气传花粉监测数据研究进展

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摘要 综述了基于气传花粉监测数据的研究进展，结果发现，利用花粉观测数据可获取某地的花粉概况，进而绘制具有临床价值的花粉日历。但因其不包含病例信息，故需结合过敏人群特征修正影响浓度阈值。此外，通过分析暴露于不同环境下的患病风险，证实了防治花粉症十分依赖于洁净的空气。局地观测环境及采样器的安放位置对监测结果有极大影响，但整体而言，北半球大多数区域花粉季延长、花粉浓度增加，并可归因于气候变暖所致。为预测花粉关键要素在未来的变化，4大类模型被广泛应用，并取得较好的预测结果。但对于预测效果较差的部分（花粉浓度极值、复杂地形等），最优解决方法则是结合高分辨率的花粉监测数据进行订正。但是，由于缺乏低成本的自动监测设备，当前花粉监测数据的分辨率仍然较低，由此带来了一系列的数据和技术壁垒。建议该领域应将开发低成本的自动监测设备作为近期发展的重点，并以此建立标准化的观测体系。

关键词 气传花粉；花粉过敏；花粉监测；花粉预测

人类的生产生活得益于地球上众多植物的存在，但是有些植物产生的花粉，散播在空气中也切实影响了我们身体的健康[1]，它不仅会带来呼吸系统疾病（变应性鼻炎、哮喘等）[2–3]，还会导致消化系统（胃癌、胰腺癌等）疾病[4]、神经系统（部分人群自杀率升高）疾病[5]的发病率增加。近年来，由于当今全球气候变暖及碳排放的增多，这些疾病呈现出明显的增加趋势[6–7]。

自19世纪，研究人员便开始进行空气花粉的监测，通过监测结果开展花粉症的防治工作。近年来，随着研究手段和分析方法的升级，对所观测的空气花粉数据进一步分析，对空气中花粉种类和浓

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度等要素的变化趋势及其对气候环境因素的响应情况,以及如何对其进行有效的预测等都有了深入的研究。

本文综述依托气传花粉监测数据所开展的各项研究工作的进展,指出当前研究中存在的一些不足,并提出应着重发展的方向。

1 花粉监测数据在预防医学方面的应用

1.1 花粉日历、浓度阈值及过敏指数

花粉日历指以可视化的图形展示某一地区全年不同时段内(通常以旬为单位),各类致敏性花粉的浓度情况[8]。借由花粉日历,医生及患者可清晰且直观地了解各类花粉的花粉季起止时间、峰值浓度等关键信息,具有一定的临床应用价值[9]。

欧洲是此项研究开展最充分的地区,研究人员从20世纪70年代便构建了花粉日历[10],并进行了持续更新[11-12]。近年来,学者们也通过多种手段降低时空不均一性的负面影响,如提高观测点密度[13]、插值补全缺测数据[14]、利用滑动平均[15]或概率密度平均[16]函数订正数据等。

由于花粉蛋白的致敏活性存在差异,所以不同种类花粉的浓度阈值有所不同[17],研究人员依据不同患者人数占比(如“第一个患者出现症状”“少数患者出现症状”“多数患者出现症状”“所有患者出现症状”等)所对应的花粉浓度值,给出了各类花粉致敏的浓度阈值[18]。在此基础上,欧洲过敏和临床免疫学研究院(EAACI)组织专家进一步审查了相关研究成果,给出了具有共识性的阈值标准[19]。法国、芬兰、奥地利的检验结果既证实了该标准的可靠性,也说明花粉浓度阈值的确定应参考过敏人群的信息[20]。此外,如果能获得某一区域的植株水平投影面积、植株高度等信息,还可将其作为自变量引入经验模型,同花粉致敏性强度、授粉原理、花粉季长度等因子一同进行评级,之后以乘积、累加的方法估算花粉过敏指数[21]。该方法被用于估算西班牙各公园的潜在过敏指数[22-23],为患者提供了直观参考。

1.2 环境暴露风险

对花粉症患者,即便外界环境中没有花粉,气象因子或污染物的变化也可能导致病情恶化[24-27],因此需综合评估环境暴露所带来的风险。

研究表明,简单的相关分析[28]或单一的线性模型[29]并不能很好地解释环境因素的影响。故近年来的研究多基于如逻辑回归[30]、结合准Poisson回归的分布式滞后模型[31]、广义加法模型[32-34]等非线性算法,并较好地预测了环境暴露下的就诊人数[35]。

通过对多要素的分析,学者们发现低浓度的花粉暴露可以有效且持续地减少花粉过敏患者的症状[36]、雷暴等特殊天气可促使花粉颗粒高度聚集,并诱发大量人群的过敏反应[37]。同时,花粉颗粒与大气污染物之间的协同作用也得到了更深入的解释:臭氧本身的刺激性即可加重花粉过敏的症状[38];NO_2和SO_2的浓度升高会促使花粉颗粒碎裂,释放更多的致敏原[39]。由于过敏原在空气中的留存时间比花粉颗粒更长[40],且可以附着在其他大气颗粒物上,在被吸入人体后,便可能加剧过敏症状[41],从机理角度证实防治花粉症十分依赖于洁净的空气[42]。

1.3 患者自查数据的应用及新冠疫情的影响

出于隐私政策等方面的限制,患者信息的获取常成为预防医学研究的阻碍,而基于患者自查报告的结果逐渐成为学者们突破该桎梏的手段。学者们利用花粉症日记系统[43]、手机应用[44]等平台免费向公众提供花粉监测、预测信息及个性化的定制服务,并允许用户进行自我症状评级和上报,以较为经济的方式实现了在临床外人群中进行症状调查(通常每年可获得2万份以上的症状自评报告),很大程度上解决了可供研究的样本数偏少的问题。基于自查报告的研究成果不仅证实了症状水平同环境中的花粉浓度、是否用药等密切相关[45],而且发现人群整体的暴露反应强度在不同的城市间也有差异[46]。

另一方面,有研究表明在大气稳定和高浓度PM_{10}的条件下,新冠病毒可以存在于室外颗粒物上[47],在新冠疫情大流行的背景下,学者们担心花粉颗粒会携带新冠病毒并加剧传播风险[48]。德国

莱比锡一项持续3个月的实验发现，花粉颗粒并不能作为病毒颗粒的载体[49]。此外，由于疫情带来的封锁，花粉症的防治也受到一定影响，意大利的医护人员总结了相关工作，并制成手册，指出过敏原特异性免疫治疗不会干扰对新冠病毒的免疫反应，故建议未感染新冠病毒的人群继续进行舌下免疫治疗；但在确诊感染新冠病毒或与确诊者有过密切接触后，应中断此项治疗。这为特殊时期的花粉症防治提供了依据[50]。但中国的经验表明，尽快控制疫情才是解决问题的根本[51]。

2　气传花粉关键要素的时间变化研究

2.1　短序列研究

花粉监测数据是防治花粉症的重要基础。对于近期未开展过相关工作的地区，利用1~3年的短期观测，即可快速确定研究区域的花粉季覆盖范围、年花粉量、峰值浓度出现时间等关键信息[52-57]。由于观测设备相对廉价，一些欠发达地区也得以开展相关研究，如在特立尼达和多巴哥建立了首个气传花粉图像汇编资料[58]；在墨西哥城发现花粉极端峰值与厄尔尼诺南方涛动现象的暖期有关，因其可引起低层大气的风速辐合，导致花粉聚集[59]。

在国内，学者们不仅分析了人口稠密地区的花粉特征[60-65]，也确认了黄土高原、新疆天山等野外环境的花粉状况[66-67]，为明确我国的致敏花粉区划特征奠定了基础[68-69]。同时，学者们也指出，未来的研究应提高花粉监测的分辨率和时间尺度[70]。

2.2　长序列研究

短期观测结果常存在稳定性不足的问题。如在同一区域（美国北卡罗来纳州），木本植物花粉浓度升高而草本植物花粉浓度降低[71]，其原因主要源自于草本植物对花粉季前的气象因子变化更为敏感。又如同一类花粉（禾本科[72-73]、桦木科[74]）在不同地区的花粉季长度、年花粉量也可能存在较大差异，其成因则主要来自于城市化建设所带来的环境改变（热岛效应、植被变化等）。

但是，若将时间序列限定在20年以上[75]，便可发现共性结果：北半球多数观测点发现了花粉季明显延长且季节性花粉浓度显著增加。进一步分析可知，花粉季延长是由于花粉季开始时间提前、结束期延后共同造成的，并导致花粉总量增加。该趋势与最高、最低气温的累积变化显著相关，证实了气候变暖、碳排放增多的影响[76]。

3　外界环境的影响研究

3.1　气象因子的影响

整体而言，气候变暖带来了更多的花粉[76]，但气象因子的具体作用却并不一致[77]。从机理角度而言，不一致性主要来自2个方面：一是植物对环境的响应存在差异。如木本植物比草本植物对气温的响应更敏感，故气候变暖导致春季花粉增量更多[78-79]。另一方面，气象因子在植物生长的不同阶段会扮演不同甚至相反的角色。如授粉前一段时间内出现了相对较多的降水，花粉产量便会增多，因为季前降水可以缓解植物可能遇到的干旱胁迫[80-81]。但授粉期内若出现较多的降水，其湿沉降作用便会影响花粉扩散，从而降低空气中的花粉浓度[82]；又如一些木本植物，既需要冬季气温足够低以完成休眠，又需要春季气温相对高作为结束休眠的触发机制[83-84]。这些差异性影响的叠加，使得可以反映气象要素综合状态的指标具有了更好的指示意义[85-86]。

因此，分析气象因子的影响，应避免简单、杂糅的关联性分析，而需要针对不同物种、不同区域开展差异化的综合分析，以找出共性特征[87]。

3.2　观测环境的影响

花粉关键指标也会受到观测环境的影响[88-89]。首先，观测点距离花粉排放源越近（远），花粉浓度便会越高（低）[90-91]。其次，观测点周边的植被覆盖面积同样会决定花粉浓度的多寡[92]。再次，观测点周边的植被种类分布差异也可带来显著影响[93]。最后，观测环境的影响会随着高度而变化：当采样高度低于10 m时，高度越低，花粉浓度越高，因为其中包含了大量周边花粉源的信息；但在10 m以上，高度对花粉浓度的影响则不显著，且花粉源的占比也较为一致[94-95]。除实地观测外，大田实验[96]、

基于城建信息的模拟[97]也得到了类似结论。因此，如期望获得某一区域的背景花粉浓度，需将采集器置于10 m以上高度。

高分卫星的遥感观测也被引入于该领域，并成功解释了植被覆盖状况如何影响花粉浓度[98–99]、较准确地预测了花粉总量[100]。但也有学者指出，植被状况的影响具有不确定性：树木冠层情况对0.5 km范围内的花粉浓度影响显著[101]，但城市的总冠层体积却与花粉浓度无关[102]。前者与普遍认知较为一致，而后者则从机理角度有如下解释：当树木间距非常小时，浓密重叠的树冠会造成花丰度降低，从而影响了花粉产量，导致多个树木的花粉总量反低于单一树木[103]。因此，需开展更多研究以确定各类遥感数据的适用性，评价多因子的综合效应[104–105]。

4 花粉关键要素的预测研究

预测未来的花粉状况，对花粉症的防治具有重要意义，但由于其不包含气象因子等信息，准确率有所欠缺[106]。目前常见的预测方法大致有如下4类。

4.1 基于统计模型的预测

统计模型被广泛应用于花粉关键指标的预测，且在时间序列[107–110]、空间分布[111–113]的预测中具有可以接受的准确率。近年来，研究人员主要从3方面开展工作以提高预测效果。（1）在建模前对数据进行标准化、人工筛选等预处理。这可提升整体准确率，但也会降低离散值的预测效果[111]。（2）利用非线性模型描述变量间的复杂关系。研究表明，无论是纯粹的非线性模型[114–116]或是叠加了线性函数的复合算法[117–118]，其预测结果均优于单一的线性模型。（3）提升自变量所包含的信息，如将前期花粉浓度[119–120]、生长度日[121]、积温[122]等表征植物生长过程的参数引入模型，以增加其的机理意义。也有学者更进一步，将视角锁定在影响植物花粉产量的雄蕊数量[123]、冠层面积[124]等要素，先基于气象因子预测植物的花粉产量，再预测空气中的花粉浓度。但此类方法容易忽略局地风场的影响，因此需进一步考虑湍流等要素以提升适用性[125]。

4.2 基于机器学习的预测

与统计模型类似，机器学习算法同样将自变量与因变量之间的关系视作“黑匣子”，但通常具有更高准确率[126–127]。近年来的研究结果表明，复杂模型的预测精度通常高于简单模型[128]，且最优算法的选取也会随变量的不同而产生差异，故需要进行多次训练[129]。由于多次训练将导致计算时长增加，研究人员便通过调整核函数[130–131]、按比例筛选训练样本[132–133]、评估自变量贡献度[134–135]等方法对模型或样本进行优化。算法、样本经优化后不仅能缩短计算时间，还能提升预测准确率。

在筛选训练样本的过程中，学者们发现除生长度日[130]、花粉累积量[136]、累积生长天数[128]等表征了植物生理状态的指标具有较高权重外，地表反照率、土壤温度、臭氧总量等一些统计模型中难以考虑到的要素也被证明具有较高影响，甚至常规气象资料也可被雷达数据所替代[137–139]。而且，植物在不同生长阶段对外界环境的响应也得到了更好解释，如湿度累积有可能比降水累积的影响更显著，因为前者促进了植物的发育[140]。

但是，机器学习对花粉关键要素的预测仍存在一定不足，目前主要集中于对极值的预测[133–134, 141–142]，其根本原因在于极值样本较少，削弱了模型的训练效果——凸显了高分辨率、长序列花粉监测数据的重要性。

4.3 基于植物生长机理的预测

研究表明，基于气温强迫[143]或累积需冷量[144]的物候模型可对花粉季开始时间进行较好预测：预测结果与实际的偏差通常小于5 d[145–147]。

但是，物候模型的预测仍有部分不足。（1）仅考虑气温强迫的物候模型并不能很好地预测花粉季结束时间[146]。该问题可以通过引入光周期等要素进行修正[148]。（2）为保证统计结果的稳定性，花粉季开始（结束）时间常被认为是出现了全年花粉总量1%（99%）或2.5%（97.5%）的日子，而非授粉期开始（结束）的日子，这导致了花粉季和授粉期不完全一致，使得模型可能出现对花粉季开始时间预测偏晚[149]、浓度峰值期同植物盛花期不匹配等偏差[150–151]。最后，由于物候模型很难考虑花粉远距

离输送,该作用的影响常被低估[152]。

4.4　基于传输模型的预测

在无明显本地源的情况下,花粉的远距离传输是高浓度花粉的主要来源[153],这些外来源的花粉既会增加过敏原的浓度,也会延长过敏原的留存时间,加剧过敏症状[154],颗粒物传输模型是分析该过程的较好方法。

由于花粉颗粒具有粒径较大、不参与化学反应等性质[155],通用模型需改进才可开展相关研究,目前改进工作主要集中于2个方面。一是针对传输过程的调整,将湍流通量[156-157]、对流速度[158]等不常用但对花粉颗粒有较高影响的因子引入模型。也有学者利用集合模式进行预测[159-160],并证明可在一定程度上消除异常值的影响。

另一种改进方案则是对参数化方案进行改进。由于花粉排放源特征差异极大,以至于经典的数据同化方法并不适用于花粉浓度的模拟[161],需要对其进行改进。结果表明,在模型中加入实时花粉信息可取得最优效果[162-163],甚至可使模型的性能翻倍[164]。实时花粉信息的获取除常规的观测获取外,由神经网络算法[165]、卫星遥感[166]等计算出的数据也被证明同样有效。

此外,由于花粉在不同地形间的传输能力存在差异[167],复杂地形下的模拟效果并不好,低分模式可能出现结果失真[168],高分模式也会在高海拔地区出现较大系统误差,而最优解决方案,仍是结合实测结果进行数据修正[169]。

5　花粉监测技术的革新

5.1　已研制完成的自动监测设备

花粉的识别和计数对人员提出了较高技术要求,且会耗费大量时间,导致数据难以实时更新[170],观测成为后续研究的瓶颈。为解决该问题,研究人员尝试研制自动监测设备,并取得长足进展[171-172]。

目前,全球范围内得到同行认可的花粉监测设备共有4种,按投入实际使用的先后顺序分别是日本大和公司的KH-3000型[173]、德国Helmut Hund公司的BAA500型[174]、瑞士Plair公司的PA-300型[175]和瑞士Swisens AG公司的Poleno型(尚未业务化运行)[176],后三者除了可以统计花粉数量外,还可进行种类识别工作。就分类准确率而言,BAA500型(90%)[177]略高于PA-300型(80%)[178]。

依托自动观测设备,学者们开展了一系列研究:德国巴伐利亚州使用多台BAA500型设备建立了全自动花粉监测网,将该区域细化为3大花粉区和8个子区[179];Chappuis等利用PA-300型设备证实了精细化采样(逐时浓度)的重要性[180-181]。此外,自动监测仪器独有的实时数据上传功能也成功对接移动互联网,满足了用户通过手机APP实时查询花粉信息的需求。

5.2　其他花粉自动识别理论

除上述自动监测仪器外,也有学者尝试通过其他方法识别花粉种类。如Klimczak等[182]提出,可以利用花粉提取物的核磁共振波普进行分类和计数,识别准确率在90%左右;Sassen等[183]认为花粉表面上的凸出裂片使之具有特殊的去极化特征,可通过配备去极化光谱的激光雷达进行识别。

Sassen的理论于2013年得以验证:Noh等[184-185]首次通过激光雷达观察到了花粉颗粒的光学特性,并测量到近3000粒·m^{-3}·d^{-1}的高花粉浓度。此后,利用激光雷达识别花粉颗粒的研究陆续展开[186-187],并计算出花粉颗粒的光学厚度[188]。但该方法目前可准确识别的花粉种类仍然较少。

5.3　其他方面的新研究

花粉采样技术在近年来同样有所革新:Miki等[189]评估了不同类型采样器的采样效率,并提出了基于花粉颗粒浓度连续性方程和碰撞理论的采样效率模型;Gharbi等[190]为解决花粉采集胶带常用粘合剂使用四氯化碳带来的高致癌性问题,利用环己烷研制了新型黏合剂;Weger等[191]为降低采样场所限制,开发了一种便携式花粉采样器;Šikoparija等[192-193]通过实验证实,对于逐时花粉浓度监测,14次以上的间歇性采样即可替代连续采样,这可降低悬浮颗粒对采样介质的负面影响。

6 不足与展望

基于花粉监测数据的研究已取得了长足进展，但作为年轻的研究领域，现有工作必然存在不足，主要集中于2个方面。

1）标准化的观测体系仍未建立。主要表现在观测设备自动化程度低、观测标准不统一。自动化的监测设备单价高、普及难，既制约了数据的采集和分析，也降低了信息传播的时效性，成为了限制学科发展的最大因素。此外，即便是传统采样方法，也存在多种采样理念和设备，不同采样方法所得结果虽被证明相关性较为一致[194-195]，但难以构建标准化数据集，影响了分析结果的全面性[196]。

2）存在数据壁垒。该领域的研究已和环境科学、卫星遥感、城建规划等学科深度绑定[197-199]，需要充分的信息共享以开展深入研究，但目前却存在明显的数据壁垒，其原因主要来自3方面：(1) 缺乏低成本、高效率的自动监测设备；(2) 缺乏长期的公益性资助经费，致使研究人员并不乐意无偿分享所得的监测数据[200]；(3) 受政策限制，病例信息等数据无法进行共享。

此外，同发展较好的欧洲相比，中国在该领域的研究还存在以下不足。(1) 研究持续时间短，深度不足。我国目前的研究多集中在5年以下，常出现观测工作随着科研项目结题而终止的现象，由此导致开创性的研究相对较少。(2) 国内缺少聚焦于该领域的高质量期刊。以“airborne pollen”和“气传花粉”为主题词分别在Web of Science和知网进行搜索，并将论文发表时间限定在2016—2020年，分别可检索到639和56篇论文，数量差距明显，且有一定数量的英文论文为国内学者的研究成果。即，国内学者更倾向于将研究成果发表于国际期刊。该现象既和职称、奖励评定看重SCI论文有关，也很大程度上因为国内并无关注于该领域的优秀期刊，缺少可靠的交流平台。

针对上述不足，应从如下4个方面开展进一步工作。

1）建立一体化的标准观测体系。此项工作需要从2个方面同时开展，一是开发低成本的自动观测设备，解决观测密度不足的问题；二是依托现有的采样设备，扩大符合观测标准的花粉种类，做好对接自动观测仪器准备。

2）通过技术革新打破数据壁垒：通过自动化监测网节省的人力成本既可在一定程度上弥补公益性经费的支出，也可为后续研究提供更广泛的支持。而对于较难获取的病例数据，可充分利用智能设备和互联网技术，在保障患者隐私的前提下，收集人群的总体信息[201]。

3）针对国内缺乏长序列观测数据的问题，机制上应鼓励科研机构同业务机构联合开展工作，实现优势互补，解决人员、场地等系列问题；技术上则应积极研制拥有自主知识产权的自动观测设备，降低观测技术门槛，制定不同地区花粉的观测标准，构建一体化观测网。

4）随着一系列“破四唯”政策的落地以及高质量科技期刊分级试点工作的推进，国内学者倾向于在国外杂志发表论文的现象必然会得到一定的缓解，但仍有必要打造高质量的期刊平台[202]以满足国内学者交流的需要。

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Progress of research based on the airborne pollen monitoring data

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Abstract This paper reviews the research based on airborne pollen monitoring data and finds out the followings. 1) a pollen profile can be obtained by using the data and then a pollen calendar with clinical value can be drawn, in which the concentration threshold should be modified based on the characteristics of allergic populations. Besides, it′s confirmed that clean air is essential for preventing hay fever through analyzing the exposure risks in different environments. 2) the local observation environment and the placement position of the sampler have a great influence on the monitoring results, but overall, the pollen season has been prolonged and the pollen concentration has increased in most regions of the north hemisphere, which can be attributed to climate warming. 3) in order to predict the future changes of airborne pollen, four types of models are widely used and the prediction results are generally accurate. For the parts with poor prediction effect (extreme pollen concentration, complex terrain, etc.), the optimal solution is to combine high-resolution pollen monitoring data for correction. 4) however, due to the lack of low-cost automatic monitoring equipment, the current resolution of pollen monitoring data is still low, which brings a series of data and technical barriers. Therefore, this paper believes that the development of low-cost automatic monitoring equipment should be the focus of recent development in this field, and that a standardized observation system should be established accordingly.

Keywords airborne pollen; hay favor; pollen monitoring; pollen predicting ●

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