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区域医疗系统抗震韧性综述

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摘 要: 韧性作为一种新的灾害风险管理理念,已成为防灾减灾领域的研究热点,考虑到医疗系统在城市运行和灾后救援中的重要作用,在地震期间和之后,区域医疗系统应该具有足够的韧性,并提供连续的医疗服务。如何综合考虑区域范围内多家医院和交通系统的安全性、应急响应能力、多系统的整合与协作,有效评估区域医疗系统的抗震韧性水平,并提出科学的改进建议,对建设韧性城乡具有重要的理论意义。本文通过梳理国内外文献,阐明了区域医疗系统韧性的概念和内涵,总结了地震后短期应急和长期修复两个阶段韧性评估的重点,归纳了现有区域医疗系统韧性的评估框架,从医院集群系统、面向医疗的交通系统、应急医疗服务系统和医疗–交通耦合系统 4 个方面阐述了现有评估方法。区域医疗系统韧性的研究旨在提高其面对灾害时的抵抗性、短期适应性和长期恢复性,这些研究对于满足紧急和日常的医疗需求以及指导灾后恢复具有重要意义。目前区域医疗系统抗震韧性的研究取得了一些进展,但仍然存在一些挑战,本文最后展望了未来的研究方向。

关键词: 区域医疗系统;单体医院;交通系统;抗震韧性;功能评估;恢复时间

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Review of seismic resilience of regional healthcare systems

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Abstract: Resilience, as a new concept in disaster risk management, has become a research hotspot in the field of disaster prevention and mitigation. Considering the significant role of the healthcare system in urban operations and post-disaster rescue, regional medical systems should possess sufficient resilience and provide continuous medical services during and after earthquakes. How to comprehensively consider the safety of multiple hospitals and transportation systems within a region, their emergency response capabilities, integration, and collaboration of multiple systems, effectively assess the seismic resilience level of post-earthquake regional medical systems, and propose scientific improvement suggestions, hold important theoretical significance for the construction of resilient urban and rural areas. This paper, through reviewing domestic and international literature, elucidates the concept and connotation of regional medical system resilience, summarizes the key points of resilience assessment in the two phases of short-term emergency and long-term restoration after earthquakes, and generalizes the existing assessment framework for regional medical system resilience. It elaborates on existing assessment methods from four aspects: hospital cluster system, medical-oriented transportation system, emergency medical service system, and interdependent transportation-healthcare system. The research on regional medical system resilience aims to enhance its resistance, short-term adaptability, and long-term recovery when facing disasters. These studies are of great significance for meeting both emergency and daily medical needs and guiding post-disaster recovery. While some progress has been made in the research on seismic resilience of regional medical systems, there are still some challenges. The paper concludes with an outlook on potential directions for future research.

Keywords: regional healthcare systems; single hospital; transportation systems; seismic resilience; functionality assessment; recovery time

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区域医疗系统是一系列相互协作的机构,包括医院、社区卫生服务中心以及公共卫生组织等。这些机构协同合作,共同提供医疗卫生服务,以满足人民的医疗需求[1]。近年来,频繁的自然灾害和突发的公共卫生事件要求医疗系统具备足够的韧性,以确保患者能得到及时的医疗救助[2-3]。在过去的20年中,地震引发的医疗设施破坏和医疗功能丧失屡见不鲜。例如,1994年的北岭地震[4]、2010年的智利地震[5]、2013年的芦山地震[6]、以及2015年的尼泊尔地震[7]都导致了当地医院的严重损坏,有些甚至失去了正常使用功能。区域医疗系统在地震发生后发挥着重要作用,需要足够的能力去提供连续的医疗救助,并应对激增的医疗需求。

考虑到地震灾害的严重性以及医疗系统的重要性[8],国内外已经推出了一系列关于医院防震减灾的法规、计划和改造项目,旨在提高医院的抗震性能。美国加利福尼亚州颁布了SB1953法令,要求所有医院在2030年之前完成加固改造,以确保在地震后能够正常运行[9]。《2015—2030年仙台减少灾害风险框架》提出了一系列优先事项[10],旨在指导医疗系统在灾害准备、预防、应对和恢复方面的工作。这些规定和计划强调灾害准备和应对,提升了医疗机构和医疗人员的灾害防备意识[11],促进医疗系统的可持续发展,并进一步推动"韧性城乡"的建设[12]。

目前已有许多关于单体医院抗震韧性的研究[13-17],这些研究从医院建筑结构、非结构和医疗设备损伤状态出发[18-20],量化医院内部关联性,建立单体医院韧性评估框架,评估医院灾后的服务功能[21]。灾后伤员需通过交通系统前往医院接受救治,而应急救援队伍和物资也需要通过交通系统抵达受灾现场。此外,灾后伤员的调度、医院间的伤员转运和医院内的分流救治对于紧急救援至关重要。当前医疗系统韧性研究主要集中在单个医院在灾后提供持续医疗服务的能力上,而考虑区域范围内受灾点、交通系统和医院之间依赖关系以及医院间的协作机制的研究仍处于初级阶段。

本文总结了区域医疗系统的研究现状。单体医院抗震韧性的总结可参考其他学者的研究[14,22],本文中的医疗系统指的是区域范围内由多个医院组成的工程系统,而非单个医院。文章阐明了区域医疗系统韧性的概念和内涵,强调了医疗系统双参数多阶段韧性评估的重要性。根据研究对象的不同,总结了目前区域医疗系统韧性的4类研究方向,并对未来研究的重点进行了展望。

1 医疗系统韧性的概念和内涵

1.1 韧性概念与内涵

近年来,在防灾减灾领域,韧性受到了广泛关注,为研究灾害对复杂工程系统的影响机理提供了全新视角。Bruneau等[23]最早将抗震韧性定义为系统降低地震风险、减轻地震破坏和缩短震后恢复时间的能力。翟长海等[24]认为抗震韧性是指系统在受到地震影响时维持或迅速恢复其功能的能力。系统的抗震韧性问题涉及技术、组织、社会、经济(TOSE)等多个维度[25]。例如,技术韧性指系统中的工程设施部分(建筑结构和非结构构件等)在地震灾害中的表现;组织韧性指的是系统决策和领导者做出的有关减轻地震灾害和采取实际行动的能力;社会韧性指灾后及时采取恢复措施以恢复社会经济生活,最小化灾害对生活质量的影响;经济韧性指系统减少间接和直接经济损失的能力。

在东日本大地震和新西兰基督城地震中出现重要建筑功能中断影响大、城市重建时间长、恢复费用高等问题[26]后,引起了学者和政府组织对抗震韧性的更深入关注。相较于过去对抗震性能的研究,抗震韧性研究的范围已从单个建筑、工程设施扩展至建筑群、基础设施系统以及城市,更加关注多个系统之间的相互作用。这种研究已经从关注人员财产安全转向综合考虑地震功能损失和恢复。

1.2 双参数韧性

传统的韧性研究中,系统的韧性常常通过功能曲线进行量化[23]。如图1所示,功能曲线的纵坐标为系统功能Q,横坐标为时间t,整条曲线可大致分为震前、震时损失和震后恢复3个阶段。为方便将系统的震后功能与震前水平进行比较,功能曲线的纵坐标经常使用归一化的系统功能值(系统震后与震前功能比)。系统功能Q随着时间t的上升或者下降反映了系统恢复阶段功能的动态变化,如式(1)所示,通过一定控制时间内的积分计算得到系统的韧性指标R[27]:

$$R = \int_{t_0}^{t_0+T_{\mathrm{Lc}}} \frac{Q(t)}{T_{\mathrm{Lc}}}\mathrm{d}t \qquad (1)$$

式中:t_0为地震发生的时刻,T_{Lc}为控制时间,$Q(t)$为系统的功能函数。图1中t_0+T_{Re}为系统维修结束时刻,T_{Re}为维修时间。

同时,工程系统的韧性包括4个基本属性,即鲁棒性(robustness)、快速性(rapidity)、策略性(resourcefulness)和冗余性(redundancy)[17,28]。鲁棒性是系统抵御灾害的能力,通常由剩余功能来衡量。快速性指系统从灾害中迅速恢复到原有或更高

水平的能力，常通过单位时间内功能恢复来评估。策略性关注系统资源及其整合资源、应对挑战的能力，决定功能恢复曲线形状。冗余性考虑多个功能相似子系统的替代性，在大型系统网络中尤为重要。

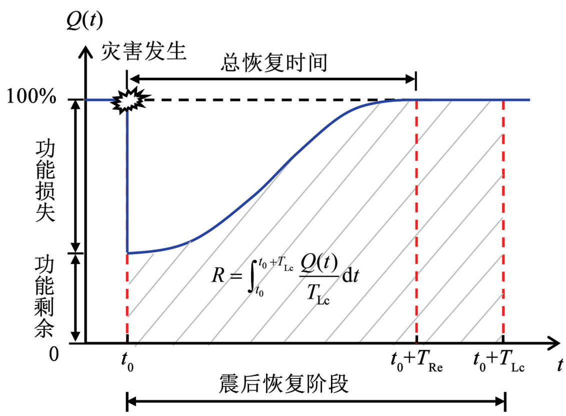

图 1　基于功能变化的韧性评估模型

Fig. 1　Functionality-based resilience assessment model

上述基于积分的韧性指标将系统的抵抗性和恢复性作为同等重要的属性进行考虑。但是由于不同地区的经济发展和韧性的要求各不相同，Zhai 等[29]提出了基于震后功能损失和恢复时间的双参数抗震韧性评价方法，同时构建了体现工程系统能力和需求的评价指标。如图 2 所示，该方法考虑了恢复过程中多个离散功能需求点的权重，从功能损失和恢复时间两个方面来衡量系统的抗震韧性，计算方法为：

$$R_F=\frac{FS_C}{FS_A} \tag{2}$$

$$R_T=\sum_{i=1}^{n}\omega_i\sum_{j=1}^{m}\gamma_j\frac{T_{i,j,C}}{T_{i,j,A}} \tag{3}$$

式中：R_F为基于功能损失的韧性指标，FS_C为系统震后功能损失的实际值，FS_A为系统震后功能损失的目标值，R_T为基于恢复时间的韧性指标，$T_{i,j,C}$为第 j 个用户的第 i 个功能需求点对应的实际恢复时间，$T_{i,j,A}$为第 j 个用户的第 i 个功能需求点对应的目标恢复时间，ω_i为第 i 个功能需求点的权重，γ_j为第 j 个用户的权重，m 为用户数，n 表示工程系统恢复过程中考虑的功能水平数量。该指标可以体现不同经济发展程度、不同设防水平下系统韧性目标的差异，方便不同量纲的物理量进行比较，改进了将震后功能和恢复时间同等重要的国际通用做法的弊端。

工程系统的防灾理念正在从单一的抗震安全性转为考虑地震功能损失和功能恢复的抗震韧性思想。这一转变包括从单一功能指标的量化评估向分阶段多指标考虑用户需求和决策权重的方向发展，以及从单个建筑结构或独立系统的韧性评价向考虑多系统相互作用的耦合系统韧性理论的转变。区域医疗系统通常由多个医院和交通系统组成，因此在评估其韧性时，需要考虑到整个区域在震前、震时、震后短期应急和长期恢复方面的特点和复杂性。双参数评估方法基于功能损失和恢复时间，充分体现了医疗系统功能损失与恢复时间之间的重要关系。这种方法符合我国对于灾前抵抗性的高度重视，也符合我国“从强调灾后救援向强调灾前预防转变”的战略需求。

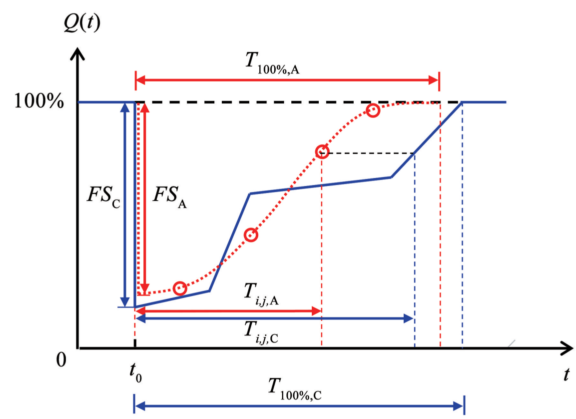

图 2　考虑决策目标的韧性评估模型

Fig. 2　Resilience assessment model considering decision targets

1.3　医疗系统的双阶段韧性

区别于其他基础设施系统，震后应急阶段内的医疗救援工作也是医疗系统抗震韧性的重要组成部分。通过搜集梳理国内汶川地震、芦山地震等地震灾害案例[30-31]，将灾后救援过程划分为现场的搜救与急救、灾区医院的早期救治和后方医院的综合治疗 3 个阶段[32-34]。在正常情况下，医疗系统通常足以应对医疗需求。但地震导致就医需求激增和医疗能力损失，严重影响救援工作。因此，有效的应急救援体系是确保医疗系统应对紧急情况高效并保证韧性的关键[35]。

结合医疗系统的自身特点，区域医疗系统震后通常被分为短期应急和长期恢复两阶段。图 3 展示了震后不同时期多个系统之间的相互依存关系。短期阶段重点在于救治地震伤员，应根据实际情况调度和治疗伤员，考虑震后伤员的激增和医疗系统的功能损失，量化应急阶段期系统面向灾害的适应性。长期修复阶段标志着应急期的结束。在这一阶段，区域内的救治需求由地震带来的挤压伤、多发伤转向为一般的常见病[32]。同时区域内的修复工作也在有序进行。在这个阶段，救治需求发生变化，需要综合考虑正常就医需求和医院损坏情况，量化医疗系统的恢复过程。

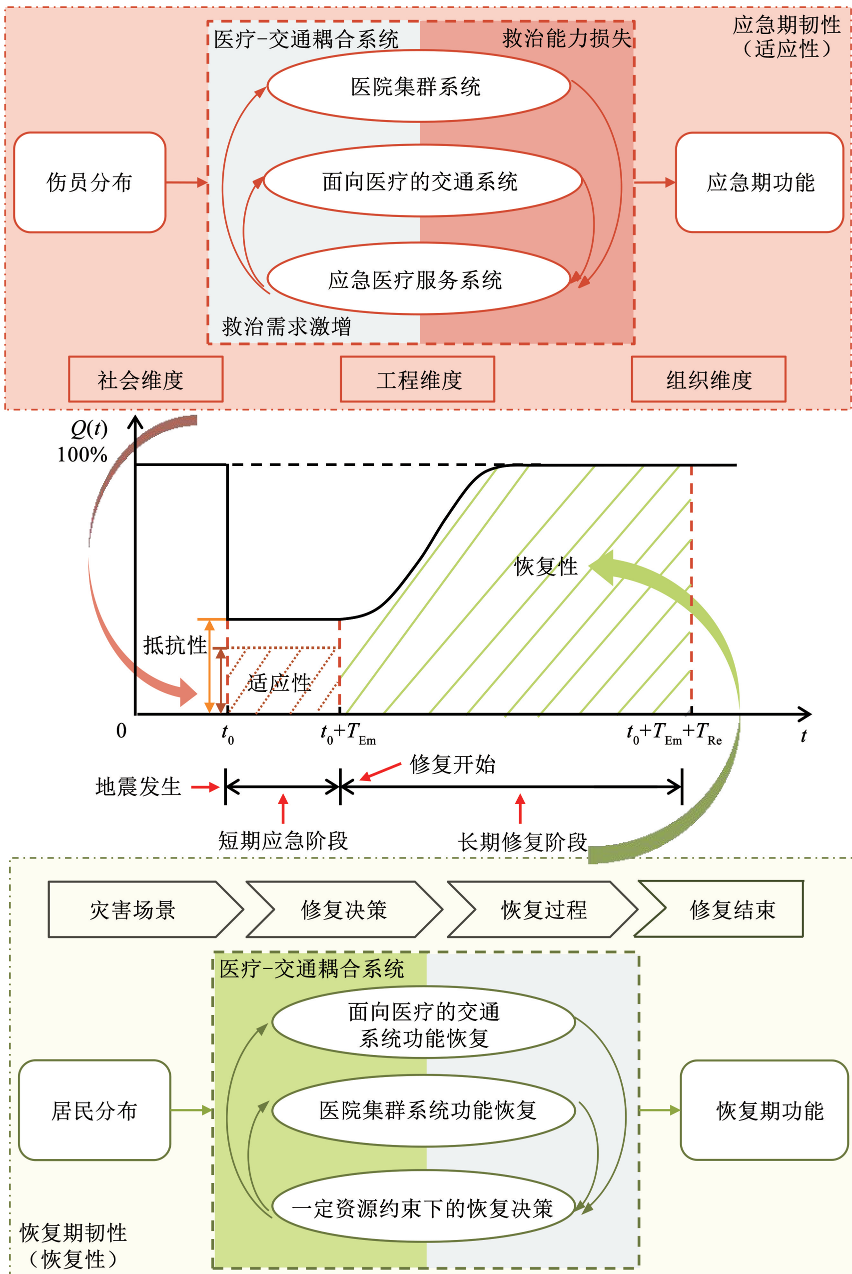

图3　双阶段韧性评估基本思路

Fig. 3　Content of the two-stage resilience assessment

如表1所示，医疗系统韧性被总结为3个方面，包括灾害期间的抗灾能力、短期紧急情况下的适应能力以及长期修复期间的恢复能力。医疗系统的抗灾能力是指系统自身抵抗灾害保障自身安全性的能力，确保区域范围内医院和交通系统在紧急情况下仍能正常运行[36]；医疗系统的适应能力代表其应对灾害的能力，这其中包含着医疗资源重新分配、病人管理和应急响应协调等多方面的考量[37]；医疗系统的恢复能力是指灾后如何通过合理资源调配来实现系统功能的快速恢复[28]。

表1　医疗韧性的内涵[38]

Tab. 1　Connotation of the resilience of regional healthcare systems[38]

医疗系统韧性	阶段	描述
抵抗性	震时	医疗系统可抵御干扰，降低灾害风险的能力[39]
适应性	短期应急	医疗系统可吸收冲击，并提供紧急医疗服务的能力[40]
恢复性	长期修复	医疗系统能迅速从破坏性事件中恢复的能力[41]

2　区域医疗系统韧性评估

医疗系统抗震韧性研究涉及多个领域，旨在增强其对灾害的抗性、应对和恢复能力。尽管已有许多针对单体医院的研究，但对于区域医疗系统的韧性研究尚未形成一致的理论框架。本节将从医院集群系统、医疗交通系统、应急医疗服务系统和医疗-交通耦合系统等 4 个方面进行梳理和总结，其具体含义和研究侧重点整理见表 2。对这 4 类研究对象的评估方法逐一进行阐述，探讨各自的评估方法，以及当前研究中存在的不足。

表 2　区域医疗系统 4 类不同研究对象的定义

Tab. 2　Definition of four different categories of research subjects in regional healthcare systems

研究对象	定义	研究重点
医院集群系统	区域内多家医院、医疗机构或医疗资源整合在一起管理和协作的系统。	侧重于整合医疗资源，使之更加协调和高效，提供更好的医疗服务。它通常涉及医院之间的合作、资源共享、病例转诊等方面。
面向医疗的交通系统	考虑区域内医疗分布的交通系统，旨在确保患者能够及时到达医疗机构接受医疗救治。	与一般的交通系统相比，面向医疗的交通系统更加关注医疗服务的需求，更注重医疗服务的可及性和效率。
应急医疗服务系统	在灾难性事件后，能够迅速组织和提供医疗救援以应对大规模伤员的系统。	应急医疗服务系统更加注重在灾难或紧急情况下的快速响应和资源调配，应急医疗服务系统高度依赖医疗-交通耦合系统以应对突发事件。
医疗-交通耦合系统	将医疗服务和交通系统紧密结合，以确保医疗服务的顺畅提供和患者的及时就医。	强调了医疗与交通之间的密切关联，医院集群和面向医疗的交通都可以被看作医疗-交通耦合系统的一部分，以确保患者的顺畅就医。

2.1　医院集群系统

关于单体医院韧性的评估方法大致分为两类：基于专家经验的医院韧性评估和基于物理机制的医院韧性评估。基于专家经验的医院韧性评估方法是通过指标打分的形式，从多个维度对医院的灾害应对能力进行量化。然而，这种方法偏向定性描述，受调查人员和专家的主观因素的影响，导致结果缺乏一致性，同时难以真实反映医院灾后恢复情况。另一种定量的评价方法是基于物理机制的医院韧性评估，该方法从医院内结构损伤、医患人员和组织管理等角度出发，对医院的运行情况进行建模，通过模型量化灾后医院性能。单体医院的性能指标大致分为可用性、救治能力和医疗服务功能 3 类。目前大多数关于单体医院的研究往往是通过故障树[42-45]和贝叶斯网络[46-47]的方法量化医院内部结构、非结构组件、设备以及相关的基础设施系统复杂的相关性，通过多智能体仿真[48-49]、离散事件模拟[16,50-51]和系统动力学方法[41]从组织管理维度模拟灾后的就医流程。医院在灾后应急响应中具有关键作用，医疗韧性已成为全球防灾减灾领域的重要研究方向[52]。

而区域范围内医院的地理分布通常会增加医疗系统韧性评估的复杂性。为了简化建模的复杂性，许多研究假设区域医疗系统可以通过一定范围内的多家单体医院表示，该类研究方法不考虑灾后交通网络的损坏对伤员就医造成的延迟和就医行为带来的改变[53]。

Yi 等[54]采用单体医院集合的形式评价医疗系统灾后的服务水平，并预测灾区内多个医院的瞬时容量。Cimellaro 等[55]提出一种描述单体医院急诊科的组织模型，并将区域医疗系统简化为多个单体医院集合的形式，评估了震后区域内医疗服务的能力。Aghapour 等[56]提出一个优化模型，用于灾难事件中医院的容量规划和重新配置，以提高系统对灾害的应对能力。

一些学者在分析医院抗震性能和灾后医院的功能性的基础上，将医院灾后的长期恢复纳入医院韧性的评价环节。同时在区域范围内，由于修复资源有限，决策者无法同时开启所有医院的维修任务。Alisjahbana 等[57]将医疗服务建模为排队系统，该系统考虑危重患者的优先治疗，并制定了一个贪婪算法来规划有效的医疗系统重建。Hassan 等[58]采用综合方法对位于田纳西州孟菲斯市的医院群震后功能和恢复过程进行了量化和评估。此外，Hassan 等[59]还研究了医疗系统应对疫情或山火等多重灾害的情况，表明医疗系统的恢复可能会因医院间的互动和资源优化而有所不同。Ugwu 等[60]提出了一个灾后恢复规划框架，使用离散事件模拟对医疗机构急诊部门的运作进行建模，并量化各医院的恢复。

这些研究将医疗系统建模为一定区域内的医院集合，仍以医院的服务功能为主要考虑因素，没有考虑交通和医疗之间的关联性。因此，这些模型无法

考虑震后交通系统内组件损伤和患者就医选择的改变对医疗系统的影响。然而,震后调查表明,桥梁和道路的损坏将降低交通系统的通行能力,并增加患者的就医时间[61-62]。交通系统中断对应急救援的影响也不容忽视,在评价区域医疗系统韧性时,量化灾后医院和交通之间的依赖关系至关重要。

2.2 面向医疗的交通系统

交通系统震后的通行状态极大地影响对医疗服务的空间可达性[63],因此评估震后区域医疗系统功能时,有必要量化交通系统的脆弱性和出行需求的变化[64],考虑交通拥堵对病人就医造成的负面影响。同时,交通系统功能评价可以为紧急医疗服务和伤员运送提供决策支持。关于灾后交通系统的功能评估方法大致分为4类,连通性方法[65-68]、交通流方法[61-62]、网络容量方法[69]和多智体仿真方法[70]。基于连通性的纯拓扑指标简单直观,易于计算和理解,通过分析节点和边的关系评估网络自身性质。交通流指标通过车流量、速度等实时数据,能够全面反映实际交通状况,提供更精确的信息。网络容量方法强调网络的容量和承载能力,更关注网络的稳定性和最大负荷。多智体仿真方法能够考虑个体行为对整体系统的影响,通过建模多个智能体(代表车辆、行人等)的行为,模拟交通系统的动态演化过程。研究人员需要根据研究具体问题,选择最合适的方法来评价震后交通系统功能损失对医疗系统的影响。

此外,可达性常被用于分析交通系统在极端事件中的脆弱性和可靠性[71-74]。可达性反映了起点与终点之间在空间上克服各种障碍进行交流的难易程度,常用的空间可达性方法包括:比例模型法、最小距离模型、两步移动搜索法、潜能模型和交通网络中心性测度法等[75]。表3列出了上述方法的基本定义、优缺点和适用范围。

表3 可达性测度常用方法

Tab.3 Common methods for accessibility measurement

方法	定义	优缺点	适用范围
比例模型法	研究公共服务资源总量和服务人口的比值。	简单易懂,较为直观;未考虑地理空间的复杂性。	适用于简单的可达性评估,对数据要求不高。
最小距离模型	服务人口到达最临近服务设施的距离。	简单、直观,计算容易;未考虑交通拥堵、地形等因素。	适用于简单的可达性评估,不涉及复杂的交通条件。
累积机会法	在一定的出行时间和距离内,可获得公共服务资源的数量。	考虑了潜在机会的累积效应,忽略了距离衰减作用。	适用于考虑潜在机会对可达性影响的情况,如商业机会、就业等。
两步移动搜索法	以供给点和需求点为基础进行二次搜索,计算供需比并加和得到可达性。	考虑了目标地点周围的机会,更符合实际情况;可能过度强调邻近性对可达性的影响。	适用于考虑邻近地区对可达性的影响,如医疗服务、教育资源等。
潜能模型	考虑公共服务设施对供给点潜在影响,通常用于预测新设施对周围区域的影响。	考虑了各地区的潜在机会和需求;对数据要求高,需要需求点和供给点详细数据。	适用于考虑区域内供需双方之间的空间阻隔的城市规划。
网络中心性	衡量了网络中节点的相对重要性或影响力。	考虑了网络结构,更贴近实际交通情况;计算较为复杂,需要详细的交通数据。	适用于对具体交通网络结构进行分析的情况,如交通规划。

Martin等[76]基于GIS建模,衡量两个地区公路网在洪水或暴雨灾害下的韧性水平。交通系统内组件受损或失效可能加重区域范围内医疗服务资源分布不均的现象[77]。目前部分学者对日常居民的就医可达性进行分析[78-83],另有一些学者将医疗服务的可达性作为医疗系统功能的一部分,评估医疗系统灾后的功能[84-86]。Petricola等[87]比较了常态下和2019年莫桑比克"伊代"气旋后的洪水事件后的医疗可达性,以评估可达性的损失。Ertugay等[88]考虑地震后建筑物倒塌对路网的影响,提出了一种面向地震情况下道路封闭的可达性建模方法。Twumasi-Boakye等[89]以坦帕湾地区的皮涅拉斯县为案例研究,考虑飓风灾害后桥梁的损坏,以老年人的就医可达性来评估老年社区的抗灾韧性。Shang等[90-91]考虑了地震对建筑物和交通网络的破坏、地震后可用的病床数量和医务人员,通过改进的两步移动搜索法评估地震后医疗服务的可达性。Pei等[47]考虑到震后不同医院内部级联的损伤情况、道路堵塞情况下震后医疗服务的折减和通行延迟,提出一种改进的重力模型的医疗可达性分析方法。

但是,这类基于可达性的研究方法中,通常简化了区域内医院的建模过程。医院的功能水平主要由院内病床数、医护人员数量和日常患者收治数量体现,医院的救治能力并未进行定量描述,震后医院内

结构、非结构、医疗设备的损坏以及灾后应急组织管理对医院功能的影响无法体现,震后具体的伤员分配方案无法提供。

2.3　应急医疗服务系统

应急医疗服务系统和医疗系统韧性之间存在密切关系,两者相互影响,共同决定了医疗系统在灾害时的适应性[92]。应急医疗服务系统旨在灾害或紧急情况下提供快速有效的医疗救助,包括现场急救、伤员运输、院前和院内急救等。该系统与受灾点、交通和灾区内各医院协同工作,其迅速响应有助于减轻医疗系统负担,确保医疗服务连续性,以满足突然增加的就医需求。

不合理的伤员运送计划可能会引起区域内各医院内部医疗供需关系的不匹配,导致某一家医院内伤员等待时间过长,造成伤情恶化[93]。部分学者针对灾难应急阶段,综合考虑不同医疗机构资源的动态变化,构建不同的数学优化模型来解决将大量伤员运送到医院的应急调度问题[94-100]。

Zhang 等[101]提出了一种双目标鲁棒优化模型,用于确定应急医疗服务站点的位置、站点的需求区域分配以及每个站点的应急车辆数量,以平衡成本和救治能力。Zhu 等[102]构建了考虑相同和不同伤害程度的两个模型,解决紧急救援路线优化需要考虑的公平性和优先性问题。Liu 等[103]建立了一个双目标优化模型,确定了最优临时医疗服务地点和医疗服务分配方案。Hu 等[104]通过整合疏散和医疗服务活动,并考虑人口昼夜变化以应对城市地区的大规模自然灾害,解决了紧急避难所和医疗网络的设计问题。Sun 等[105]提出了一种基于场景的鲁棒双目标优化模型,该模型集成了医院选址、伤员运输和考虑分诊的救援物资分配,旨在最大程度减少因医疗服务延迟而造成的人员伤亡。Ceferino 等[106-107]提出了一种考虑医院功能损失和地震造成的伤员的应急响应评估方法。所提出的方法可以帮助决策者设计有效的患者转移计划以及救护车和移动手术室的分配方案,通过各医院的协调配合,解决这种需求和能力不匹配的问题,减少患者的等待时间。

这些模型为政府及相关部门的应急决策方案提供理论支持,提高整个医疗体系的韧性,以在灾害和紧急情况下提供高效、协调的医疗服务[108-109]。然而,目前对于医疗系统韧性的评价大多集中于灾后的单体医院的功能性损失和长期恢复过程,很少关注应急期内的医院之间的协调配合和应急医疗服务系统。

2.4　耦合的医疗系统

医疗系统、居民小区以及交通系统之间有着复杂的交互关系,其关联机制直接影响医疗系统的评估及提升方法。部分学者从震后伤员紧急就医的角度,研究震后医疗-交通耦合系统的功能。

Lupoi 等[110-111]考虑了震后交通和医疗之间的相互依赖关系,通过蒙特卡洛方法求解可靠性问题,研究了区域医疗系统的抗震性能,评估了相互依赖的医院网络或医疗桥梁网络的区域治疗能力,实现了一种新颖的“动态“就医模型。Dong 等[112]提出了医疗机构-桥梁网络耦合系统的性能评估框架,根据组件的损坏情况计算行程和等待时间,以此评估系统的性能。Xu 等[113]提出了一种联合分析方法,考虑地震后医疗救援的需求、倒塌建筑物的影响,设计了一种路线规划算法,以快速将医院与受伤人员匹配并运送到医院。Gu 等[114]提出了一个实时仿真模型,考虑伤员分布、道路交通和医院等待时间的变化,将地震前后伤员接受治疗的平均最短时间之间的比值作为功能指标。

另有部分学者将应急医疗纳入韧性评价体系。Wu 等[115]通过考虑建筑、伤员、受损的医院、应急服务车辆、中断的交通网络和自然灾害之间的相互作用,制定了评估应急医疗服务的交通网络韧性的框架。Pei 等[38]构建了关于伤员应急调度和救治模型,将地震后应急医疗救援系统中的物理损失、组织管理和应急医疗服务系统相结合,以震后震前救援效率之比作为医疗系统的应急期韧性指标,提出了考虑内部相互依赖关系的交通-医疗系统应急期韧性评估框架,量化了交通和医疗之间的级联效应。

综上所述,医疗系统的抗震韧性研究需考虑医院内结构及设备间的相互作用,也需关注医疗系统与交通系统的功能关联,在此基础上研究考虑系统关联的抗震韧性评估及提升方法。目前,医疗系统与交通系统关联性研究主要聚焦医院到居民区的可达性,多系统的耦合修复方法很少被应用于医疗系统韧性建模之中,考虑医疗系统与交通系统关联性的韧性研究尚处发展阶段。

3　结论与讨论

医疗系统是城市基础设施的核心,其影响广泛,渗透到社会结构、经济发展和城市规划的各个方面。在应对地震或其他突发公共卫生事件中,确保医疗服务的稳定性和高效性至关重要,是建设“韧性城乡”的关键环节之一。然而,现有医疗系统功能评价和韧性研究方法仍有局限性,尤其是在考虑区域医疗系统的全面性和应对长期恢复的挑战方面。因此,为深度整合医疗救援过程与医疗韧性,以下建议需要在后续研究中细化考虑:

1)综合灾前、灾后应急和灾后恢复全过程的医疗系统韧性提升。在考虑系统关联的医疗系统抗震韧性研究的基础上,利用机器学习等算法建立快速评估医疗系统韧性指标的高精度代理模型,为决策者提供全过程韧性提升方案。

2)探索“平急结合”的医疗系统韧性发展新思路,即在日常运行中确保高效医疗服务的同时,建立完备的应急响应体系,以快速响应和提供紧急救治。

3)工程技术、组织管理、社会经济等多维度的有机融合。工程方面通过医院建筑结构、非结构和医疗设备的抗震设计确保系统安全功能;组织方面制定应急响应计划保障医院有序运营;社会方面的财政支持、政策制定和卫生教育保证医疗系统的可持续性。这些多维度的有机融合可以提高医疗系统的整体韧性,使其更好地迎接未来挑战。

4)将韧性评价延申至韧性设计,即基于韧性视角进行城市规划,考虑医疗系统在日常和灾害场景下的需求,并研究医疗系统与其他城市工程系统的耦合机制,以指导城市内医疗系统的韧性设计,确保其在应急情况下能迅速恢复。

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