Research on Modularized Design and Allocation of Infectious Disease Prevention and Control Equipment in China

Xin Zhao, PhD; Yun-dou Wang, PhD; Xiao-feng Zhang, MD; Shu-tian Gao, MD; Li-jun Guo, MD; Li-na Sun, PhD

ABSTRACT

For the prevention and control of newly emergent or sudden infectious diseases, we built an on-site, modularized prevention and control system and tested the equipment by using the clustering analysis method. On the basis of this system, we propose a modular equipment allocation method and 4 applications of this method for different types of infectious disease prevention and control. This will help to improve the efficiency and productivity of anti-epidemic emergency forces and will provide strong technical support for implementing more universal and serialized equipment in China. (*Disaster Med Public Health Preparedness*. 2017;11:375-382)

Key Words: infectious disease, system methodology, modularization, allocation

New or sudden infectious diseases are increasingly emerging with the growing world population and globalization. As the scope of impact continues to expand, infectious disease has become a serious threat to human life and health, imposing high demands on the prevention and control of epidemics. Infectious disease prevention and control (IDP&C) is an effective process for coping with an outbreak and controlling the epidemic. Accordingly, as the material basis for supporting on-site prevention and control of infectious disease, equipment is playing an increasingly significant role.

At present, the serialization level of medical equipment development in China is low and the allocation mode of equipment is unconfined. The allocation of IDP&C equipment at centers for disease control and prevention in China is often in the form of "buying what is temporarily needed," and research and development on equipment merely focuses on filling in gaps in task needs in the initial stage. Although more importance is being given to IDP&C equipment and to developing a level of universalization, serialization, and modularization, there are still few systematic modularized platforms put into practice in the field of IDP&C in China.

Modularization refers to the process of establishing and utilizing modules by means of breaking up and assembling the equipment in a specific way on the basis of the structured form of the equipment or system.[1,2] Targeting the requirements of IDP&C, we designed an equipment system based on modularization theory. Through module combination and allocation, the system can provide rapid and effective decision strategy for anti-epidemic emergency teams. Furthermore, guided by modularization theory, integrated platforms of IDP&C equipment can be developed for specific teams by catering to different requirements. These modularized equipment schemes and platforms can effectively save costs, mitigate wasting of resources, and improve the efficiency of the use of equipment for IDP&C.

With the development of modularization theory and its application in the field of medical equipment, many integrated mobile platforms for IDP&C have been developed in some developed countries, such as the Mobile Biological Clinical and Analytical Laboratory (developed by Orlando Systems LLC)[3] and the Mobile Molecular Detection Laboratory (developed by Pierce Manufacturing Inc).[4] We studied the modular design and allocation of equipment aimed at the requirements of IDP&C in China. Different equipment allocation schemes were further established for different levels of anti-epidemic emergency teams. Our efforts provided the theoretical basis for the research and development of a new generation of IDP&C platforms as well as contributed to enhancing our support capability of dealing with anti-epidemic emergencies and improving universalization and serialization of IDP&C equipment in China.

METHODS

This study used the method of system division and module recombination, guided by the principle of system methodology. The IDP&C equipment series were defined as a whole system. To divide the system into subsystems by the method of system division, we first analyzed the function of the system and then divided it so that the complex system was split into simple systems. Each subsystem constituted a basic module of the entire modularized system. After modular recombination based on the relationships between each module in the hierarchy, function, and structure, the basic modules could be recombined to form a modularized system through system normalization and interface standardization for different tasks.

System Division

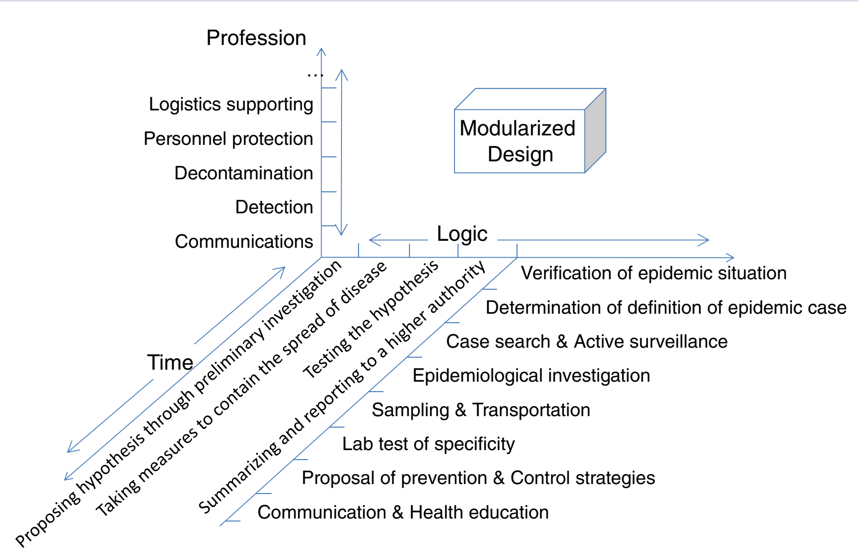
Referring to Hall's three-dimensional morphology,[5] the equipment system fell into 3 aspects: time dimension, logic dimension, and profession dimension (Figure 1). In 2012, the China Ministry of Health and the National Center for Disease Control and Prevention (CDC) jointly issued "The Work Specification of National CDC Response to Public Health Emergency,"[6] which stipulated the content and process of IDP&C as well as on-site disposal of infectious disease outbreaks by relevant institutions. Concerning the logic dimension, the content of public health emergency included 4 aspects: proposing a hypothesis through preliminary investigation, taking measures to contain the spread of disease, testing the hypothesis, and summarizing and reporting to a higher authority. Concerning the time dimension, the work flow included 8 elements: verification of an epidemic situation, determination of the definition of the epidemic case, case search and active surveillance, epidemiological investigation, sampling and transportation, lab test of specificity, proposal of prevention and control strategies, and communication and health education. By division of the 2 dimensions, the functional requirements for on-site disease prevention and control equipment could be clearly defined, including the equipment needed for epidemiological survey, environmental monitoring, sample collection and transportation, pathogen detection, decontamination, personal protection, propaganda and education, immunization and inoculation, etc, in order to realize the functional division of the IDP&C equipment and establish the modules of the system. Concerning the profession dimension, IDP&C equipment technology covers many fields, such as communications, detection, decontamination, personnel protection, logistics support, etc. According to the above-mentioned systematic division, the IDP&C equipment system could be further divided into 8 functional modules and several professional modules. The function modules included command and communication, monitoring, sampling, detection, decontamination, protection and immunization, logistics support, and propaganda and education.

Module Recombination

Module recombination refers to recombination based on the relationships among different modular functions so that the hierarchal and structural relationship of the modules can be achieved. IDP&C has cooperative and sequential links such as "investigation," "detection," and "decontamination." Therefore, the detection module could be combined with the sample preparation module as the sample processing module; the monitoring module, sampling module, and sample processing module could be combined into the investigation and detection module. Furthermore, the investigation and

FIGURE 1

Three-Dimensional Structure of the Infectious Disease Prevention and Control (IDP&C) Equipment System.



detection module and the decontamination module could be combined into the on-site disposal module. In the same way, other professional modules could be recombined with regard to function and technological connections.

Through the division and recombination of modules as indicated, the IDP&C equipment could be divided into 5 function modules: (1) command and communications, (2) on-site disposal, (3) protection and immunization, (4) logistics support, and (5) propaganda and education, forming ordinal relations in terms of the time dimension and logic dimension. Submodules were formed by further division in view of the functional and technological differences among modules regarding the 3 dimensions.

RESULTS AND DISCUSSION

After module recombination, the modularized equipment system of IDP&C was established as shown in Figure 2. The modules of command and communications, protection and immunization, and logistics support were divided into submodules, and the module of on-site disposal was divided into 5 submodules regarding functional and technological differences. The modularized system consisted of 7 leveled structures and 36 submodules.

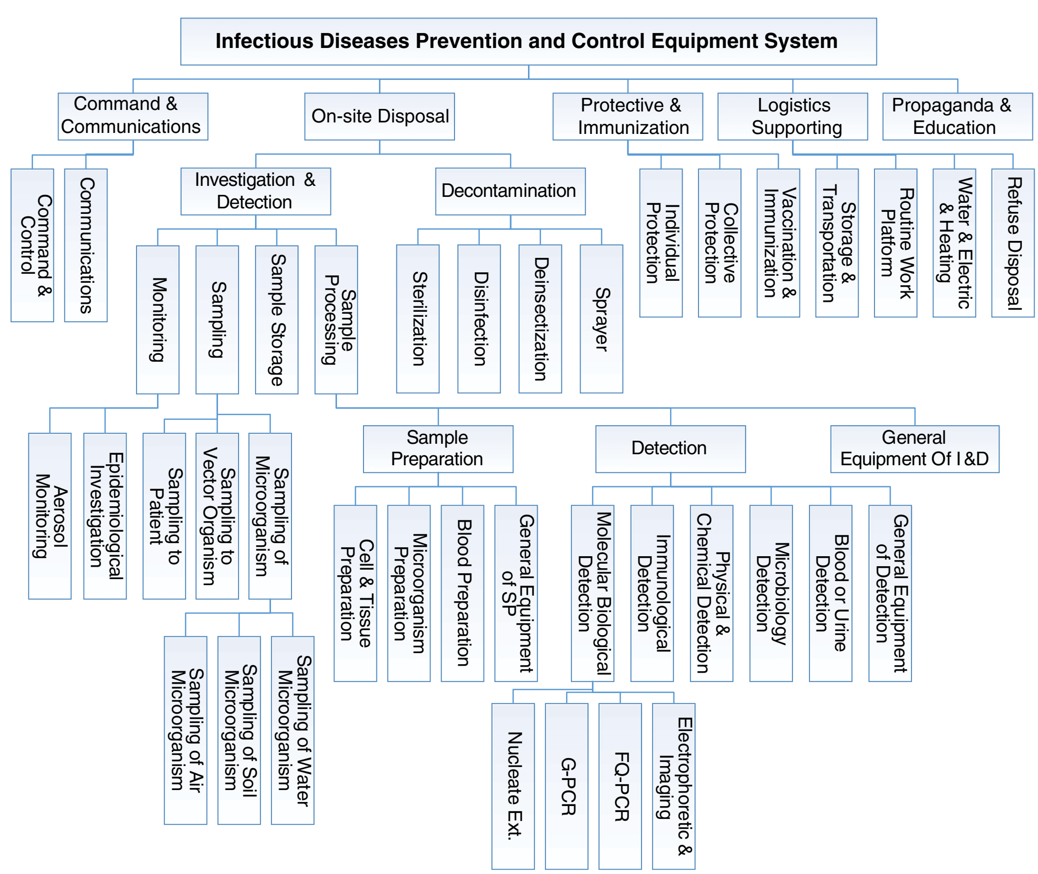
Verification of the Mathematical Model

Cluster analysis, an important branch of data mining, classifies a set of objects on the basis of their inherent relationship and clusters those with similar features to form a module.[7] Therefore, cluster analysis is an effective method of mathematical modeling in module recombination. Cluster analysis can be used to realize modular clustering in a complex equipment system or to mathematically verify the conclusion of a modularized design by using the subjective method of division.

In order to realize modular division by way of cluster analysis, it was first necessary to digitize the equipment for mathematical calculation. Referring to Baldwin's design structure matrix (DSM) method, the matrix of the equipment was built

FIGURE 2

Modular System of the Infectious Disease Prevention and Control (IDP&C) Equipment.



Abbreviation: G-PCR, general polymerase chain reaction; Q-PCR, quantitative polymerase chain reaction; SP, sample preparation.

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in the following way.[8] First, the equipment was defined as Sn and the contiguous matrix as $A = [S_{ij}]$ according to the interconnections of the equipment. Then, the matrix was built contingent on whether the equipment was needed at the same time to complete the task in the process of disease prevention and control as j for relations of coordination or share. The mathematical description was as follows:

$$S_{ij} = \begin{cases} 0 & S_i \text{ and } S_j \text{ are not shared or collaborative relationship} \\ 1 & S_i \text{ and } S_j \text{ are shared or collaborative relationship} \end{cases}$$

This study adopted the K-means clustering method based on Euclidean distance for cluster analysis, which calculated the difference among the lines (and distance). The objective for measuring the distance was the Euclidean distance, defined as $d(i,j) = \sqrt{|x_{i1} - x_{j1}| + |x_{i2} - x_{j2}| + \cdots + |x_{in} - x_{jn}|}$.

The shorter the distance, the higher the degree of similarity.

This study referred to the report "Demonstration Report on Service Requirements and Support Flow" (a report from the research of China National Projects "Top-Level Design and Comprehensive Demonstration Research of Mobile Equipment Platform for Newly-emerged or Sudden Infectious Diseases", unpublished, October 2013). The report puts forward a standard of basic health equipment of IDP&C assigned for CDC. The standard listed 24 pieces equipment as being on-site detection, disposal, and protection equipment, which were chosen to be applied to the algorithm for clustering. The numbered equipment is shown in Table 1. The matrix A of the equipment above is shown in Table 2. The Euclidean distance is calculated as shown in Table 3.

Take the equipment $d(i,j) = 0$ in the same row for one module. For example, the values of D1-2, D1-4, D1-13, D1-14, and D1-16 are 0; therefore, the corresponding number A1, A2, A4, A13, A14, and A16 should be clustered into the same module that includes the knapsack ultra-low-volume sprayer, motorized knapsack sprayer, truck-mounted ultra-low-volume sprayer, portable smoke sprayer, hand-push ultra-low-volume sprayer, and microparticle sprayer. The functions of the contained equipment determine it as the sprayer module. In the same way, A6, A20, and A22 could be clustered as the sample storage module; A8, A9, A10, and A17 as the sampling module; and A12, A15, A18, and A19 as the microbiology detection module. Other equipment constituted modules of command and communication, immunological detection, physical and chemical detection, blood or urine detection, sterilization, deinsectization, and individual protection. This method, which can also be used to cluster other equipment, verified the system division and recombination method of IDP&C equipment mathematically.

Application of the Modular System to the Method of Equipment Allocation

The Module Property

Based on the above-mentioned system, the modules could be aligned with the time dimension, ie, the demands of IDP&C, by defining the structural properties and functional properties of different modules in detail in order to provide a basis for modular allocation and optimization. According to the requirements of different tasks, the structural properties could be categorized into properties of basic, compulsive, and elective, fulfilling the demands for recombining equipment allocation. Modular properties included specialized modules and general modules. For instance, the sample processing module and its subsidiary sample index module along with detection module might contain the general equipment of the submodules, such as the centrifugal machine and sample preparation module, inverted fluorescence microscope and detection module, which ensured the implementation of tasks imposed by the submodules of the higher-level modules. Thus, such submodules might be classified into general modules as a separate category to bring about the general utilization of equipment recyclability and resource efficiency.

Allocation Application of Equipment

According to the three-dimensional morphology, the requirement for equipment could be determined by the time and profession dimensions, which means that the requirement for equipment could be determined by the technological requirements of each work process of IDP&C. Based on the system methodology above and the fundamental characteristics of the types of infectious diseases, the

TABLE 1

On-site Detection, Disposal, and Protection Equipment

A1	Knapsack ultra-low-volume sprayer	A9	Vector biological sampling system	A17	Biological sampling box
A2	Motorized knapsack sprayer	A10	Vector biological sampling box	A18	Microbiology detection box
A3	Knapsack suction trap	A11	Gas chromatography with electroantennogram system	A19	Automatic microbiology detection system
A4	Truck-mounted ultra-low-volume sprayer	A12	Food microbiology detection box	A20	Temperature-controlled refrigerator
A5	GPS	A13	Portable smoke sprayer	A21	Rapid-detection package of blood-borne pathogens
A6	Adiabatic transport box	A14	Hand push ultra-low-volume sprayer	A22	Liquid nitrogen jar
A7	Ethylene oxide sterilization device	A15	Water microbiology detection box	A23	Positive-pressure protective suit
A8	Air microorganism sampling box	A16	Microparticle sprayer	A24	Pathogenic bacteria rapid detection system

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TABLE 2

Matrix of On-site Detection, Disposal, and Protection Equipment

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24
A1	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
A2	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
A3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
A5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
A7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A8	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
A9	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
A10	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
A11	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
A12	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0
A13	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
A14	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
A15	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0
A16	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
A17	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
A18	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0
A19	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0
A20	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
A21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
A22	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
A23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
A24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

TABLE 3

The Euclidean Distance of Each Piece of Equipment

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23
D2	0.0	2.6	0.0	2.6	3.0	2.6	3.2	3.2	3.2	2.6	3.2	0.0	0.0	3.2	0.0	3.2	3.2	3.2	3.0	2.6	3.0	2.6	2.6
D3		2.6	0.0	2.6	3.0	2.6	3.2	3.2	3.2	2.6	3.2	0.0	0.0	3.2	0.0	3.2	3.2	3.2	3.0	2.6	3.0	2.6	2.6
D4			2.6	1.4	2.0	1.4	2.2	2.2	2.2	1.4	2.2	2.6	2.6	2.2	2.6	2.2	2.2	2.2	2.0	1.4	2.0	1.4	1.4
D5				2.6	3.0	2.6	3.2	3.2	3.2	2.6	3.2	0.0	0.0	3.2	0.0	3.2	3.2	3.2	3.0	2.6	3.0	2.6	2.6
D6					2.0	1.4	2.2	2.2	2.2	1.4	2.2	2.6	2.6	2.2	2.6	2.2	2.2	2.2	2.0	1.4	2.0	1.4	1.4
D7						2.0	2.6	2.6	2.6	2.0	2.6	3.0	3.0	2.6	3.0	2.6	2.6	2.6	0.0	2.0	0.0	2.0	2.0
D8							2.2	2.2	2.2	1.4	2.2	2.6	2.6	2.2	2.6	2.2	2.2	2.2	2.0	1.4	2.0	1.4	1.4
D9								0.0	0.0	2.2	2.8	3.2	3.2	2.8	3.2	0.0	2.8	2.8	2.6	2.2	2.6	2.2	2.2
D10									0.0	2.2	2.8	3.2	3.2	2.8	3.2	0.0	2.8	2.8	2.6	2.2	2.6	2.2	2.2
D11										2.2	2.8	3.2	3.2	2.8	3.2	0.0	2.8	2.8	2.6	2.2	2.6	2.2	2.2
D12											2.2	2.6	2.6	2.2	2.6	2.2	2.2	2.2	2.0	1.4	2.0	1.4	1.4
D13												3.2	3.2	0.0	3.2	2.8	0.0	0.0	2.6	2.2	2.6	2.2	2.2
D14													0.0	3.2	0.0	3.2	3.2	3.2	3.0	2.6	3.0	2.6	2.6
D15														3.2	0.0	3.2	3.2	3.2	3.0	2.6	3.0	2.6	2.6
D16															3.2	2.8	0.0	0.0	2.6	2.2	2.6	2.2	2.2
D17																3.2	3.2	3.2	3.0	2.6	3.0	2.6	2.6
D18																	2.8	2.8	2.6	2.2	2.6	2.2	2.2
D19																		0.0	2.6	2.2	2.6	2.2	2.2
D20																			2.6	2.2	2.6	2.2	2.2
D21																				2.0	0.0	2.0	2.0
D22																					2.0	1.4	1.4
D23																						2.0	2.0
D24																							1.4

assignment of equipment modules for IDP&C could be established as shown in Figure 3. In light of the module property, the modules of monitoring, sampling, sample processing, detection, and decontamination were assigned as basic modules according to the characteristics of types of infectious diseases. The modules of communication,

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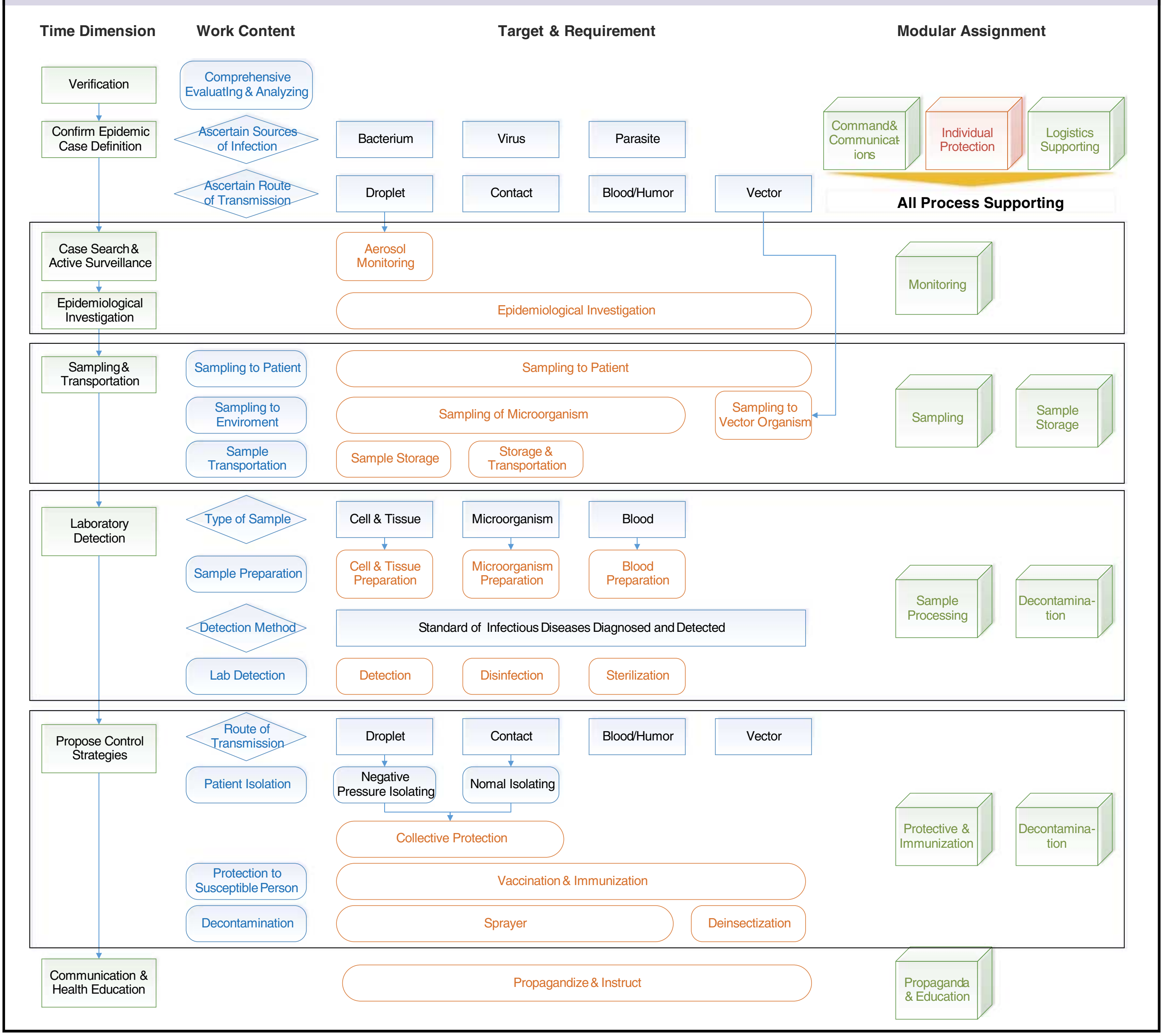
FIGURE 3

Assignment of Equipment Modules for Work Processes.



collective protection, and propaganda and education, which were elective modules, were assigned according to the task requirement, such as the distribution of anti-epidemic emergency teams, or the disease characteristics and the range of infection.

In the aforementioned chart of assignment, the on-site disposal equipment was assigned on the basis of the fundamental characteristics of different types of infectious diseases. China's latest revised version of the Infectious Disease Control Law[9] divided China's common infectious diseases into 3 types and 39 subtypes. The degree of gravity of infectious diseases is determined in light of the different types, the range involved, and the number of confirmed cases. The assignment of on-site disposal modules is determined by the infection source and route of transmission. The assignment of sampling module is contingent on the classification of infection sources, whereas the routes of transmission could determine the assignment of the monitoring module and the decontamination module. The China national Ministry of Health promulgated the standard for the diagnoses and detection of 39 infectious diseases, which could also determine the assignment of the sampling module, sample processing module, and detection and decontamination module. The assignment requirement for the on-site disposal module is shown in Figure 4.

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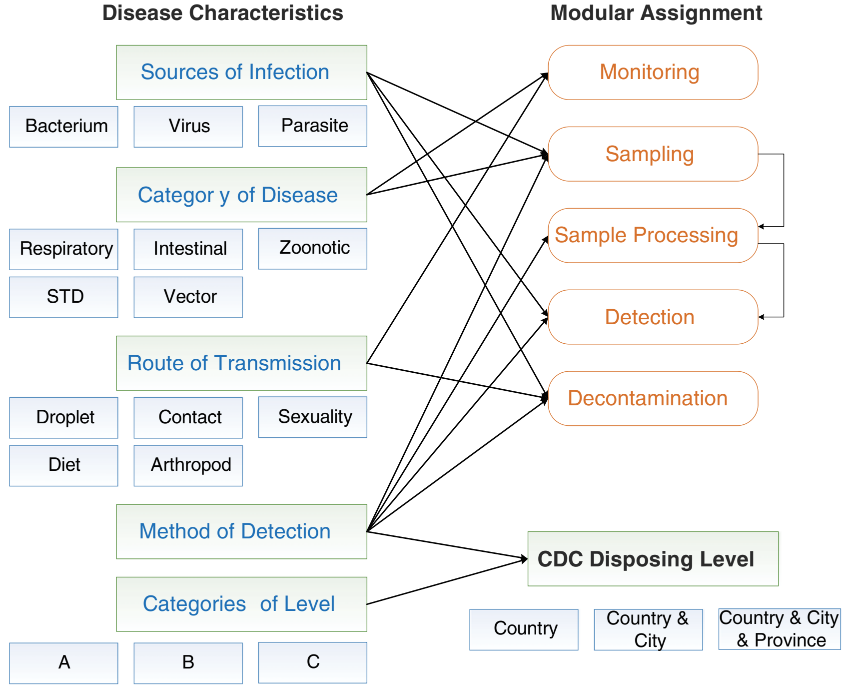
FIGURE 4

Module of On-Site Disposal Assigned by Disease Characteristics.



Abbreviations: CDC, Center for Disease Control and Prevention; STD, sexually transmitted disease.

Chinese anti-epidemic emergency teams are divided into 4 levels: national, provincial, municipal, and county. The modularized assignment above and the personnel composition improve the equipment in need-oriented allocation, flexible organization, equipment sharing, and rational use.

Practice of Modularized System of IDP&C Equipment

Simulation System of IDP&C Equipment

Based on the conclusion of our study, the research project developed a simulation system for corresponding facilities to simulate the allocation, operation, and evaluation of IDP&C equipment. The system was developed based on GIS, including the geographic information of 10 provinces and regions of China, and geographic, equipment, and other basic information of related CDCs in the above regions. The system can simulate typical infectious disease outbreaks in typical areas, distribute the equipment modules for different anti-epidemic needs, and evaluate the support capability of equipment according to the performance parameters of equipment and the task needs in type and quantity of equipment. By simulating the allocation of equipment in modularization, the system can facilitate the corresponding facilities in task planning of IDP&C and improve the efficiency of equipment allocation.

Modularized Carrying Equipment System

In view of the conclusions of our study, the research project developed a series of modularized carrying equipment containing 24 pieces of IDP&C equipment in 7 module classes: command and communications, monitoring, sampling, detection, decontamination, storage and transportation, and protective and immunization. The system tremendously enhanced the efficiency of equipment allocation in the experiences of IDP&C. In 2015, China's third batch of anti-Ebola teams carried the equipment system to Freetown to assist Sierra Leone, with the resulting outcome of augmented detection and decontamination. During the mission, there were 1035 pieces of Ebola samples, 343 pieces of malaria samples, and 7 patients tested biochemically, with the accuracy and result delivery rate in 24 hours being 100%.

Modularized Tent System of Infectious Disease Detection

According to the conclusions of our study, the research project developed a tent system of infectious disease detection containing 3 kinds of operation tents (sample-processing unit, immunological detection unit, and molecular biological detection unit) and several general tents (channel tent, decontamination tent, waste disposal unit, etc). By assembling with support vehicles and establishing standard size parameters for tent modules and chest modules, differently shaped tent systems can be established for IDP&C. The tent system will be sent to Sierra Leone for system demonstration after 2016.

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Modularized Allocation and Demonstration Test of IDP&C Equipment

The research project designed standard chests for module recombination and allocation according to the modular classification of equipment. The chests, which were designed on the basis of the specifications and functions of equipment, included 4 sizes (200*1000*700, 800*600*600, 800*600*500, and 800*550*400[mm]) in 2 forms (withdrawal and unfolding). The modularized allocation and demonstration test were carried out on the basis of these standard chest structures.

The types of equipment can be determined according to the method of allocation mentioned above and the function of the different levels of anti-epidemic emergency teams. The number of equipment modules can be determined according to the number of anti-epidemic emergency team members and the research results of the expert investigation. Then the allocation scheme of IDP&C equipment can eventually be formulated for the 3 levels of Chinese anti-epidemic emergency teams: 25 modules of 58 kinds of equipment for the county level, 34 modules of 114 kinds of equipment for the municipal level, and 36 modules of 138 kinds of equipment for the provincial level.

Demonstration tests for the research were carried out by the China anti-epidemic emergency team (PLA) in Beijing and Tianjin according to the allocation scheme and different levels of epidemic backgrounds defined by China Infectious Disease Control Law (common, less serious, serious, and particularly serious epidemic). The equipment for the tests contained 4 systems: county equipment system, carrying equipment system, tent system, and mobile laboratory system. A common epidemic was treated with the county equipment system and carrying equipment system, a less serious epidemic was treated with the county equipment system combined with the carrying equipment system or mobile laboratory, and a particularly serious epidemic was treated with all 4 systems. During the test, the allocation and transportation of equipment took approximately 2 hours, and positioning and debugging of the systems for different epidemic backgrounds took 1 to 3 hours. The test showed that modular allocation could effectively improve the pertinence and efficiency of equipment allocation. Compared with the common mobile platforms applied in developed countries, our equipment allocation of IDP&C equipment based on modularization theory was much more flexible and resulted in effective assignments for different grades of epidemic backgrounds and different levels of anti-epidemic emergency teams. Accordingly, this system will allow more efficient links between epidemic background and equipment positioning with the anti-epidemic emergency team members, which will further improve application efficiency. Meanwhile, the system platforms designed in the project still have some deficiencies in detection and disposal of fulminating infectious disease owing to the limits of the technical level of equipment.

CONCLUSIONS

The urgency of responding to infectious disease imposes high demands on equipment design and assignment. As a result, IDP&C equipment must be utilized abiding by the principles of speediness, accuracy, economy, and high efficiency. Modularized design is an effective method for meeting this objective. Using the method of modular recombination and meta synthesis to analyze, divide, and recombine the system of IDP&C equipment, we could establish a modularized system of equipment. Using the clustering analysis method and data mining technology to verify the conclusions of the modularization provides reliable theoretical support. The modularized assignment based on research on the process of IDP&C can realize the system's integrated classification, hierarchical assignment, structural optimization, and flexible combination. Furthermore, the modularized equipment system can provide effective technical support in actualizing equipment generalization and serialization and improving the field capability of anti-epidemic emergency teams.

About the Authors

Institute of Medical Equipment, Academy of Military Medical Sciences, Tianjin, China (Drs Zhao, Wang, Zhang, Gao, and Guo), and School of Foreign Languages, China University of Petroleum, Beijing, China (Dr Sun).

Correspondence and reprint requests to Professor Yundou Wang, Institute of Medical Equipment, 106 Wandong Road, Tianjin, China 300171 (e-mail: 13312039963@126.com).

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