Virtual Autopsy in Entomology: A Digital Perspective on Insect-Based Forensic Investigation

Aditya Verma[1*], Tanu Rajput[1], Devesh Tiwari [2]

[1]Department of Forensic Science MATS University, Raipur (C.G.), India

[2]Department of Forensic Science Uttaranchal University, Dehradun (U.K.), India

Corresponding Author: aadityaverma9691@gmail.com*

Abstract:

Virtopsy has evolved as a contemporary, non-intrusive imaging technique that enhances the established method of autopsy. In the past few years, its scope has broadened in the forensic entomological field. Through cross-sectional imaging methods consisting of MRI, micro-CT scans, CT scans, and digital imagery measurements, investigating officials can examine the insect processes without physical disruption. These techniques make it possible to clearly visualize features such as maggot masses, larval tunnels, pupal cases, tissue destruction, and other insect-related changes that develop during decomposition. By optimizing these particulars, virtopsy supports in tracing how and when insects populate at distinctive parts of the body, which is essential for estimation of the time since death. An additional advantage is that virtopsy creates permanent digital records that can be reviewed later by experts, used for teaching, or presented in court to support transparency and accuracy. While it cannot entirely replace a hands-on entomological examination, it greatly improves documentation, reduces the risk of contaminating evidence, and allows early detection of insect activity—especially useful when a traditional autopsy cannot be performed right away. This review outlines the recent advances, challenges, and future potential of combining virtual autopsy with forensic entomology, showing how this approach can strengthen PMI estimation and enhance overall forensic reliability.

Keywords: Virtopsy, Entomology, MRI, Micro-CT scan, insects.

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Abbreviations:

3D – Three-Dimensional
SEM – Scanning Electron Microscopy
VOCs – Volatile Organic Compounds
PMI – Postmortem Interval VA – Virtual Autopsy
PMCT – Postmortem Computed Tomography PMMRI – Postmortem Magnetic Resonance Imaging
CT – Computed Tomography
MRI – Magnetic Resonance Imaging
LMM – Larval Mass Mapping AI – Artificial Intelligence
ML – Machine Learning
CAD – Computer-Aided Design VR – Virtual Reality
AR – Augmented Reality
PBS – Postmortem Biological Substrates
PMD – Postmortem Decomposition HPMI – Hybrid PMI Estimation CSI – Crime Scene Investigation DVI – Disaster Victim Identification

1. Introduction

In recent years, forensic science has undergone a significant transformation due to the rapid development of digital imaging and non-invasive diagnostic tools. Among these advancements, **virtual autopsy (virtopsy)** has emerged as one of the most influential technologies, offering a non- destructive and highly precise method for documenting and analyzing human remains (Thali et al., 2019; Jackowski & Ruder, 2020). Unlike conventional autopsy, which relies on physical dissection, virtopsy employs imaging modalities such as postmortem CT, MRI, micro-CT, and 3D surface scanning to produce high-resolution digital reconstructions of the body. These technologies allow forensic experts to assess internal and external findings without altering the physical condition of the remains (Cattaneo et al., 2021).

The integration of virtual autopsy with **forensic entomology** represents a novel interdisciplinary approach that has gained considerable attention in international research. Forensic entomology focuses on studying insect activity on decomposing human or animal remains, primarily to estimate the time since death, or PMI (Amendt et al., 2011). Traditionally, entomological analyses require physical collection of insects, removal of larval masses, and external examination of colonization sites. However, these procedures can disturb or alter evidence, especially delicate early-stage larvae or hidden infestations (Matuszewski, 2021).
Virtual autopsy offers a solution to these challenges by enabling investigators to **visualize, document, and analyze insect activity inside and outside the body without disturbing the remains** (Dekeirsschieter et al., 2022). Imaging techniques such as micro-CT can detect larval penetration pathways, feeding tunnels, subcutaneous infestations, and internal decomposition changes associated with insect activity long before they become visible externally (Ferreira et al., 2022; Blau et al., 2021). These digital datasets allow forensic entomologists to track the progression of colonization and evaluate insect distribution with greater accuracy than manual inspection alone.

Furthermore, virtopsy allows the preservation of entomological evidence in a **tamper-proof digital archive**, which is especially important in judicial contexts where the integrity and reproducibility of evidence are critical (Urbanová et al., 2018). Digital records of larval clusters, oviposition patterns, decomposition gases, and soft-tissue collapse can be reviewed repeatedly, integrated with 3D reconstructions, and presented in court without relying solely on physical samples (Peñaranda et al., 2023).

As global research in the fields of forensic imaging, decomposition studies, and insect ecology continues to grow, the synergy between virtopsy and entomology offers new possibilities for more accurate PMI estimation and improved crime scene reconstruction. Recent publications highlight how non-invasive imaging has become indispensable in cases involving advanced decomposition, inaccessible body cavities, or sensitive cultural contexts where invasive autopsy is restricted (Ross & Cattaneo, 2019; Anderson et al., 2022). This growing body of evidence indicates that digital methods do not replace traditional entomology but rather enhance it by providing deeper, earlier, and more objective insights into insect-related postmortem changes.

This review aims to explore the expanding integration of virtual autopsy within forensic entomology. It discusses the theoretical background, methodological approaches, imaging tools, and current applications while also addressing recent technological advancements, challenges, and future developments. By synthesizing findings from global studies, the review provides a comprehensive, updated perspective suitable for forensic biology researchers, postgraduate students, and practitioners seeking a deeper understanding of the digital transformation of entomology-based investigations (Chen et al., 2020; Gupta & Verma, 2023).

2. Virtual Autopsy Overview:

Virtual autopsy, or *virtopsy*, refers to a set of non- invasive imaging techniques used to examine human remains without the need for traditional dissection. The concept was first formalized in the early 2000s, but its scientific foundation emerged as soon as advanced imaging technologies became accessible for medical and forensic applications (Thali et al., 2003; Thali et al., 2019). Virtopsy integrates **postmortem computed tomography (PMCT), postmortem magnetic resonance imaging (PMMRI), micro-CT, 3D surface scanning, and image post-processing software** to reconstruct bodies in high detail. These digital models can be manipulated, magnified, and re-examined repeatedly, providing an advantage over conventional autopsy, where findings may be lost or altered once a dissection is performed (Jackowski & Ruder, 2020; Ross & Cattaneo, 2019).

Among the most widely used modalities, **PMCT** has gained dominance because of its ability to visualize skeletal trauma, internal gas patterns, insect-related tissue changes, and decomposition processes (Schweitzer et al., 2021). PMMRI, although less commonly used, is highly suitable for detecting soft-tissue changes, edema, organ liquefaction, and patterns of fluid accumulation that correlate with early decomposition and insect activity (Cattaneo et al., 2021). **3D surface scanning**, often performed using structured light or laser scanners, captures external anatomical details, including skin defects, bite marks, and insect colonization points on the body surface (Urbanová et al., 2018).

The primary purpose of virtual autopsy is to complement—rather than replace— traditional autopsy. It is particularly useful in cases involving **advanced decomposition**, **sensitive cultural or religious contexts**, **disaster victim identification**, or **legal situations requiring non-destructive examination** (Anderson et al., 2022). As forensic science moves toward a more digitized workflow, virtopsy has proven essential for creating permanent, tamper-proof archives that can be reviewed by investigators, pathologists, and courts at any time (Peñaranda et al., 2023).

Virtual autopsy has also shown significant value in detecting subtle postmortem indicators such as **gas production, abdominal distension, soft-tissue collapse, and air distribution**, all of which provide clues to decomposition stage and biological activity (Ferreira et al., 2022).
Because many of these postmortem changes are influenced by the presence and activity of insects—especially blowflies, flesh flies, and beetles—virtopsy naturally intersects with forensic entomology (Matuszewski, 2021; Blau et al., 2021).

2.1 Role of Forensic Entomology:

Forensic entomology is centered on the study of insects and arthropods associated with decomposing remains. The primary application is **PMI estimation**, although entomological evidence can also assist in determining movement of the body, manner of death, presence of drugs or toxins, and circumstances surrounding burial or concealment (Amendt et al., 2011; Matuszewski, 2021). Insects colonize remains in a predictable sequence known as **insect succession**, which depends on temperature, humidity, body accessibility, and geographical factors (Anderson et al., 2022).

Traditionally, entomologists rely on field observations, manual collection of specimens, morphometric analysis, and DNA-based identification (Charabidze & Gosselin, 2020). While these methods are indispensable, they have limitations. Physical removal of specimens may disturb delicate early-stage eggs or internal larval channels. Furthermore, entomologists often struggle with detecting **internal infestations**—for example, larvae that migrate under the skin, into natural orifices, or deep into decomposing tissues (Ferreira et al., 2022).

This is where virtual autopsy becomes particularly valuable. It allows investigators to visualize insect activity **without altering the body**, producing a permanent record of colonization pathways, larval masses, and tissue changes associated with entomological activity (Dekeirsschieter et al., 2022). For instance:

- **Early egg clusters on the skin** can be recorded with high-resolution 3D imaging.
- **Subcutaneous larval migration** becomes visible through PMCT.
- **Deep tissue destruction** caused by feeding larvae can be mapped with micro-CT.
- **Gas pockets produced by decomposition and microbial-insect interactions** can be quantified (Schweitzer et al., 2021).

Additionally, forensic entomology benefits from VA by improving evidence preservation. Digital datasets allow experts to revisit the state of colonization even years later, aiding research and legal reviews (Urbanová et al., 2018). Studies have shown that integrating entomology with virtopsy helps minimize human error and provides richer data for PMI models (Peñaranda et al., 2023; Gupta & Verma, 2023). This demonstrates that entomology is not merely an add-on to virtual autopsy but an essential complementary discipline that strengthens forensic interpretations in decomposed bodies.

2.2 Background:

The integration of virtual autopsy and forensic entomology is rooted in the shared goal of **accurate postmortem reconstruction**. Historically, autopsy and entomology operated separately—autopsy focused on anatomical injury, while entomology dealt with insect evidence recovered from the remains. However, with technological advancements, researchers began recognizing that decomposition processes, insect succession, and internal body changes occur simultaneously and influence each other (Amendt et al., 2011; Matuszewski, 2021).

Early studies in the 2000s explored how CT scans could visualize gas formation patterns during decomposition, which were indirectly related to insect activity (Thali et al., 2003). Soon after, PMCT was used to document larval masses in body cavities, demonstrating that imaging could detect insect presence even before external signs became apparent (Dekeirsschieter et al., 2022). As micro-CT matured, researchers began using it to examine **individual larvae, puparia, and feeding pathways** paving the way for entomological studies that required fine-scale anatomical resolution (Blau et al., 2021).

The development of **3D scanning and photogrammetry** provided additional support by enhancing surface visualization of colonization sites, maggot masses, and oviposition patterns (Urbanová et al., 2018). This improved the ability to differentiate between **trauma-induced wounds and insect-produced artifacts**, a task that often challenges forensic pathologists (Cattaneo et al., 2021).

Recent literature highlights several key reasons why VA and entomology are increasingly combined:

1. **Non-invasiveness** – VA documents insect- related changes without physically disturbing larvae or eggs.
2. **Enhanced visualization** – Internal insect activity becomes visible through PMCT and micro-CT (Ferreira et al., 2022).
3. **Accuracy in PMI estimation** – Imaging- based decomposition markers complement insect developmental data (Peñaranda et al., 2023).
4. **Improved evidence preservation** – Digital datasets reduce the risk of sample degradation or mishandling (Ross & Cattaneo, 2019).
5. **Legal acceptance** – Courts increasingly prefer objective, reproducible digital evidence (Anderson et al., 2022).

The background of this interdisciplinary approach demonstrates that combining virtopsy with entomology is not merely a modern trend but a natural progression resulting from decades of technological growth and the demand for more precise mortuary science.

3. Methods and Tools Used in Virtopsy for Entomology:

The effectiveness of virtual autopsy in forensic entomology relies heavily on the use of **advanced imaging modalities and complementary digital techniques**. These methods allow investigators to visualize and document insect activity in decomposing bodies in a non-invasive and highly accurate manner. Each technique offers unique advantages, and often, a combination of modalities provides the most comprehensive assessment.

3.1 Postmortem Computed Tomography (PMCT):

PMCT is the most widely used imaging modality in virtual autopsy. It uses X-ray beams to produce cross-sectional images of the body, which can then be reconstructed into three-dimensional models (Jackowski & Ruder, 2020). For forensic entomology, PMCT has several key applications:

1. **Detection of Internal Larval Masses:** PMCT can identify subcutaneous or deep-tissue larval infestations that may not be visible externally. Studies by Dekeirsschieter et al. (2022) showed that PMCT detected maggot tunneling in abdominal muscles and soft tissue, which helped establish PMI more accurately than surface observation alone.

2. **Gas Distribution and Tissue Decomposition:** PMCT visualizes postmortem gas formation, a process accelerated by microbial activity and maggot feeding (Ferreira et al., 2022). Gas pockets correlate with areas of intense larval activity, allowing mapping of feeding sites.

3. **Non-invasive Documentation:** PMCT preserves the integrity of insect colonies and fragile tissues, enabling repeated review and legal admissibility (Urbanová et al., 2018). This is especially crucial when dealing with early colonization or small larvae that could be destroyed during dissection.

4. **Integration with 3D Software:** Cross- sectional PMCT images can be processed into 3D reconstructions, showing the spatial distribution of larvae and colonization pathways within body

cavities (Peñaranda et al., 2023).

Recent studies emphasize PMCT's reliability in **advanced decomposition** and **concealed environments**, such as buried or partially submerged bodies, where insect access is irregular (Schweitzer et al., 2021). By combining PMCT with environmental data, researchers can model insect development and refine PMI estimates more precisely.

3.2 Postmortem Magnetic Resonance Imaging (PMMRI):

PMMRI provides detailed soft tissue imaging using magnetic fields and radio waves, without ionizing radiation. Although less frequently applied than PMCT, PMMRI offers unique advantages for forensic entomology:

1. **Soft Tissue Visualization:** PMMRI identifies fluid accumulation, edema, and organ liquefaction caused by decomposition and insect feeding (Cattaneo et al., 2021). It allows observation of early tissue changes before external signs become apparent.
2. **Subtle Colonization Detection:** Larval migration under the skin, in joints, or in confined cavities can be observed in PMMRI scans (Blau et al., 2021). MRI is particularly effective in detecting small larvae in moist or enclosed tissue areas.
3. **Combination with Diffusion Techniques:** Advanced PMMRI sequences such as diffusion-weighted imaging (DWI) can reveal tissue microstructural changes caused by enzymatic and mechanical larval activity (Chen et al., 2020). This helps differentiate insect-induced damage from other postmortem trauma.
4. **Research Applications:** PMMRI supports developmental studies of larvae in situ, contributing to entomological modeling for PMI calculations (Anderson et al., 2022).

PMMRI's main limitation is cost and availability, but its contribution to **non- invasive soft tissue analysis** makes it an essential tool when combined with PMCT in entomological investigations.

3.3 Micro-Computed Tomography(Micro- CT):

Micro-CT is an **ultra-high resolution imaging modality** capable of visualizing minute structures in the submillimeter range. Its applications in forensic entomology include:

1. **Larval Morphology:** Micro-CT allows visualization of larval and pupal anatomy without dissection (Blau et al., 2021). Detailed imaging can reveal mouth hooks, spiracles, and digestive tracts, which aids in species identification.
2. **Feeding Pathways:** Micro-CT detects the tunnels created by larvae inside muscles, fat, or organ tissue (Dekeirsschieter et al., 2022). These tunnels are often invisible externally and are key indicators of feeding duration and PMI.
3. **Preservation of Specimens:** Unlike traditional dissection, micro-CT preserves larval morphology for further morphological or DNA-based studies (Ferreira et al., 2022). This is particularly valuable for legal cases, where evidence integrity is paramount.

4. **Quantitative Analysis:** Micro-CT enables precise measurement of larval tunnel dimensions, volume of tissue affected, and larval density, which can be correlated with development rates to refine PMI estimations (Matuszewski, 2021).

Micro-CT is increasingly recognized as a bridge between imaging and classical entomology, providing both **structural and developmental insights** while minimizing invasive sampling.

3.4 3D Surface Scanning:

3D surface scanning captures the **external morphology of the body and insect colonization** in fine detail. Techniques include structured light scanning, laser scanning, and photogrammetry. Applications include:

1. **Mapping Oviposition Sites:** Early egg clusters and larval masses can be recorded without disturbance (Urbanová et al., 2018). This is critical for early- stage PMI estimation.

2. **Visualizing Trauma vs. Insect Damage:** By creating a detailed surface model, entomologists can differentiate between insect feeding marks and traumatic injuries (Cattaneo et al., 2021).

3. **Digital Archiving:** 3D scans produce permanent, reproducible records that can be revisited for research, comparison, or legal purposes (Peñaranda et al., 2023).

4. **Integration with Internal Imaging:** 3D surface models can be combined with PMCT or micro-CT scans to create comprehensive visualizations of both external and internal insect activity (Ross & Cattaneo, 2019).

3.5 Photogrammetry:

Photogrammetry uses overlapping photographs to construct **accurate 3D models**. Although less common than laser scanning, it is useful for:

1. **Field Documentation:** Scenes with insects colonizing the body can be digitally preserved (Anderson et al., 2022).
2. **Non-specialist Accessibility:** Photogrammetry is portable and cost-effective, making it suitable for on-site documentation in outdoor investigations (Gupta & Verma, 2023).

3.6 Multispectral and Hyperspectral Imaging:

These techniques detect **light reflected at multiple wavelengths** to identify tissue changes and insect activity:

1. **Detecting Larval Excretions and Feeding Marks:** Certain wavelengths highlight chemical changes in tissue caused by larval feeding (Cruz et al., 2020).
2. **Estimating Decomposition Stage:** Spectral signatures correlate with microbial and insect-mediated decomposition (Ferreira et al., 2022).

Multispectral imaging is still emerging but shows promise in enhancing detection of early colonization, especially in bodies with limited visible damage.

3.7 Thermal Imaging:

Thermal cameras detect **temperature variations** caused by insect activity, particularly larval aggregations, which generate metabolic heat:

1. **Maggot Mass Identification:** Larvae often produce localized heat; thermal imaging can detect these areas non-invasively (Matuszewski, 2021).
2. **Monitoring Activity:** By mapping temperature over time, investigators can correlate larval metabolic rates with PMI estimates.

Thermal imaging is particularly effective in outdoor scenarios or when maggot masses are hidden under clothing or soil.

4.Integration of Multiple Methods:

While each modality offers unique insights, the combination of PMCT, PMMRI, micro-CT, 3D scanning, and thermal or spectral imaging produces a **comprehensive entomological analysis**. Integrating these methods allows investigators to:

- Map larval colonization in three dimensions
- Estimate PMI using larval development and decomposition markers
- Differentiate insect activity from trauma
- Preserve both internal and external evidence digitally
- Enable repeated analysis for legal, research, and educational purposes (Peñaranda et al., 2023; Blau et al., 2021; Dekeirsschieter et al., 2022).

5. Integration of Imaging and Entomological Evidence:

The integration of virtual autopsy imaging with forensic entomology represents a major advancement in postmortem investigation. Traditionally, entomological evidence and autopsy findings were considered in isolation: forensic pathologists focused on trauma, internal organ changes, or decomposition, while entomologists analyzed larvae, pupae, and insect succession patterns. However, this separation often limited the accuracy of PMI estimation and the overall interpretation of postmortem events (Amendt et al., 2011; Matuszewski, 2021).

By combining imaging data with entomological analysis, investigators can achieve a **holistic understanding of decomposition**. For example:

1. **Spatial Correlation of Insects and Tissue Changes:** PMCT and micro-CT allow visualization of larval distribution within the body alongside soft-tissue decomposition patterns. This helps identify which organs or tissues were targeted first and how insect activity influenced decomposition (Dekeirsschieter et al., 2022; Ferreira et al., 2022).

2. **Temporal Correlation:** Digital imaging enables repeated, time-stamped observations of larval growth and colonization over postmortem intervals, which can be linked to temperature, humidity, and environmental factors. This strengthens PMI estimation by combining insect development rates with decomposition staging (Peñaranda et al., 2023).

3. **Non-invasive Preservation of Evidence:** Imaging ensures that fragile insect evidence, such as early-stage eggs or delicate larval tunnels, is preserved in situ. Unlike manual collection, which may destroy evidence, virtopsy allows repeated review and comparison for research or court purposes

(Urbanová et al., 2018; Ross & Cattaneo, 2019).

4. **Distinguishing Insect-induced Changes from Trauma:** Combining 3D surface scans with internal imaging helps forensic experts differentiate between insect feeding marks and pre-mortem trauma. This is particularly important in forensic investigations of suspected abuse, homicide, or accidental deaths (Cattaneo et al., 2021).

5. **Integration with Software and AI Tools:** Modern virtopsy workflows often incorporate **AI algorithms and 3D reconstruction software** to automatically detect larval clusters, measure tissue degradation, and model colonization pathways. This improves efficiency, accuracy, and reproducibility, especially in large- scale or disaster victim identification scenarios (Chen et al., 2020; Anderson et al., 2022).

This integrated approach effectively bridges the gap between **digital forensic documentation** and **biological insect evidence**, creating a synergistic methodology that enhances both research and practical casework. By considering entomological evidence alongside high- resolution imaging, investigators can make more informed and defensible conclusions in forensic cases.

6. Applications of Virtual Autopsy in Forensic Entomology:

Virtual autopsy, when applied to forensic entomology, enhances the **accuracy, speed, and reliability** of several key forensic applications. These include postmortem interval estimation, insect mapping, colonization analysis, and wound interpretation.

6.1 Postmortem Interval (PMI) Estimation:

Estimating PMI is one of the primary objectives in forensic entomology. Insects colonize remains in predictable patterns, with blowflies and flesh flies typically arriving first (Amendt et al., 2011; Matuszewski, 2021). Traditional PMI estimation relies on larval development rates, temperature, and environmental conditions. However, imaging-based virtopsy introduces **direct observation of larval activity inside tissues**, which allows:

- Detection of **internal larval tunnels** not visible externally (Blau et al., 2021).
- Correlation of **larval mass size and location** with decomposition markers (Ferreira et al., 2022).
- Integration of **micro-CT and PMCT data** to calculate larval age and body decomposition stage simultaneously (Dekeirsschieter et al., 2022).

Studies show that combining virtopsy with entomological data reduces the **error margin in PMI estimation** compared to traditional surface- only methods (Peñaranda et al., 2023). For instance, Matuszewski (2021) demonstrated that internal mapping of larval masses correlated with precise PMI windows within ±12 hours, which was previously unattainable in complex cases.

6.2 Insect Mapping:

Mapping the location of insect colonization provides critical insight into decomposition dynamics and body accessibility. Virtopsy methods allow investigators to:

- Create **3D reconstructions of larval distribution**, showing both surface and internal colonization.

- Identify preferential feeding sites, such as **orifices, wounds, and soft tissues** (Urbanová et al., 2018).
- Document **larval progression over time**, which can reveal the order of insect colonization and help differentiate primary from secondary insect activity (Anderson et al., 2022).

This mapping is particularly useful in legal contexts, where a digital record can illustrate insect activity without altering the physical body, ensuring that evidence remains admissible in court (Ross & Cattaneo, 2019).

6.3 Colonization Analysis:

Colonization analysis examines **which insect species and developmental stages** are present, as well as **the spatial and temporal pattern of their activity**. Virtopsy enhances this analysis by:

1. Visualizing **larvae in internal cavities** using PMCT or micro-CT (Ferreira et al., 2022).
2. Identifying **species-specific colonization behavior** through size, shape, and location of larval masses (Blau et al., 2021).
3. Tracking **succession patterns** in decomposing remains without disturbing larvae, which is critical for accurate PMI estimates (Peñaranda et al., 2023).

Furthermore, imaging allows integration with **AI-based species recognition algorithms**, facilitating rapid and objective identification of larvae at different developmental stages, which reduces human error and increases reproducibility (Chen et al., 2020).

6.4 Wound Interpretation:

In forensic investigations, distinguishing **ante-mortem trauma** from **postmortem insect damage** is critical. Virtopsy contributes to wound interpretation by:

- Providing **3D surface models** that reveal bite marks, scratches, and punctures created by insects (Cattaneo et al., 2021).
- Using PMCT or micro-CT to observe **subcutaneous feeding damage**, tunnels, and tissue liquefaction (Dekeirsschieter et al., 2022).
- Helping forensic pathologists differentiate **insect-induced defects from sharp or blunt force trauma**, enhancing accuracy in cause-of-death determination (Ross & Cattaneo, 2019).

This capability is particularly valuable in cases with advanced decomposition, where traditional autopsy may struggle to accurately identify trauma.

Summary of Applications

Virtual autopsy, when combined with forensic entomology, provides a **non-invasive, precise, and reproducible method** for:

- Accurate PMI estimation
- Detailed mapping of insect activity
- Analysis of colonization dynamics and species succession
- Distinction between ante-mortem trauma and postmortem insect damage

The integration of imaging data with classical entomology significantly enhances investigative accuracy and legal defensibility, making virtopsy an indispensable tool in modern forensic science (Peñaranda et al., 2023; Anderson et al., 2022; Blau et al., 2021).

7. Case Study:

Case Study: Larval Mapping in a Decomposed Body Using PMCT and Micro-CT

A forensic investigation was conducted on a

partially decomposed body discovered in a rural environment in northern Europe. Initial examination revealed extensive external larval activity, but investigators suspected significant internal colonization. Using **postmortem computed tomography (PMCT)**, internal larval tunnels were visualized in the abdominal cavity and subcutaneous tissue. Subsequent **micro-CT imaging** allowed detailed examination of larval morphology and feeding pathways without disturbing the remains (Dekeirsschieter et al., 2022). Integration of these imaging findings with classical entomology (larval species identification and development stage analysis) enabled a precise **postmortem interval (PMI) estimation of 7–9 days**, which was corroborated by environmental temperature data and insect succession models. This case demonstrated the **non- invasive documentation of internal insect activity** and highlighted virtopsy's role in enhancing entomological accuracy and evidence preservation (Blau et al., 2021; Ferreira et al., 2022).

8. Recent Advancements:

The field of virtual autopsy in forensic entomology has witnessed multiple technological advancements that enhance both detection and analysis capabilities:

1. **High-resolution Micro-CT Scanning:** Enables detailed visualization of larval anatomy and feeding tunnels, improving species identification and PMI estimation accuracy (Blau et al., 2021).

2. **Multispectral and Hyperspectral Imaging:** Emerging methods detect chemical and optical signatures of decomposition and larval activity, allowing early-stage detection of colonization (Cruz et al., 2020; Ferreira et al., 2022).

3. **Thermal Imaging:** Thermal cameras can detect metabolic heat from large larval aggregations, assisting in mapping concealed maggot masses (Matuszewski, 2021).

4. **3D Surface Reconstruction and Photogrammetry:** Advances in portable and cost-effective scanners have facilitated precise mapping of external colonization and oviposition sites, allowing digital preservation and court-ready documentation (Urbanová et al., 2018; Peñaranda et al., 2023).

5. **Integration with AI and Machine Learning:** AI algorithms now support automated detection of larvae, classification by developmental stage, and correlation with decomposition patterns, reducing human error and speeding analysis (Chen et al., 2020; Anderson et al., 2022).

6. **Hybrid PMI Models:** Combining virtopsy imaging with environmental and entomological data has improved the accuracy of PMI prediction, particularly in advanced decomposition or atypical cases (Gupta & Verma, 2023).

7. **Remote Collaboration and Digital Archiving:** Cloud-based platforms allow forensic teams to share high-resolution datasets with experts globally, supporting collaborative analysis and research in real-time (Ross & Cattaneo, 2019).

These advancements demonstrate a **trend toward fully integrated digital forensic workflows**, where virtual autopsy not only documents decomposition but actively contributes to forensic entomology research and application.

9.Challenges:

Despite its potential, the integration of virtual autopsy with forensic entomology faces several challenges:

1. **Limited Access to Advanced Imaging Modalities:** High- resolution tools such as micro- CT and PMMRI are costly and often unavailable in many forensic laboratories, particularly in developing regions (Cattaneo et al., 2021; Blau et al., 2021).

2. **Technical Expertise Requirements:** Proper interpretation of imaging data requires specialized training in both forensic radiology and entomology. Misinterpretation of larval tunnels, gas pockets, or tissue changes can lead to inaccurate PMI estimations (Dekeirsschieter et al., 2022).

3. **Complexity of Decomposition Variables:** Environmental factors, body mass, clothing, and burial conditions influence insect colonization and decomposition. Even with high-resolution imaging, integrating these variables into accurate models remains challenging (Matuszewski, 2021).

4. **Data Management and Storage:** High-resolution imaging generates large datasets that require secure storage and long-term digital archiving. Maintaining accessibility, data integrity, and compliance with privacy regulations can be difficult (Peñaranda et al., 2023).

5. **Legal Acceptance and Standardization:** Although virtopsy is increasingly recognized, not all judicial systems accept imaging evidence as equivalent to traditional autopsy. Standardized protocols and validation studies are needed to ensure admissibility (Ross & Cattaneo, 2019; Anderson et al., 2022).

6. **Limited Species-Specific Validation:** While imaging can detect larval presence and tunnels, most species- specific developmental data are based on traditional dissection methods. Bridging this gap requires extensive calibration studies correlating imaging findings with biological development (Ferreira et al., 2022).

10. Future Directions:

The future of virtual autopsy in forensic entomology is promising, with several areas of potential development:

1. **Integration of AI and Predictive Modeling:** Machine learning algorithms can automate larval

detection, species classification, and PMI prediction, reducing human error and increasing reproducibility (Chen et al., 2020; Anderson et al., 2022).

2. **Portable Imaging Solutions:** Development of compact, field-deployable imaging tools (e.g., handheld CT or portable 3D scanners) could enable on-site entomological analysis, particularly in remote or disaster scenarios (Urbanová et al., 2018).

3. **Enhanced Multispectral and Thermal Imaging:** Future research may refine spectral signatures for early detection of insect activity, even in concealed or partially decomposed bodies (Cruz et al., 2020).

4. **Standardization of Protocols:** International guidelines for virtopsy application in entomology could improve legal acceptance and facilitate multicenter research collaboration (Peñaranda et al., 2023).

5. **Hybrid Forensic Models:** Combining digital imaging, environmental data, microbial profiling, and classical entomology could produce more accurate, integrative PMI estimation models (Gupta & Verma, 2023).

6. **Longitudinal Data and Digital Archiving:** The creation of centralized databases of virtopsy datasets with correlated entomological findings could enhance research, training, and forensic validation worldwide (Ross & Cattaneo, 2019).

11. Conclusion:

Virtual autopsy represents a **transformative advancement** in forensic entomology. By integrating PMCT, PMMRI, micro-CT, 3D scanning, and complementary imaging modalities, investigators can non-invasively document larval colonization, feeding patterns, and decomposition changes. These methods enhance PMI estimation, enable detailed insect mapping, and help differentiate postmortem insect damage from trauma.

While challenges such as cost, technical expertise, and data management remain, ongoing technological improvements—including AI integration, portable imaging, and multispectral techniques—promise to expand the applicability and accuracy of virtopsy in entomology. As a result, virtual autopsy is poised to become a **core component of modern forensic workflows**, providing a reliable, reproducible, and legally admissible approach to studying insect-mediated decomposition.

The convergence of digital imaging and entomology not only enhances investigative precision but also preserves fragile evidence, supports research, and advances educational opportunities in forensic science. By continuing to refine methods, standardize protocols, and integrate predictive technologies, the field can achieve more accurate postmortem interval estimation, improved legal outcomes, and deeper scientific understanding of decomposition dynamics.

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