中国激光

短波紫外线的消杀机制与影响因素

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摘要 在COVID-19大流行期间，人们在不断探索寻求高效、安全、环保的防疫方法，短波紫外线具有消杀效果好、无毒害、无污染等特性，受到了国内外的广泛关注。鉴于此，本文详细介绍了短波紫外线在消杀机制、影响因素与安全性等方面的研究与应用进展。在消杀机制方面，通过对比两个不同波段（200～230 nm与250～280 nm）短波紫外线消杀机制的差异，分析了其对微生物灭活的影响因素及制约因素；在消杀影响因素方面，通过分析紫外线波长、辐照剂量、生物类型以及消杀环境等因素对消杀效率的影响，总结得出了短波紫外线消杀的最佳操作参数；在消杀安全性方面，总结了短期低剂量短波紫外线辐照在医疗方面的应用，概述了长期高剂量222 nm紫外线辐照实验研究的结论，提出了短波紫外线消杀未来的研究方向。

关键词 生物光学；短波紫外线；消杀机制；影响因素；安全性
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1 引 言

根据世界卫生组织公布的数据，目前全球COVID-19确诊病例累计超6.3亿，死亡病例超662万。日常防范病毒的传播与蔓延成为人们生活中不可或缺的一部分。冠状病毒可通过气溶胶传播，为了阻断病毒传播，国内外针对空气的消毒方法进行了研究[1]。

人们发现短波紫外线消杀在疫情防控方面具有独特优势。短波紫外线可以降低通过空气传播的传染性疾病的发病率，有效灭活通过空气传播的活性病原体[2]。因此，了解短波紫外线消杀的机制与影响因素，对于其在疫情防控中的应用具有重要意义。近年来，国内外研究人员利用不同波长的短波紫外线对不同的微生物进行了机制性实验以及消杀效果实验，探索了紫外线消杀的机制以及最佳消杀方案。为使短波紫外线更快地进入市场应用，人们对紫外线消杀的生物安全性进行了研究。根据前人的经验与实验，本文论述了短波紫外线对微生物的消杀机制以及短波紫外线消杀的影响因素，并简单讨论了短波紫外线消杀的生物安全性问题。

2 紫外线

2.1 定义与分类

紫外线（UV）是一种波长位于可见光与X射线之间的电磁波，其波长在100～400 nm之间[3]。根据波长，紫外线可分为长波紫外线（UVA）、中波紫外线（UVB）、短波紫外线（UVC）及真空紫外线（VUV）[4]，如表1所示。

表1 紫外线的分类
Table 1 Classification of ultraviolet rays

Classification	Wavelength /nm
Long-wave UV(UVA)	315–400
Medium-wave UV(UVB)	280–315
Short-wave UV(UVC)	200–280
Vacuum UV(VUV)	100–200

2.2 短波紫外线消杀的优势

COVID-19的大流行导致人们对公共卫生提出了更严格要求。为阻断病毒传播，防止疫情反弹，各地公共场所或人流密集区域都需要进行日常消毒。《新型冠状病毒肺炎防控方案》指出，COVID-19属于β属冠状病毒，乙醚、75% 乙醇、含氯消毒剂等化学试剂均可实现灭活该病毒的效果，且COVID-19对紫外线和热敏感。因此，化学消杀、紫外线消杀和高温消杀是灭活COVID-19的有效方法。目前，化学消杀是人们常用的消杀方法。虽然化学消杀的效果较好，但是存在消耗一定人力资源且消杀人员暴露在危险环境中等问题。COVID-19对热敏感，但高温灭活适用范围较窄，具有一定的限制性。

与上述消杀方法不同，短波紫外线消杀具有更有效、更安全的特点，而且已被广泛应用于医疗、食品、环境卫生等领域[5]。与化学消杀相比，短波紫外线消杀是非化学过程，不会产生化学残留，而且无须运输、储

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存及后续处理，无须人为干预，操作简单。与热消杀相比，短波紫外线消杀具有不受温度影响、适用范围广、杀菌效率高等优势。这些优势是短波紫外线消杀备受青睐的重要原因。

3　短波紫外线消杀的机制

短波紫外线具有很强的消杀效果，遗传物质被损伤和蛋白质被破坏可能是短波紫外线实现消杀的原因。如图 1 所示，根据消杀机制，短波紫外线可分为 200～230 nm、230～250 nm 与 250～280 nm 三个波段，而 230～250 nm 波段紫外线的消杀效果不显著，且研究较少，故而本文未进行探究。生物的重新激活机制在生物灭活中担任着重要角色，因此对它的探究不可或缺。

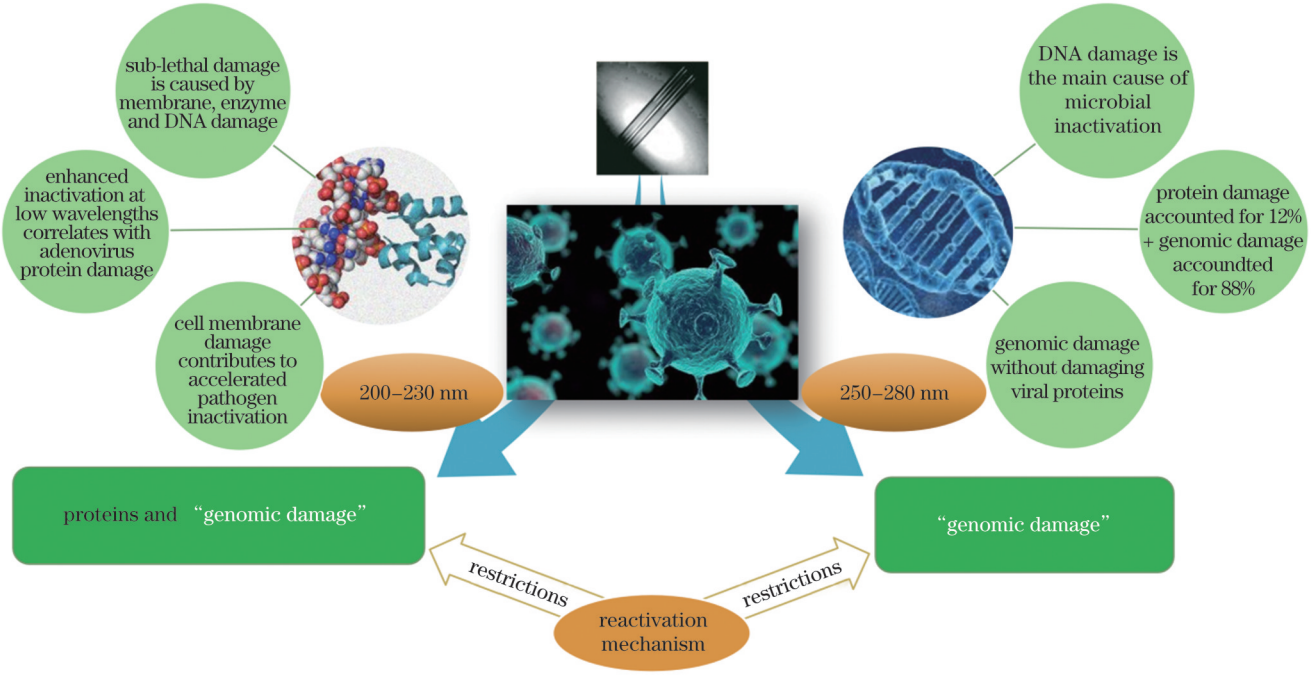

图 1　短波紫外线的消杀机制

Fig. 1　Elimination mechanism of UVC

3.1　200~230 nm UV

200～230 nm 波段的紫外线可以通过图 2 所示的两种不同的方式对生物造成损伤：1）细胞组分，如 DNA、蛋白质等成分，直接吸收紫外线辐射并受到损伤；2）光敏过程产生的氧化产物对细胞组分造成二次损伤。Kang 等[6]利用食源性病原菌进行实验，并探究了 222 nm KrCl 紫外灯与 254 nm 低压汞灯的消杀机制，结果发现：与 254 nm 低压汞灯的消杀效果相比，222 nm KrCl 紫外灯具有更强的杀菌效果；222 nm KrCl 紫外灯对细胞的优异灭活作用不仅仅是因为细胞直接吸收紫外线而影响了 DNA 的完整性，还因为紫外线会对细胞酶或膜脂造成影响，同时，普遍存在的发色团（如氨基酸）可以在该波长下产生活性氧（ROS），即使 DNA 不能很好地直接吸收 222 nm 的紫外线辐射，也会间接地被产生的 ROS 显著破坏。除了生化方式以外，物理方式也可以对生物灭活产生一定影响。赵志斌等[7]发现 228 nm 脉冲激光通过光化和光热两种方式取得了良好的生物灭活效果。

200～230 nm 波段紫外线对微生物的灭活能力相比 250～280 nm 波段紫外线更强。由于微生物基因组受到紫外线损伤后存在重新激活机制，单纯的基因组损伤制约着 250～280 nm 波段紫外线的灭活效果，而 200～230 nm 波段紫外线对蛋白质的损害可能是其灭活效果增强的重要原因。对于腺病毒来说，感染的成功与否与病毒蛋白密不可分，即使其 DNA 受到损害，也能成功感染宿主细胞[8]。Beck 等[9]利用带有带通滤光片和紫外发光二极管的氘灯探究了短波紫外线（大约 10 nm 带宽）辐射对腺病毒蛋白的影响，结果发现：病毒蛋白的损伤发生在 240 nm 以下，在 220 nm 处发射的 38 mJ/cm^2 剂量的紫外线能将六邻体和五邻体蛋白质的量分别减少到原始量的 33% 和 31% 左右；相比之下，400 mJ/cm^2 剂量的 261 nm 和 278 nm 紫外线可将蛋白质的量分别降低到原始量的 66%～89% 和 80%～93%；254 nm 处 400 mJ/cm^2 剂量的紫外线对蛋白质没有明显损伤。因此，200～230 nm 波段紫外线灭活能力更强的原因很有可能与蛋白损伤相关。蛋白质是细胞膜和生物酶的重要组成部分，200～230 nm 波段紫外线对蛋白造成的损害会直接导致细胞膜裂解和酶结构损伤，从而干扰细胞的正常生命活动，使细胞难以存活。Ha 等[10]在奶酪表面食源性病原体的研究中发现 222 nm KrCl 紫外灯与 254 nm 紫外灯相比灭

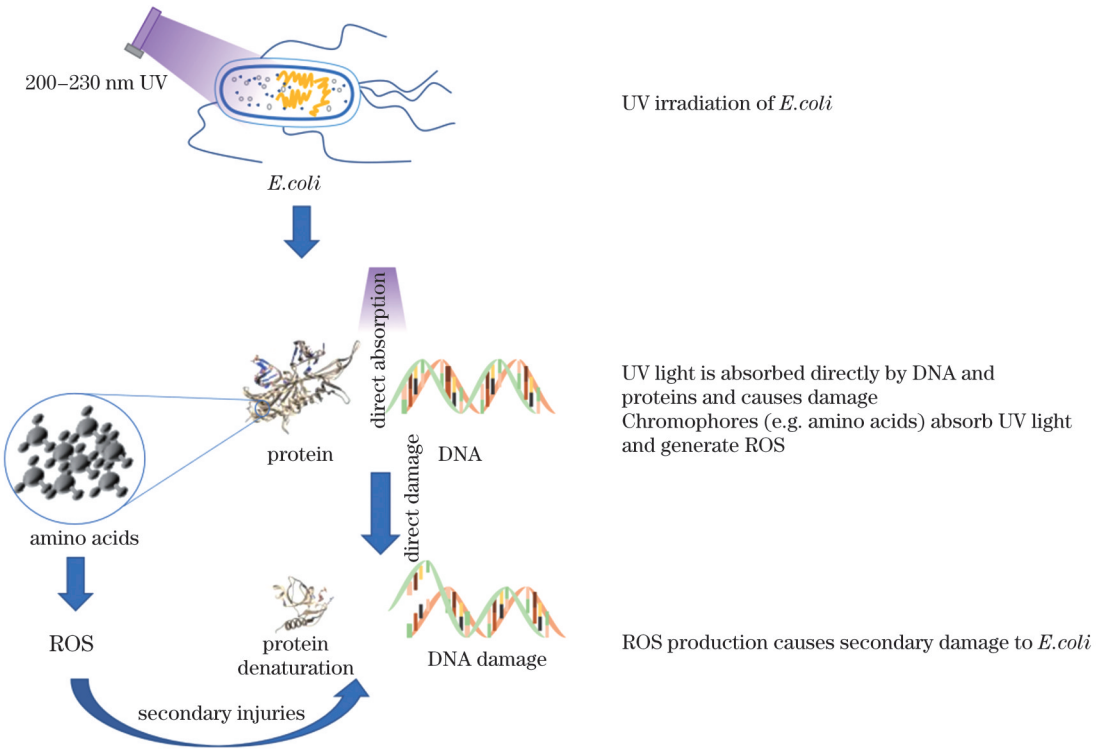

图 2　200～230 nm 紫外线消杀机制

Fig. 2　Killing mechanism of 200 - 230 nm ultraviolet ray

活能力更强，而且数据显示 222 nm KrCl 紫外灯对食源性病原体的灭活可能与细菌细胞膜的破坏、酶活性有关。因此，虽然 222 nm KrCl 紫外灯辐照后的 DNA 吸收系数与 254 nm 紫外灯辐照后的相比有所降低，但外膜损伤和较低的酶活性可能是其消杀效果增强的重要原因。

3.2　250~280 nm UV

短波紫外线造成的 DNA 损伤主要包括两种类型：1）碱基的修饰，将正常碱基变为异常碱基；2）氧化损伤，紫外线辐射诱导的活性氧等物质对病毒 DNA 造成损伤[11-12]。Beck 等[13]选用对紫外线具有抵抗性的腺病毒作为研究对象，利用短波紫外线探究了其灭活原理。结果发现在 240～290 nm 波段紫外线辐照下，DNA 损伤是微生物灭活的主要原因，而且 260 nm 紫外线辐射对核酸的损害大于病毒感染性的降低。由此，Beck 等推测这是由于在感染性测定期间受损 DNA 被重新激活。已有研究表明生物有能力修复紫外线辐射造成的 DNA 损伤[14-15]。因此，认识 250～280 nm 波段紫外线的消杀机制不仅仅要了解其遗传物质的损伤，也要了解其重新激活机制，该机制将在 3.3 节进行详细介绍。

250～280 nm 波段紫外线对微生物灭活的主要作用机制是基因组的损伤。紫外线辐照过程中能够形成有害物质，如环丁烷嘧啶二聚体（CPD）、嘧啶 6-4 嘧啶酮光二聚体（6-4PPs）及杜瓦价异构体[11-12,16]，也会造成致突变性 DNA 损伤。240～320 nm 紫外线的主要光产物是 CPD 和 6-4PPs。杜瓦价异构体是 6-4PPs 暴露于高波长紫外线（UVA 或 UVB）辐射时迅速转化而成的，用短波紫外线对其进行照射，可能会进一步还原为 6-4PPs[6]。TATA 结合蛋白质（TBP）是对 DNA 损伤和修复具有直接影响的转录因子之一。如图 3 所示，通过研究酵母活性 SNR6、GAL10 基因的 TATA 盒发现，两种基因的 TATA 盒经过 TBP 诱导后，在 DNA 弯曲的位点观察到了同样的选择性以及增强的 6-4PPs 形成，而 CPD 在 TATA 盒边缘和外部形成[17]。Rastogi 等[12]的研究显示：紫外线照射后，CPD 成为最丰富且可能最具细胞毒性的病变，占据 DNA 损伤产物的 75%；而 6-4PPs 可能具有更严重的、潜在的致死性、致突变作用，且占据 DNA 损伤产物的 25%。图 3 中（A）[11]所示为 6-4PPs 形成过程，主要形成在 DNA 的 5′-胸腺嘧啶-胞嘧啶-3′、5′-胞嘧啶-胞嘧啶-3′、5′-胸腺嘧啶-胸腺嘧啶-3′处；如图 3 中（B）[11]所示，CPD 是胸腺嘧啶经上述光化学反应形成的，即相邻的两个胸腺嘧啶在吸收紫外光子之后中间形成了化学键，其他碱基之间也会发生光化学反应形成相应的 CPD，如胸腺嘧啶与胞嘧啶、胞嘧啶与胞嘧啶。RNA 细胞相应的光化学反应发生在尿嘧啶之间。与胞嘧啶-胸腺嘧啶和胞嘧啶-胞嘧啶序列相比，胸腺嘧啶-胸腺嘧啶和胸腺嘧啶-胞嘧啶序列的光反应更强，且主要光产物为顺式构型的 CPD 病变，反式构型的 CPD 病变则较少形成[12]。大多数生物的遗传信息都储存在 DNA 中，而 RNA 在遗传信息表达中占据重要地位。

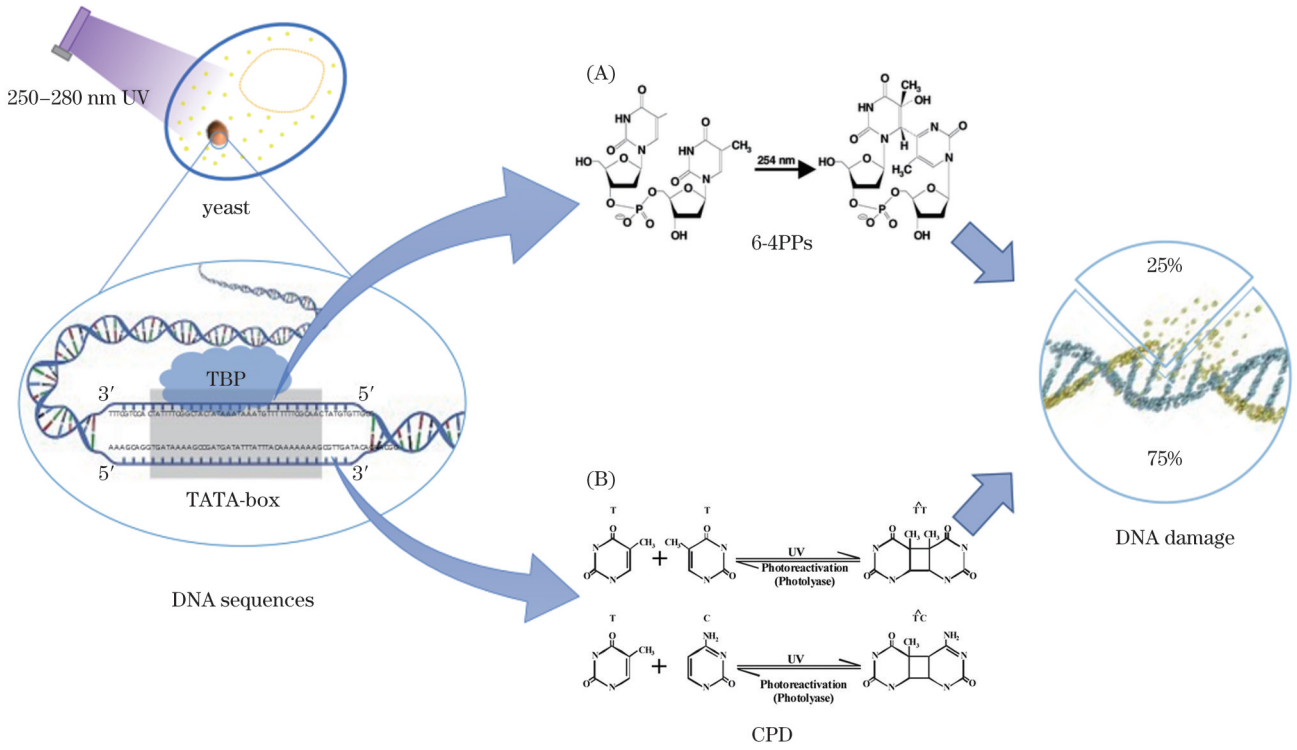

图 3　250～280 nm 紫外线消杀机制图[11]

Fig. 3　Killing mechanism diagram of 250–280 nm ultraviolet rays[11]

据报道，CPD 会抑制 DNA 聚合酶的运行进程。CPD 和 6-4PPs 也会使哺乳动物 RNA 聚合酶Ⅱ停滞[18-19]。如果胞内损伤未修复，单个 CPD 便足以对遗传信息的表达造成严重影响。因此，游离 RNA 聚合酶会因持续性的病变导致总浓度降低，甚至消除它所对应基因的转录。每个 CPD 都可以阻断遗传信息的转录和复制，只有一小部分二聚体会导致突变[20]。因此，如果这些损伤的 DNA 未修复，CPD 和 6-4PPs 的形成便可能会持续干扰 DNA 转录和复制，当 CPD 和 6-4PPs 达到临界值时，DNA 丧失复制或转录能力，并可能导致细胞突变和死亡。

3.3　重新激活机制

研究发现，有些微生物在遗传信息复制与转录过程中具有修复或绕过 DNA 链中损伤的机制，如，有些病毒能够利用宿主的再激活酶实现再激活。从上述两个不同波段紫外线的消杀机制来看，250～280 nm 波段紫外线受此机制的影响相对更大。生物的重新激活机制有很多种，根据 Bolton 等[21]的研究，可将这些机制分为光机制与暗机制。光机制是由光诱导逆转紫外线损伤的光活化。与光活化相比，暗机制的修复途径有所不同，它无法直接逆转 DNA 损伤。暗机制可分为以下两种：1）取代紫外线损伤的核苷酸；2）DNA 分子复制过程中未受损区域组合。

光活化过程是通过一种被称为“光解酶”的光活化酶进行的，在细菌、真菌、病毒中，甚至在多种古细胞中都发现了光解酶的存在，因此，光机制是最简单、最古老的活化机制。据报道，光解酶利用可见光/蓝光（>380 nm）直接活化环丁烷嘧啶二聚体，以此实现受紫外线辐射损伤的基因组的逆转[22-24]。每吸收一个蓝光光子大约可以分裂一个二聚体[25]。短波紫外线的强度会显著影响光活化的效率。Zhang 等[24]探究了短波紫外线对光活化的影响，结果表明：随着短波紫外线的辐射照度由 1.1 μW/cm^2 增大到 68.5 μW/cm^2，光解酶的存活率由 100% 降低到 2.6%。Zhang 等认为：当短波紫外线的辐射照度不大于 25.5 μW/cm^2 时，光活化是有效的；当短波紫外线的辐射照度超过 25.5 μW/cm^2 时，光解酶的结构发生变化，其催化活性受损；强烈的短波紫外线照射会削弱光活化。

根据 DNA 修复机制的原理，暗机制可能包括切除修复、诱变修复或病变旁路、重组修复等修复方式。根据 Sinha 与 Häder[11]的研究，可将切除修复途径分为以下两类：

1）核苷酸切除修复（NER），即取代紫外线损伤的核苷酸。在这种情况下，紫外线光产物（例如 CPD 和 6-4PPs）和邻近核苷酸序列在 DNA 序列中被识别并被切除，之后 DNA 聚合酶填补缺口，链由 DNA 连接酶封闭，重新合成相应序列。

2）碱基切除修复（BER）。DNA 糖基化酶是 BER 过程的关键酶，它通过碱基与核苷酸残基的 2-脱氧核糖之间的 N-糖苷键的裂解来去除不同类型的改性或受损的碱基，一旦碱基被移除，无嘌呤/嘧啶（AP）内切酶或 AP 裂解酶就可以移除 AP 位点，剩余的脱氧核糖磷酸残基由磷酸二酯酶切除，DNA 聚合酶填补缺口，而链则由 DNA 连接酶密封。

诱变修复是细胞在无法修复情况下存活的唯一方法。由紫外线辐射造成的突变可能是由翻译合成过程引起的，在这个过程中，当聚合酶或复制装配遇到非编码或错误编码的病变时，就在病变的对面插入错误的核苷酸，然后继续延伸[26]。例如，在大肠杆菌中，umuC，D基因产物与DNA聚合酶结合，对稳定插入的新碱基放松了要求，从而使其能够进行DNA翻译合成[27]。与诱变修复相反，重组修复通过将先前存在的互补链从DNA同源区域转移到与损伤相反的位点来填充子链间隙。重组修复在父母将遗传信息正确地传递给下一代过程中具有重要作用。

3.4　短波紫外线的消杀机制

当短波紫外线照射微生物时，微生物中的生物组分对紫外线进行不同程度的吸收，但只有蛋白质和包含DNA、RNA的核苷酸会吸收短波范围内的大量紫外线[21]。短波紫外线对微生物消杀机制的研究结果如表2所示。250～280 nm波段紫外线的主要吸收单元为核苷酸，因此，遗传物质的损伤是此波段下微生物灭活的主要原因；200～230 nm波段的紫外线会被蛋白质大量吸收，导致蛋白质的结构发生变化，同时遗传物质也会受到损伤，因此，遗传物质的损伤与蛋白质结构变化的联合作用是此波长下微生物灭活的主要原因。有研究表明，微生物中存在遗传物质受紫外线辐射后发生病变的重新激活机制，可能正是由于这一机制，200～230 nm波段紫外线的消杀效率相比于250～280 nm波段紫外线的消杀效率更高[10]。

表2　短波紫外线的消杀机制

Table 2　Elimination mechanism of UVC

No.	Research subject	UV wavelength / nm	Elimination mechanism	Reference
1	Adenovirus	210–290	DNA damage at 240–290 nm is the main cause of microbial inactivation, and the presence of components other than DNA damage below 240 nm leads to microbial inactivation	[13]
2	Bacillus alicyclic acid	275	DNA damage is the main cause of microbial inactivation	[28]
3	Foodborne pathogens and yeasts	266–279	DNA damage is the main cause of microbial inactivation	[29]
4	MHV-A59 virus	254	Protein damage accounts for 12% and genomic damage accounts for 88%	[30]
5	SARS-CoV-2	253.7	Genomic damage without damaging viral proteins	[31]
6	Gram-positive and Gram-negative pathogenic bacteria	222, 254	Sub-lethal damage from 254 nm low pressure mercury (LP Hg) lamp treatment is mainly due to DNA damage, while sub-lethal damage from 222 nm KrCl UV lamp treatment is due to membrane, enzyme, and DNA damage	[6]
7	*Salmonella* Typhimurium and *Lactobacillus monocytogenes*	280, 222	Cell membrane damage contributes to accelerated pathogen inactivation caused by combination therapy	[32]
8	Foodborne pathogens	UVC and HClO	The mechanism of synergistic effects is related to membrane damage and, to a lesser extent, changes in membrane permeability	[33]
9	Foodborne pathogens on the surface of cheese	222	The synergistic effect of outer membrane damage and lower photo-reactivation rate may cause an enhanced dissipative effect	[10]
10	Adenovirus	200–300	Enhanced inactivation at low wavelengths correlates with adenovirus protein damage at these wavelengths	[16]
11	*E. coli* O157:H7	222, 282, and 254	The higher elimination efficiency of 222 nm than 254 nm and 282 nm UV sources may be due to the damaged cell envelope	[34]

4　短波紫外线消杀的影响因素

紫外线消杀的影响因素包括紫外线波长、辐照剂量、生物类型以及消杀环境等。其中紫外线波长和总紫外线暴露(通常称为紫外线辐照剂量或通量)是紫外线消杀的两个关键参数[35-36]。

4.1　紫外线波长

波长不同的紫外线具有不同的杀菌效果，杀菌作用光谱能清楚地描述这一情况。如图4所示，虽然不同微生物的杀菌作用光谱有所不同[37]，但它们具有一些共同特征，如：在200～240 nm波段，紫外线的灭活效率随波长的增大而降低，而且在200～230 nm波段，核酸与蛋白质会吸收紫外线，在此波段对微生物进行灭活往往更有效；在260～270 nm波段有一个局部峰，在此处，核酸直接吸收紫外线辐射而裂解，导致微生物的灭活达到一个小峰值；在270～300 nm波段，紫外线的灭活效率随波长增大而降低。

4.2　辐照剂量

在相同的紫外线辐射照度下，紫外线消杀效果随着辐照剂量的增加而增强。符纯愿等[38]采用波长为

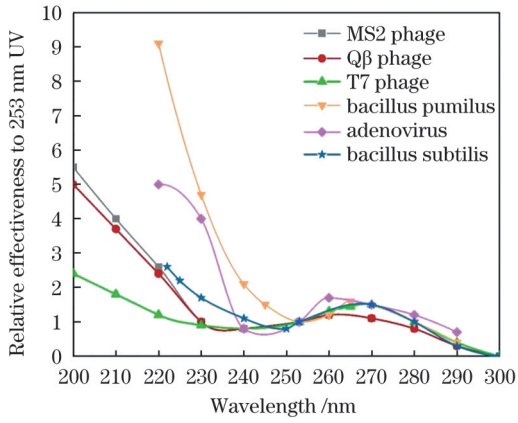

图 4　不同微生物的杀菌作用光谱

Fig. 4　Bactericidal spectra of different microorganisms

275 nm±5 nm、输出功率为 0.085 W 的紫外 LED 灯进行了金黄色葡萄球菌的灭活实验。由于辐照剂量是辐射照度与照射时间的乘积，所以设置了 6 组实验，并设计照射距离为 10 cm，照射时间以 60 s 为一个间隔从 60 s 延长至 360 s，以达到辐照剂量分别为 2238、4476、6714、8952、11190、13428 μJ/cm^2。实验结果表明：随着辐照剂量增大，金黄色葡萄球菌的杀菌效果变好，当辐照剂量达到 11190 μJ/cm^2 以后，杀菌率可以达到 99.90% 的临界值，此辐照剂量可以满足对金黄色葡萄球菌的有效灭活。Murashita 等[39]使用 UVC-LED 对冰块中的大肠杆菌 O157:H7、鼠伤寒沙门菌和单核细胞增生李斯特菌等病原体进行了不同辐射照度下的消杀实验，他们将辐射照度分别设为 0.084、0.025、0.013、0.007、0.005 mW/cm^2。实验结果表明，紫外线辐射照度越大，消杀效果越强。宋孟鑫等[40]通过调节紫外线辐射照度和照射时间控制紫外线辐照剂量，探究了大肠杆菌在不同紫外线辐照剂量下的复活率。在实验中，当将照射时间定为 21 s，采用辐射照度为 1.28、2.72、4.42 mW/cm^2 的紫外线对大肠杆菌进行灭活时，发现辐射照度越强大肠杆菌的复活率越小；当将辐射照度定为 4.42 mW/cm^2，对大肠杆菌进行 7、14、21 s 的紫外线灭活时，发现紫外线照射时间越长，大肠杆菌的复活率越小。Bowker 等[41]利用 275 nm 紫外 LED 灯、254 nm 紫外 LED 灯和 254 nm 低压汞灯探究了三种微生物（大肠杆菌、MS-2 噬菌体和 T7 噬菌体）灭活与紫外线辐照剂量之间的关系，结果如图 5 所示。可见，三种微生物在三种不同紫外灯下都显示出紫外线辐照剂量与微生物灭活程度成正相关关系。Gopisetty 等[42]在进行蔓越莓味水中大肠杆菌 O157:H7 和沙门氏菌的灭活实验中发现，紫外线辐照剂量越大，微生物的灭活效果越好。在探索新型冠状病毒灭活的适用紫外线辐照剂量实验中，很多人通过在固定辐射照度的条件下控制照射时间来实现辐照剂量的递增，并发现灭活效果随着辐照剂量增加而变好，并最终确定适宜的灭活辐照剂量[43-46]。

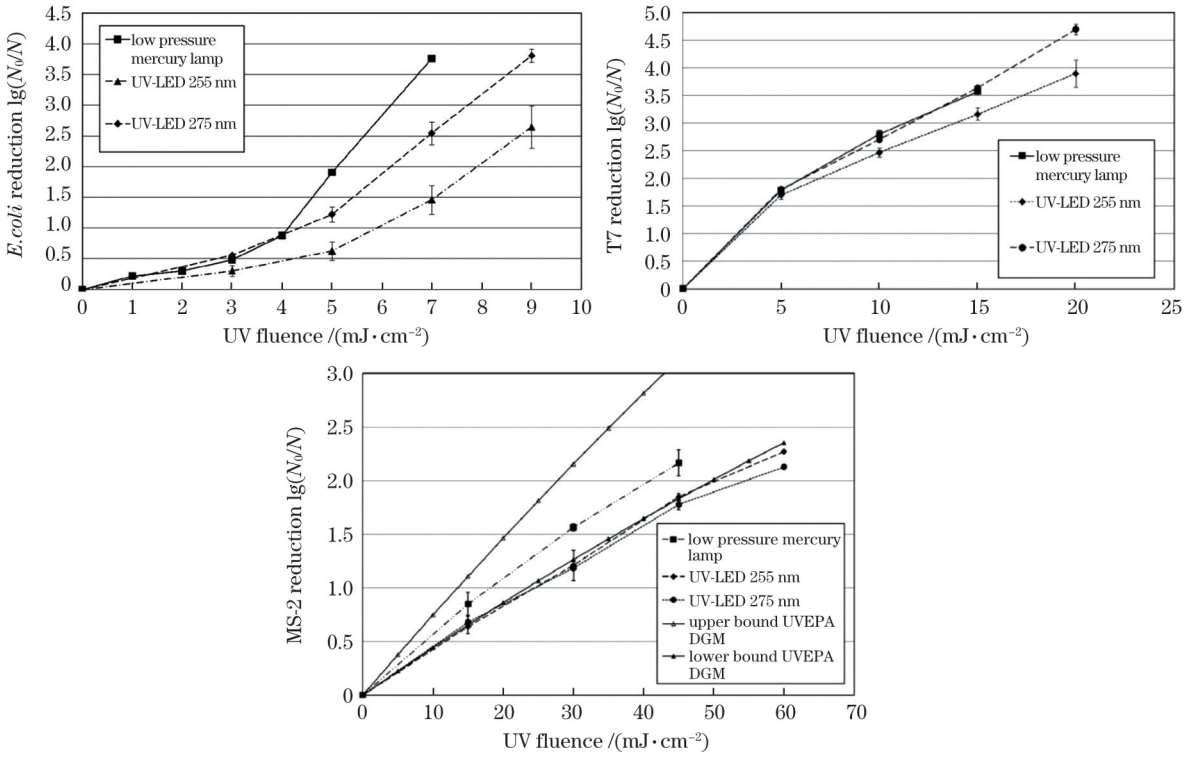

图 5　紫外线辐照剂量与微生物灭活程度的关系图[41]

Fig. 5　Relationship between UV radiation dose and microbial inactivation degree[41]

4.3　生物类型

微生物的类型不同，意味着生物自身的蛋白质与核苷酸不同。有人认为基因组大小（以千碱基或千碱基对计量）是决定病毒对紫外线辐射反映的关键因

素[47-50]。因此，大基因组为光化学反应提供了更多机会，这也是大基因组病毒生物相对较快被灭活的原因之一。病毒、细菌、真菌存在组成结构上的差异，因此在紫外线消杀过程中会表现出不同的敏感性。Kim等[29]利用波长为280 nm的UV-LED列阵研究了病毒、细菌、真菌这三类微生物对紫外线的敏感性，并在拟合存活种群曲线过程中计算得到了每种微生物的灭活速率常数（k），该常数可以直观地展现各微生物的灭活程度。RNA噬菌体MS2、Qβ和DNA噬菌体ΦX174等的灭活速率常数分别为0.28、0.44、2.02 mJ/cm^2；大肠杆菌O157∶H7、鼠伤寒沙门菌、单核细胞增生李斯特菌和金黄色葡萄球菌的灭活速率常数分别为4.70、1.90、2.23、2.64 mJ/cm^2；黄曲霉和粳稻链霉的灭活速率常数分别为0.38、0.40 mJ/cm^2。Kim通过该研究得出下列结论：1）在三种噬菌体中，ΦX174对紫外线的敏感性最高，推断认为DNA病毒比RNA病毒更容易受到短波紫外线损伤；2）紫外线辐照对上述细菌与病毒（除ΦX174）的灭活程度与它们的体积大小有关，细菌的直径能达到2 μm，而病毒的直径仅在20～30 nm之间，不能完全暴露在紫外灯下，因此，除ΦX174外，细菌的灭活是MS2、Qβ的10～20倍；3）真菌相比细菌对短波紫外线具有更高的抗性，虽然真菌的光敏感性与MS2、Qβ相近，但真菌的体积却与细菌的体积相近甚至更大，所以真菌光敏感性较低的原因并不是未充分暴露在紫外线辐射下。

4.4　消杀环境

相比于其他条件，环境因素是紫外消杀过程中最难调控的，但为了保障紫外设备的市场应用，环境因素就不得不考虑。虽然远UVC的波长更容易被目标病原体吸收，但外部环境制约着紫外光子的吸收。新型冠状病毒在空气中的传播途径包括飞沫或气溶胶，而飞沫本身通常含有相对较高浓度的蛋白质，这些介质的存在可能会限制远UVC辐射进入气溶胶，这取决于气溶胶的直径和成分，而气溶胶的直径和成分又会影响光子向目标病原体的传递，从而降低病毒的灭活效果[51]。这些环境因素导致了紫外杀菌剂量测定的困难，因此在设计紫外消毒系统时需要考虑更多因素。

相启森等[52]利用UVC-LEDs对玻璃片、OPP薄膜、不锈钢片和牛皮纸表面的大肠杆菌O157∶H7、单核细胞增生李斯特菌进行了灭活实验，并分别探究了材料的表面粗糙度、表面亲水性对灭活效果的影响，其中玻璃片、OPP薄膜、不锈钢片和牛皮纸的表面粗糙度R_a分别为0.53、1.09、1.19、4.71 μm，它们的表面亲水性差异较大，水接触角分别为41.95°、73.92°、88.74°、112.15°。结果显示：灭活效果随着表面粗糙度的增大而降低，随着接触材料表面亲水性的增大而增强。Adhikari等[53]发现：与哈密瓜、草莓相比，在苹果、梨表面上观察到的单核细胞增生李斯特菌的减少程度更大。单核细胞增生李斯特菌比大肠杆菌O157∶H7具有更强的抗性。与表面粗糙的水果（哈密瓜、草莓和覆盆子）相比，表面光滑的疏水性较低的水果（苹果和梨）表面细菌的灭活率更高。他们认为，短波紫外线可以有效减少水果表面大肠杆菌O157∶H7和单核细胞增生李斯特菌种群，并且表面特性会影响短波紫外线对细菌的灭活功效。

5　短波紫外线消杀安全性

短波紫外线是紫外线消杀的主力军，已在食品医疗、动物保健、空气及水处理等领域被广泛应用。在医疗卫生方面，短波紫外线常用于辅助医疗。如表3所示，所统计的医疗方案主要使用波长为254 nm的短波紫外线，其治疗时间短且低频。在传统医疗的基础上辅以短波紫外线进行治疗，效果更好，且安全性较高。因此，短时间的短波紫外线照射对人体无害。

长时间和近距离暴露于波长较长（如254 nm）的短波紫外线会对人体造成直接影响，如会造成眼睛或皮肤损伤等。但有研究表明200～230 nm波段的紫外线具有“对人体友好”的优点。为尽快厘清短波紫外线长期高剂量照射对人体的影响，人们利用短波紫外线直接照射小鼠探究了紫外光对人体的安全性，实验结果都显示短波紫外线照射对小鼠无危害，如图6所示。Buonanno等[66-67]探究了207 nm与222 nm紫外线照射对小鼠皮肤的影响，为了保证实验的准确性，他们利用紫外线对小鼠进行了长期照射，实验结果显示没有对小鼠皮肤产生危害。其他研究人员[68-69]也证明了222 nm紫外光不会对小鼠的眼睛产生损伤。Narita等[70-71]通过实验发现222 nm紫外线不会对小鼠伤口产生影响，并在之后的实验中发现长期高剂量的222 nm紫外线照射也不会引起小鼠皮肤的DNA损伤或表皮病变。

针对人体的安全性实验是短波紫外消杀能否直接应用于市场的关键环节。关于伤口消毒的医疗应用的实验[72-73]表明，222 nm紫外线对人体是相对安全的。2015年，Woods等[74]利用222 nm紫外线对人体皮肤的耐受性进行了评估，实验结果显示：该紫外线能够诱导人体皮肤中红斑和CPD的形成，会对人体产生一定危害。2020年，Fukui等[75]利用222 nm紫外线照射志愿者的背部皮肤，对222 nm紫外线照射诱导红斑的可能性进行了评估，结果显示：此波段紫外线在500 mJ/cm^{2}以下为安全辐照剂量，对人体皮肤无危害。

以上研究主要是围绕长期或高剂量222 nm紫外线照射的安全性开展的。由小鼠和人体的相关实验结果可以推断出此波段紫外线对人体基本无害，但此波段紫外线是否对人体友好的研究实验还相对匮乏，未来应加强此方向的研究。

表 3　短波紫外线在医疗方面上的应用

Table 3　Short-wave UV for medical applications

No.	Medical symptom	Whether it is better than traditional medical?	Illumination time	Whether it it safe?	Ref.
1	Herpes pharyngitis in children	Yes	Illumination 8–10 s	Yes	[54]
2	Pediatric herpetic stomatitis	Yes	Once a day, 4–6 s each time, for 5 d	Yes	[55]
3	Mouth ulcers after chemotherapy for childhood leukemia	Yes	First irradiation 6 s, 1 time per day	Yes	[56]
4	Pediatric pneumonia	Yes	Increases with age, maximum time 5 s,	Yes	[57]
5	Oral mucositis in hematopoietic stem cell transplant patients	Yes	6 s for the first irradiation, 1 s for each increment, 1 time per day	Yes	[58]
6	Post-burn residual wounds	Yes	Irradiation 20–30 s	Yes	[59]
7	Radioactive oral mucositis	Yes	First treatment 1–10 s, increasing by 1 s day by day	Yes	[60]
8	Acute drug phlebitis	Yes	Irradiation for 10–20 s, 1 time per day	Yes	[61]
9	Oral mucositis after chemotherapy for ovarian cancer	Yes	Illumination 5–10 s		[62]
10	Oral mucositis after hematopoietic stem cell transplantation	Yes	The first irradiation is 6 s, and each time increases by 1 s		[63]
11	Poor incision healing after cesarean section	Yes	Adjustment between 1 and 60 biological doses depending on the actual situation		[64]
12	Herpes zoster	Yes	Initial dose of 8–10 biological doses, followed by incremental increases of 20%–30%		[65]

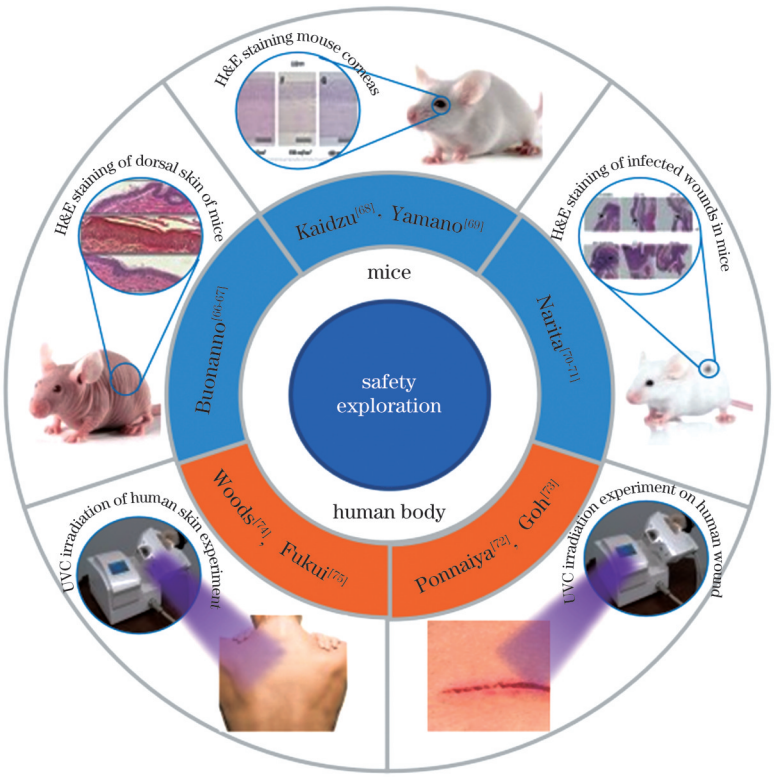

图 6　短波紫外线消杀安全性

Fig. 6　Sterilization safety of UVC

6　结束语

病毒可以通过飞沫或气溶胶传播，也可以通过接触传播，所以，对公共场所、室内环境与物品进行消毒等都是阻断病毒传播的有效方法。与其他消毒方法相比，紫外线消毒具有杀菌快、操作简单、无化学残留等

特点，在未来的消毒领域具有广阔的前景。

根据短波紫外线的消毒机制，200～230 nm 波段紫外线不仅会破坏微生物的遗传信息，还会使细胞内蛋白受损，且受重新激活机制的影响较小。因此，相比于 250～280 nm 波段的紫外线，200～230 nm 波段紫外线具有更强的灭活能力。200～230 nm 波段紫外线具有“对人体友好”的特点，这使得其在疫情防控方面具有更大潜力。虽然 200～230 nm 波段紫外线具有优异的消杀能力，但其会受周围环境介质的影响。例如，空气飞沫或气溶胶中含有一定量的蛋白质，它能吸收紫外线从而导致紫外线的灭活效率降低，不能有效消杀空气飞沫或气溶胶中的病原体。为了使紫外线消杀在阻断病毒传播方面发挥更大作用，应在以下几方面开展重点研究：

1）针对特定微生物，探究特定波长下的消杀机制，找到波长与生物灭活之间的关系，为未来的应用与探究提供理论基础。

2）在不同环境中测试 200～230 nm 与 250～280 nm 波段紫外线设备的消杀效率，探究设备的最佳波长、辐射照度等。同时，在短波紫外线的应用中关于去除杂光的研究以及短波紫外线消杀在公共场所中的应用也是研究热点。

3）开展 200～230 nm 波段紫外线对人体友好方面的研究，以确保光源的安全性。很多研究结果显示 222 nm 紫外线对皮肤、伤口或眼角膜处的细胞不会产生 DNA 损伤，但吸收紫外线后的蛋白质是否会对细胞产生影响还尚不清楚，因此，对此波段紫外线消杀机制的研究也具有重要意义。

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UVC Sterilization Mechanism and Influencing Factors

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Abstract

Significance The novel coronavirus pandemic has caused great concern in global public health. According to data released by the World Health Organization (WHO), the cumulative number of new confirmed coronavirus cases worldwide now exceeds 630 million and the number of deaths exceeds 6.62 million. The daily prevention of the spread of the virus has become an essential step in our lives. The coronaviruses plays an important role in transmission through aerosol transmission, so much research has focused on methods to disinfect the air to interrupt the spread of the virus.

Short-wave ultraviolet (UV) can reduce the incidence of airborne infectious diseases, effectively inactivate airborne active pathogens, and has non-toxic, non-polluting properties, providing an efficient, safe, and environmentally friendly epidemic prevention and control method. According to the New Coronavirus Pneumonia Prevention and Control Program, it is pointed out that the new coronavirus belongs to the beta genus coronavirus, and chemical reagents, such as ether, 75% ethanol, and chlorine-containing disinfectants can make the virus inactivate, and the new coronavirus is sensitive to ultraviolet light and heat, thus, chemical disinfection, ultraviolet disinfection, and high-temperature disinfection are effective methods for inactivating the virus. Currently, chemical disinfection is a common disinfection method, although it is effective, there are problems, such as consuming certain human resources and directly exposing disinfection personnel to danger; although the new coronavirus is sensitive to heat, high temperature inactivation has a narrow scope of application and is somewhat restrictive.

Unlike the above disinfection methods, short-wave UV disinfection is more effective and safer. With the advantages and characteristics of short-wave UV disinfection, it is widely used in medical, food, environmental health, and other areas. Compared with chemical disinfection, short-wave UV disinfection is a non-chemical process that does not produce chemical residues and does not require transportation, storage and subsequent treatment, and is simple to operate without human intervention; compared with thermal disinfection, short-wave UV disinfection has the advantages of being unaffected by temperature, wide range of application, and high sterilization efficiency. Therefore, short-wave UV disinfection has shown its unique advantages in epidemic prevention and control and has attracted much attention.

Recently, researchers at home and abroad have used different wavelengths of short-wave ultraviolet light to conduct experiments on the mechanics of different microorganisms as well as the effect of disinfection, exploring the mechanism of UV disinfection and the best disinfection plan. Some researchers have also conducted biosafety studies to bring short-wave UV into the market faster. Much progress has been made, but there is still a series of challenges in the mechanistic research and market feasibility. Therefore, it is important to understand the mechanism of short-wave UV killing, its influencing factors and biosafety research, for its research and application in epidemic prevention and control.

Progress　The research progress of short-wave UV in terms of the extinction mechanism, influencing factors and safety is summarized. Firstly, the extinction mechanism of short-wave UV was introduced, and the inactivation factors of microorganisms in two different wavelengths (200–230 nm and 250–280 nm) of short-wave UV were analyzed by comparing the differences in their extinction mechanisms (Table 2). According to previous research reports, the constraint mechanism of the short-wave UV extermination process is summarized, and this mechanism can be divided into light mechanism and dark mechanism. Secondly, the influencing factors of short-wave UV extermination were introduced, and the optimal operating parameters for extermination were summarized by analyzing the effects of UV wavelength, radiation dose, exterminating organisms, and extermination environment on the extermination efficiency. Thirdly, based on previous studies, it was found that the UV wavelengths of 254 nm and 222 nm were more meaningful for research, and the application of short-term low-dose radiation in health care using 254 nm UV was summarized (Table 3). This is followed by a summary of the findings of experimental studies related to long-term high-dose radiation using 222 nm UV, and an outlook on future research and development of short-wave UV (Fig. 5). Finally, the issues facing the field and the ongoing research trends are discussed, including the extinction mechanisms of different wavelengths of short-wave UV, the application studies of short-wave UV, and the investigation of the biosafety of short-wave UV.

Conclusions and Prospects　With the new coronavirus pandemic, epidemic prevention has been gradually integrated into our lives. Compared with other disinfection methods, short-wave UV disinfection has the characteristics of fast sterilization, simple operation, and no chemical residue. Therefore, short-wave UV disinfection has a broad prospect in the future of the disinfection field. The disinfection mechanism of short-wave UV differs depending on the wavelength. The destruction of genetic material by UV in the 250–280 nm band is the main reason for the disinfection of microorganisms, while the damage to proteins by UV in the 200–230 nm band is the reason for its enhanced disinfection effect. The advantage of "human friendly" makes it a broader research value. The efficiency of disinfection in different environments is also determined by factors, such as UV wavelength and radiation illumination, so research on the application of short-wave UV should not be slackened, while research on the removal of stray light in the application of short-wave UV and application in public places are also current hot spots. In summary, the investigation of the mechanism, biosafety and application of short-wave UV is of great significance to its research and promotion, and still needs to be explored in depth and detail to promote the development of short-wave UV in academic and engineering aspects.

Key words　bio-optics; short-wave ultraviolet rays; extermination mechanisms; influence factors; safety