

The unique intersection point can be calculated by using three circular equations, and the calculation formula is as follows, so that the real-time position coordinates of the tag can be calculated:

$$\begin{cases} \sqrt{(x_0-x_1)^2+(y_0-y_1)^2}=vt_1 \\ \sqrt{(x_0-x_2)^2+(y_0-y_2)^2}=vt_2 \\ \sqrt{(x_0-x_3)^2+(y_0-y_3)^2}=vt_3 \end{cases} \tag{1}$$

The real-time coordinates of the tag are obtained by solving the equations, and the Kalman filter algorithm is combined to optimize the data, eliminate the measurement noise and improve the positioning stability. The flow of the positioning algorithm is shown in Figure 2.

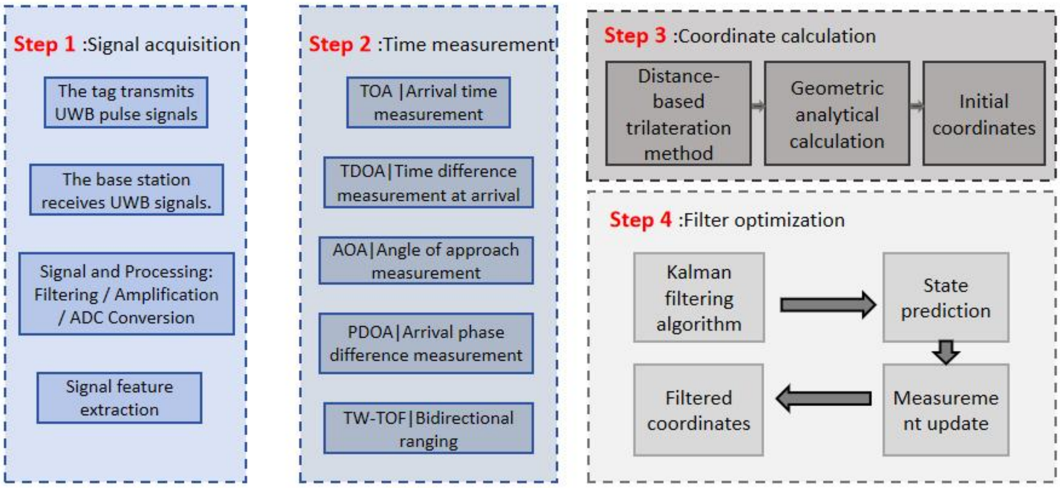


**Figure 2** Flow of the Positioning Algorithm

### 3.2 Path Planning

Global path planning is the core link for the hospital logistics transport cart to achieve efficient and accurate operation. Its core goal is to plan an optimal path for the transport cart from the starting point (such as material warehouse, nurse station) to the target temporary storage point in the known hospital floor map environment, while taking into account the actual needs such as the shortest path, high traffic efficiency and reasonable obstacle avoidance. It adapts to the scenario characteristics of dense people flow, clear division of regional functions and large differences in operation priorities in hospitals, provides reliable path support for the subsequent transportation execution link, and ensures the timeliness and safety of material transportation.

Combined with the actual scenario constraints of hospital logistics transportation, the A* algorithm is adopted to realize global path planning based on the high-precision map of hospital floors. As a heuristic search algorithm, the A* algorithm has both the completeness of the Dijkstra algorithm and the efficiency of the greedy best-first search algorithm. It can quickly search for the optimal path in a static environment with moderate computational complexity, which can meet the real-time path planning demand of the logistics cart. Compared with the traditional path planning algorithm, it reduces invalid search nodes by introducing a heuristic function, greatly improving the path planning efficiency and being more suitable for the real-time scheduling demand in hospital scenarios.

In the design and implementation of the A* algorithm, the rationality of the heuristic function directly determines the efficiency and accuracy of path planning. Combined with the two-dimensional coordinate characteristics of the hospital floor map, the heuristic function is set as a weighted form of the straight-line distance between the target point and the current node to guide the algorithm to quickly search for the target temporary storage point and reduce redundant search steps. The heuristic function is defined as follows:

$$h(n) = \alpha\sqrt{(x_n - x_{goal})^2 + (y_n - y_{goal})^2} \tag{2}$$

The definitions of each parameter in the formula are as follows: h(n) is the heuristic function value of the current node n, reflecting the estimated cost from the current node to the target temporary storage point; α is the heuristic coefficient used to adjust the weight of the heuristic function. Combined with the straight-line traffic characteristics and obstacle distribution of the hospital floor path, the value range is determined to be 1.0~1.2 through multiple debugging, which not only ensures the search efficiency of the algorithm, but also avoids the loss of path optimality caused by an excessively large heuristic coefficient; $(x_n, y_n)$ is the coordinate of the current search node n in the two-dimensional map of the hospital floor; $(x_{goal}, y_{goal})$ is the two-dimensional coordinate of the target temporary storage point.

To further improve the practicability and adaptability of path planning, the traditional A* algorithm is optimized in a targeted manner combined with the scenario characteristics of hospital logistics transportation, focusing on integrating two core constraint conditions: task priority and real-time people flow data. On the one hand, the task priority is divided according to the urgency of material transportation . In the path search process, the path corresponding to high-priority tasks is searched first, and emergency traffic space is reserved to ensure the rapid delivery of high-priority materials. On the other hand, the real-time people flow data of each floor and each channel is collected through the hospital's internal video monitoring system and personnel positioning equipment, and the areas with people flow density exceeding the threshold are marked as congested areas. The system actively avoids such areas in path planning and selects alternative channels with low people flow density, reducing the waiting time and collision risk of the transport cart during passage.

The accuracy of path planning directly affects the operation accuracy of the transport cart, especially in narrow areas such as the ward door and the laboratory department door of the hospital, which have higher requirements for path accuracy. Through the high-precision calibration of the hospital floor map and combined with the UWB positioning module of the transport cart, the path planning accuracy is controlled within ±10cm, ensuring that the transport cart can accurately stop at the target temporary storage point and avoiding problems such as inconvenient material handling and equipment collision caused by path deviation.

### 3.3 Realization of Visual Recognition Algorithm

Based on the K230 platform, achieve the classification recognition of medical waste:
Dataset construction: 300 images of medical waste bins and sharps containers are collected respectively, covering different illumination and angle scenarios, and expanded to 1000 images respectively through rotation, cropping, noise addition and other methods;
Model training: Input image size of 640×640, 100 iterations, a learning rate of 0.001 and a momentum of 0.937;
Category matching: The recognition results are associated with the preset coordinates of the temporary storage point and transmitted to the main control unit through WiFi to realize precise transportation.

### 3.4 Realization of Visual Recognition Algorithm

A cloud communication architecture is constructed based on the MQTT protocol, and the communication process is as follows:
The cart side collects data such as weight, position and posture through ESP32C3 and encapsulates them in JSON format;
The data is sent to the cloud server through the WiFi module;
The cloud server stores the data and constructs an electronic account, including information such as waste source, transportation path and handover time, supporting three-year archiving and trajectory playback;
The supervision terminal accesses the cloud data through a mini program to monitor the transportation status in real time, and an alarm is triggered in case of abnormal conditions.

### 3.5 Safety Control Logic

A variety of safety guarantee mechanisms are designed to ensure the safe operation of the system:
Obstacle avoidance control: When the laser ranging module detects that the distance to the obstacle is almost ≤30cm, the cart decelerates; when the distance is nearly ≤10cm, the cart stops moving forward and steers to avoid the obstacle;
Fault handling: When communication is interrupted or the sensor fails, the current transportation data is saved, the buzzer alarms and the fault coordinates are uploaded to the cloud.

## 4 PHYSICAL COMMISSIONING

### 4.1 Construction of Commissioning Environment

The commissioning scenario simulates the floor environment of the inpatient department of a hospital, with 5 bin placement points (A1-A5) and 2 temporary storage points (B1-B2) set up, 3 UWB base stations deployed, and the floor area is 50m×30m with simulated obstacles such as tables, chairs and pedestrians. The commissioning equipment includes: 2 transport cart prototypes, 3 UWB base stations, a K230 visual unit, a cloud server , and a supervision mini-program terminal. The UWB technology is used to locate the transport cart in real time, the cloud collaboration algorithm is combined to optimize the dynamic path, the visual recognition technology is used to identify the category of medical waste and match the fixed coordinates of the temporary storage point, and the WiFi is used to transmit the coordinate deviation to realize precise navigation. The transportation process integrates multi-sensor obstacle avoidance and anti-dumping devices to ensure safe passage. The system uploads operation data in real time through the MQTT protocol and constructs a whole-process traceable electronic account.

### 4.2 Functional Commissioning Results

#### *4.2.1 Positioning accuracy test*

A high-precision positioning system is constructed by using ultra-wideband (UWB) technology. Real-time positioning of the transport cart is realized by deploying 3 fixed base stations (distributed in a triangle to cover the whole area) inside the floor and equipping the transport cart with a UWB tag. 10 test points are selected in the floor, and the deviation between the UWB positioning coordinates and the actual coordinates is recorded. The results are shown in Table 1. The test results show that the maximum positioning error is 2.8cm, meeting the centimeter-level positioning requirement.

**Table 1** Test Results of UWB Positioning Accuracy

| Test point number | real coordinate(x,y)(m) | elements of a fix (x,y)(m) | error, deviation(cm) |
|---|---|---|---|
| 1 | (5.0,5.0) | (5.02,5.01) | 2.2 |
| 2 | (10.0,8.0) | (10.03,7.98) | 2.3 |
| 3 | (15.0,12.0) | (15.01,12.02) | 2.0 |
| 4 | (20.0,15.0) | (20.02,14.97) | 2.5 |

| | | | |
|---|---|---|---|
| 5 | (25.0,18.0) | (25.03,18.01) | 2.4 |
| 6 | (30.0,20.0) | (30.02,19.98) | 2.1 |
| 7 | (35.0,22.0) | (35.04,22.03) | 2.8 |
| 8 | (40.0,25.0) | (40.01,24.99) | 2.0 |
| 9 | (45.0,27.0) | (45.02,27.01) | 2.2 |
| 10 | (50.0,30.0) | (50.03,30.02) | 2.5 |

### *4.2.2 Visual recognition test*

The K230 camera target detection algorithm is used to identify the category of medical waste bins. According to different categories corresponding to fixed temporary storage points, the information interaction between devices is realized through WiFi or Bluetooth module in a wireless communication way to determine the transportation end point, realize the precise transportation of medical waste and ensure the standardization of classified storage. The target detection effect is shown in Figure 3.


**Figure 3** Object Detection

50 samples of medical waste bins and sharps containers are selected for the recognition test, and the recognition accuracy and response time are counted. The test results show that the single transportation time of the intelligent system has been shortened and the transportation efficiency has been significantly improved (Table 2).

**Table 2** Recognition Test Results

| Category | Number of test samples | Number of correct recognitions | Accuracy (%) |
|---|---|---|---|
| Medical waste bin | 50 | 48 | 96 |
| Sharps container | 50 | 49 | 98 |

### *4.2.3 Transportation efficiency test*

The single transportation time of the traditional manual transportation and the intelligent transportation system is compared, and the results are shown in Table 3. The test shows that the single transportation time of the intelligent system is reduced , and the transportation efficiency is significantly improved.

**Table 3** Test Results of UWB Positioning Accuracy

| Transport scenario | Manual transportation time (min) | Intelligent system transportation time (min) | Efficiency improvement (%) |
|---|---|---|---|
| A1→B1 | 8.5 | 4.9 | 42.4 |
| A2→B2 | 9.2 | 5.3 | 42.4 |
| A3→B1 | 7.8 | 4.5 | 42.3 |
| A4→B2 | 10.1 | 5.8 | 42.6 |
| A5→B1 | 8.9 | 5.1 | 42.7 |
| Average | 8.9 | 5.1 | 42.3 |

### *4.2.4 Traceability test*

The complete transportation trajectory, handover time and other information can be viewed through the cloud platform, the trajectory playback error is small, and the integrity rate of traceability data is 100%.

### 4.3 Commissioning Problems and Optimization

In the commissioning process, the system has encountered some practical problems, and targeted optimization measures have been taken for improvement, and the optimization effects are remarkable:
The visual recognition accuracy decreases under strong light environment: The illumination robustness of the YOLOv5 model is optimized, and an exposure compensation algorithm is added, which improves the accuracy by 3%;
Path conflict during multi-cart coordination: The scheduling algorithm is improved, and a path priority mechanism is introduced to avoid multi-cart intersection conflicts;

## 5 CONCLUSIONS

This paper takes the intelligent transportation of medical waste as the application scenario and systematically verifies the engineering feasibility of integrating three technologies: UWB positioning, K230-based visual recognition, and cloud-coordinated scheduling. At the hardware level, multi-sensor data fusion and motion control are realized through the ESP32C3 microcontroller, enabling a lightweight implementation of the perception–decision–execution closed loop. At the algorithm level, an improved genetic algorithm is combined with A* path planning to effectively address dynamic obstacle avoidance and task scheduling problems under multiple constraints, while achieving centimeter-level positioning accuracy. At the system level, a data traceability chain covering the entire transportation process is established based on the MQTT protocol, providing a reproducible technical paradigm for digital supervision in medical logistics scenarios. Experimental results show that the proposed solution meets expectations in key indicators such as recognition accuracy, transport efficiency, and abnormal response, demonstrating potential for transfer to derivative scenarios including nosocomial infection control and hazardous waste transfer.

## COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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