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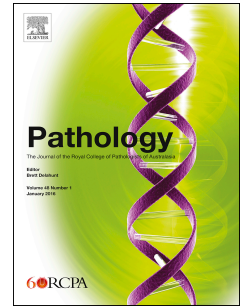


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DIGITAL PATHOLOGY

What is the carbon footprint of a 100% digital pathology scenario in France?

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Abstract

Healthcare systems contribute to 5–10% of annual greenhouse gas (GHG) emissions and must reduce them to meet the 2016 Paris Agreement targets. Workflows in many areas of medicine are digitised, including surgical pathology. This is the case in France, the second most populous country in the European Union (68 million inhabitants/ 0.8% of world population) with an energy supply that is primarily sourced from nuclear power. We aimed to evaluate the carbon footprint (CF) in a theoretical scenario where all French surgical pathology laboratories implement full digitisation. Data on annual surgical pathology activities were obtained from the French National College of Pathologists. We defined the steps required by histological slide digitisation (scanning, image management software (IMS), data workflow, desktop tools, and storage) and inventoried the tools and their CF using a specific database and bibliography. This study was extrapolated to a national digitisation scenario without artificial intelligence (AI). Digitisation of a single French laboratory was also compared to the same laboratory, non-digitised. In 2021, 28,932,624 slides were generated, corresponding to more than 43PB (1.5 GB per whole-slide image (WSI)) shared by 250 surgical pathology laboratories using 500 scanners (i.e., two per laboratory working 12 hours per day). Digitising pathology resulted in 1,103 to 1,259 tons of carbon dioxide equivalent (CO₂eq) for three months compared to 2,116 to 2,923 t CO₂eq for one year of digital storage. This is equivalent to the GHG emissions of a combustion-powered car travelling around the Earth 145 times and 336 times, respectively. Data storage was the main contributor to the CF, regardless of storage type and duration (local or external for three months or one year). The other contributors included in decreasing order were desktop tools, scanners, and IMS. Finally, for one French surgical pathology laboratory, the CF of full digitisation increased by 4% to 8% (three months to one year of digital storage) compared to the current non-digitised CF. Such additional impact was equivalent to adding 13 to 26 minus 80-degree freezers in the laboratory. Full digitisation of surgical pathology has a significant environmental impact on global warming, even without the use of AI. Reducing storage duration and increasing the lifespan of digital equipment are the main strategies to mitigate these impacts.

Key words: Sustainable development, surgical pathology, digital pathology, carbon footprint (ecodesign of care)

1. Introduction

In the current global climate emergency, awareness of healthcare systems' contributions and responsibility is growing worldwide, particularly in France. Globally, healthcare systems account for 5% of annual greenhouse gas (GHG) emissions expressed in carbon dioxide equivalent (CO₂eq). Like other sectors, they are required to achieve a 55% reduction in net GHG emissions by 2030 compared to 1990 levels to meet the European Climate Law.¹ In France (the second most populous country in the European Union (68 million inhabitants/ 0.8% of the world population) and with an energy supply primarily sourced from nuclear power), the healthcare system is responsible for 8–10% of national GHG emissions.²

An increasing number of professional organisations, such as the French Society of Anaesthesia and Intensive Care Medicine and the French Dialysis Society, have recently drafted recommendations for greener practices.^{3,4} In the field of surgical pathology, no sustainable guidelines are available so far, but since 2023, there has been a rise in publications addressing the environmental impact of surgical pathology and proposing greener solutions without compromising worker safety or analytical quality.⁵ Béchu *et al.* published the first study on the carbon footprint (CF) of a non-digitised surgical pathology laboratory, revealing that consumables are the most impactful category, far surpassing transport, waste, and energy.⁶ Trecourt *et al.* extended this research by analysing the CF of various techniques, including one haematoxylin-phloxine-saffron slide from a biopsy, one from a surgical specimen, an immunohistochemical slide, and one frozen section.⁷ Unsurprisingly, consumables, especially reagents and packaging, were the main contributors to CF across all techniques.

From a solution perspective, Vergara *et al.* highlighted the potential of reducing the use of reflex first-line techniques to incorporate eco-design principles without compromising the quality and safety of care.⁸ Additionally, recycling materials and reagents like formalin offers another pathway to mitigate environmental impact.⁹

The digitisation of surgical pathology workflow, as in other medical fields, is a new step for the speciality that may cancel out the first mitigation effort, especially since there is no ambitious worldwide carbon constraint in information communication technology.¹⁰ Indeed, despite the perceived benefits of dematerialisation, digital technology remains a highly material industry, involving significant GHG emissions, water and mineral resource consumption, and social impacts. These effects are not limited to the hardware manufacturing phase but also extend to the usage and end-of-life phases. Moreover, the global recycling capacity for digital equipment remains limited.¹¹ In surgical pathology, digitisation has led to scanning histological glass slides to produce digital WSI for analysis and reporting. This represents an additional step in the diagnostic workflow. For many users, digital pathology is considered a solution that enhances diagnostic capabilities. This can be achieved by developing computer vision and software-assisted diagnosis assistants, education and continuous training via online or offline interactive training sessions, and research (i.e., multiplex immunofluorescence big data acquisition and analysis). This could also help counteract the pathologist shortage, and improve quality of life through remote work opportunities.¹² In France, recent policies promoting e-healthcare, combined with public funding, have accelerated the digitisation of surgical pathology laboratories. However, the environmental impact of widespread digitisation in this field has not yet been evaluated.

Our objective is thus to assess the carbon footprint of fully digitising all French surgical pathology laboratories in a hypothetical 100% digital pathology scenario.

2. Materials and Methods

2.1 Study design and data

For this modelling study, we began by collecting relevant data and parameters for a digital pathology workflow. The data included the number of glass slides produced annually by the 250 surgical pathology laboratories (public and private sectors) registered in France. We obtained the latest available data on surgical pathology activities from the French National College of Pathologists (2021). We also defined the main steps involved in the digital pathology workflow: slide scanning, imaging management systems (IMS), data workflow, desktop tools for digital analysis (including remote work), and data centre for data storage (Fig. 1). The use of artificial intelligence (AI) for diagnosis assistance was not included in this study.

2.2 Equipment selection and evaluation

To ensure the accuracy of our modelling study, we aimed to reflect current French digitisation practices while leveraging the limited data available in the literature. For the scanner evaluation, we selected the NanoZoomer S360 (Hamamatsu), identified as the most widely used scanner in France.^{13,14} Two scanners were assigned to each surgical pathology laboratory, considering the need for backup systems. The median size of single whole-slide imaging (WSI) was estimated at 1.5 GB, regardless of the scanner type.

For data storage, we modelled two types of capital equipment: local and external storage systems. We selected the Dell R740 server for local storage and the Summer (i.e. Stockage Unifié Mutualisé Massif Evolutif et Réparti) data centre, a French example of data centre, for external storage, as both were representative of their respective categories and had specific life cycle assessments (LCAs) in open-access resources.^{15,16}

2.3 Carbon footprint assessment

Most of the information for the carbon footprint assessment (CFA) was sourced from the French Agence De l'Environnement et de la Maîtrise de l'Energie (ADEME) database¹⁷ in collaboration with the Association Bas Carbone (ABC), Ecoinvent, and Ecodiag (from Ecoinfo). When data were unavailable, scientific literature and open-access databases (including those from manufacturers) were explored. If necessary, a model-based approximation was performed using information from similar equipment with a known CF. The study covered all capital equipment used for digital pathology: scanners, IMS, data workflow infrastructure (cables), desktop tools (computers, screens), local storage, and data centres.

2.4 Data collection and carbon footprint assessment

Regarding scanners, no specific life-cycle assessment (LCA) was available from manufacturers or in the literature. Scanners CF assessment was modelled according to the components described by the manufacturer. Such components included a graphics processing unit, two cameras, a tablet, a microscope, an internal and external case (plastics and metals), and rare metals (like those of a computer). The weight of each component, as a proportion of the total scanner weight (117 kg), was multiplied by its emission factor to estimate the CF. Transportation CF was calculated based on the type of transport (plane), distances (9,844 km from Japan to France, in beeline using Google Maps), and total scanner weight.

Scanner electricity consumption was assessed based on the manufacturer's website information including the scanner power (200 Watts), the digital speed (82 glass slides/hour), the operational lifetime (seven years) and the geographic location of manufacturing (Japan).¹⁸ The

electricity consumption was calculated using the following formula: scanner power (200W) x usage time (12h/working days) /1000 = electrical consumption expressed in kWh. End-of-life disposal was assumed to align with electronic waste processing within the Waste Electrical and Electronic Equipment (WEEE) sector.

The IMS software evaluation was conducted using an adapted version of the Green Digital Software Index (GDSI) method, developed by GreenSpector—a French company specialised in assessing the environmental impact of digital services. The GDSI methodology allows calculation of environmental indicators such as carbon footprint of software applications, including IMS.¹⁹ To assess the IMS software CF, a typical user workflow was defined in collaboration with three different IMS software coming from three different volunteer companies. This was not a programming script, but rather a sequence of tasks that a pathologist would routinely perform when using IMS software. Each workflow included at least four core actions: logging in, searching and selecting a WSI, navigating the slide, and using the zoom function. Additional optional actions included viewing multiple slides simultaneously or adding annotations. Workflows were encoded to automate the process. Core action measurements were taken on physical smartphones under controlled lab conditions, following GreenSpector's standard mobile evaluation procedure. Although the primary use of WSI software occurs on desktop computers with HD monitors, the mobile-based method was used due to the availability of validated tools for consistent measurement on smartphones. A correction factor was applied to adjust the carbon footprint data to reflect usage on a desktop computer. Then, to assess the overall carbon footprint of IMS, we calculated the three IMS CF average.

Desktop tools mainly consist of a computer, a Wi-Fi terminal, and a screen. While most of this equipment is already available in laboratories, HD (4K) screens are often specifically purchased for WSI analysis. The shift toward digitisation also presents an opportunity to adopt partial remote work. This transition requires fully equipped home workstations, i.e., monitor, tower, keyboard, mouse, and an additional HD screen. Wi-Fi terminals were excluded from the assessment, as they are widely available in French households. Since no specific data on the CF or LCA of HD screens was found, their environmental impact was approximated based on data for 24- to 31-inch screens. Only the manufacturing, usage and end of life phases of desktop tools were considered, as data on transportation to the workplace or home were unavailable.

The evaluation of data storage considered two potential scenarios: local and external storage. For each scenario, the CF of data centre was assessed based on the LCA of the computer server and the Power Usage Effectiveness (PUE) metric. PUE measures the efficiency of data centre operations and is calculated as follows: total electrical energy consumed by the data centre/ total electrical energy consumed by the computer servers.²⁰ The total energy consumption of the data centre includes key components such as server cooling, air treatment, converters, and other supporting systems. We used a PUE equal to 1.4 as recommended by Ficher *et al.*²¹ For local storage, the evaluation criteria for the Dell R740 server CF, provided by the manufacturer, included storage capacity, production usage, and the end of its four-year lifecycle. The CFA of external storage (Summer data centre), previously published, was tailored for WSI storage, featuring three interconnected data centres.¹⁵ These centres provide backup and synchronous replication services while ensuring a high level of data security and integrity. In terms of storage duration, two scenarios were considered: three months versus one year, with or without WSI duplication (applicable to external storage only), and using two scanners per laboratory. The storage volume number was obtained by dividing the total annual data volume (GB) by 254 working days. The data volume/working days was then multiplied by storage duration (in days) to obtain the data volume per storage duration. This result was divided by the server storage

capacity to assess the number of servers needed for local storage. For external storage, the data volume per storage duration was multiplied by the emission factor of storing one GB in external data centre (Summer data centre), after adjustment with current French energy mix.¹⁵ The carbon footprint of electrical consumption was calculated considering that French energy (also called energy mix) is essentially decarbonised because it is composed of 72% nuclear energy, 16% renewable energy, and 10% fossil fuels. Thus, the sources of energy of each country worldwide will modify the carbon footprint of the same initiative.

The evaluation of the data workflow was negligible for local storage. For external storage, it primarily accounted for the transmission of WSI from the scanner to the data centre and was evaluated according to Ficher *et al.*²¹ All aspects of the network infrastructure were evaluated: optical fibres, active equipment (e.g., routers, optical transport network switches, and amplifiers), and the network supervision centre.

2.5 Data analyses

Quantitative data were expressed as median and extremes. The CF was calculated using the following formula:

Item quantity (units: kg, km, kWh, etc.) \times emission factor of the item (kg CO₂eq/unit) = total CO₂eq emissions.

For example, the electricity consumption CF of scanners corresponded to the electricity consumption (kWh) multiplied by the emission factor of the French energy mix (g CO₂eq / kWh) = total emissions (g CO₂eq). The local storage CF was calculated multiplying the number of servers needed (Dell R740 server) by the emission factor of one server (kg CO₂eq).

The overall CF of the 100% digital pathology scenario was determined by summing the CO₂eq emissions of all components. The relative contribution of each component was calculated by dividing its CO₂eq emissions by the total CO₂eq emissions.

To estimate the impact of converting a non-digitised surgical pathology laboratory to a fully digitised setup, previously published data were used.⁶ The results were then extrapolated to encompass all surgical pathology laboratories in France (n=250).

To evaluate the potential rate of carbon saving concerning the main items of digitisation, the reference CF of the item was compared to its eco-design counterpart, and the difference was expressed in CO₂eq and percentage.

3. Results

3.1 Carbon footprint of the 100% digital pathology scenario

From 1 January to 31 December 2021, approximately 28,932,624 glass slides (equivalent to 43,398,936 GB, i.e., approx. 43 PB) were produced and analysed in France by 1,672 surgical pathologists. This translates to 113,908 slides corresponding to a data volume of 170,862 GB per working day. For each surgical laboratory (n=250), two scanners were required: one would be allocated for routine techniques, and the other for special techniques (e.g., immunohistochemistry, immunofluorescence, frozen sections, cytology, or as a backup).

The CF to manufacture one scanner was 442.2 kg CO₂eq and the different items are detailed in **Fig. 2**. Taking into account the lifespan of the scanner (seven years), the CF of 500 scanners, operating 12 hours per day (254 working days), was estimated at 161 t CO₂eq annually, with the breakdown for each component summarised in **Fig. 3**. Transportation (by plane) emerged as the largest contributor, accounting for 60% of the total CF, followed by manufacturing, end-of-life, and energy consumption. The visualisation (or streaming) of a single WSI emitted a

median of 2.3 g CO₂eq (range: 1.6–3.1 g CO₂eq). When extrapolated to the total annual volume of slides, WSI visualisation accounted for 67 t CO₂eq. The CF of the additional desktop tools amounted to 482 t CO₂eq. Of these, the HD screen was the most impactful component, with a CF twice as high as that of the computer (**Table 1**).

The CF of data storage was comparable between local and external data centres, with storage duration being the most significant factor. For local storage, the CF ranged from 549 t CO₂eq for three months of storage to 2,214 t CO₂eq for one year of storage (**Supplementary Table S1**). For external storage, the CF ranged from 393 t CO₂eq for three months of storage to 1,406 t CO₂eq for one year of storage (**Supplementary Table S2**). Data duplication, which was only available for external storage, doubled the environmental impact as it requires twice the storage capacity. The annual data workflow emitted 61 t CO₂eq.

Fully digitising surgical pathology in France resulted in a CF of 1,259 t CO₂eq for three months of storage and 2,923 t CO₂eq for one year of storage with local storage (**Fig. 4; Supplementary Table S3**). This is equivalent to the GHG emissions of a combustion-powered car travelling around the Earth 145 times and 336 times, respectively, or the annual GHG emissions of 114 and 266 European inhabitants, respectively.²² It requires from 6.7 to 15.6 km² (2.4x10⁻⁵ %) of the worldwide forest to sequester the CO₂ emissions (**Fig. 5**).²³ It is equivalent to adding 3,597 to 8,351 minus 80-degree freezers in the laboratory.

For external storage, the CF associated with digitising pathology was approximately 1,103 t CO₂eq for three months of storage and 2,116 t CO₂eq for one year of storage. Data duplication doubled the GHG emissions as well (**Fig. 4**).

In the three-month local storage scenario, storage accounted for 44% of the total impact, followed by desktop tools (38%) and scanners (13%) (**Fig. 4; Supplementary Table S3**). In the one-year storage scenario, storage was the most significant contributor (76%), followed by desktop tools (16%) and scanners (6%) (**Fig. 4; Supplementary Table S3**). For external storage, the proportions were similar (**Fig. 4**).

The CF gross values of scanner, desktop tools and IMS were constant whatever duration storage because they are exclusively linked to the number of slides produced yearly.

3.2 Comparison with the carbon footprint of a surgical pathology laboratory

The CF of the surgical pathology laboratory at Saint Vincent's Hospital in Lille, France, was 117 t CO₂eq in 2021, reflecting its annual activity of managing 86,707 slides.⁶ Digitising such a laboratory would require two scanners, several servers (depending on storage duration), and updated desktop tools. The estimated CF for digitisation per year would range from 5 t CO₂eq for three months of storage to 9.2 t CO₂eq for one year of storage.

At the scale of a typical French surgical pathology laboratory, the CF of digitisation, excluding AI, would result in an increase in CF of 4% to 8% compared to the current non-digitised CF, depending on whether a three-month or one-year digital storage scenario is considered. Such additional impact was equivalent to adding 13 to 26 minus 80-degree freezers in the laboratory (one minus 80-degree freezer=0.35 t CO₂eq /year.⁶

3.3 Potential carbon saving by ecodesign of digitisation

For the three main items impacting the carbon footprint of digitisation i.e. storage, desktop tools and scanners, the consequences of some tangible ecodesigned alternatives are evaluated in **Table 2**. The reduction of local storage from 3 months to 1 month could save 366 t CO₂eq corresponding to 67% of the item CF. The increased lifespan of desktop tools by x 1.5 (i.e., from 5 to 7.5 years), could decrease by 31% the item CF. For scanners, the lifespan extension

(x 1.5) could also reduce by 32% the item CF whereas the optimisation of slide scanning in France by scanner mutualisation (multiple users) and increasing duration (24h/working day) could save 87% of the item CF. The reduction of WSI value from 1.5 to 1 GB could also decrease by 185 t CO₂eq the CF (34% of CF item).

4. Discussion

The objective of this study was to evaluate the CF of implementing full digitisation in routine practice at French surgical pathology laboratories. We found that the CF of digital pathology varied from 1,103–1,259 to 2,116–2,923 t CO₂eq, depending on the type and duration of data storage. The main emission items were data storage and desktop tools. Thus, the cost of implementing this technology would increase the annual CF of a surgical pathology laboratory by 4% to 8%.

4.1 Health care digital revolution

The expansion of applied technology is evident across all medical disciplines. Following advancements in radiology and cardiology, it is now time for surgical pathology to embrace the digital revolution. These three specialities face the same challenge: an increasing workload paired with a shrinking workforce. However, the sustainability of this technological revolution has not been fully anticipated at any level, whether internationally, nationally, within healthcare structures, or within specific specialities. In radiology, implementing Picture Archiving and Communication Systems (PACS) and next-generation interpretation tools integrated into "all-inclusive" workstations has boosted productivity and diagnostic accuracy while rendering traditional radiology films obsolete.²⁴ The added value of digitisation in surgical pathology, however, is harder to measure due to its more recent and partial implementation. Initially, it was developed in countries experiencing a shortage of pathologists, such as Canada.²⁵ The pandemic caused by SARS-Cov-2 virus further highlighted the importance of digitising pathology to maintain diagnostic activities and facilitate education through remote work. However, it is still too early to draw definitive conclusions regarding productivity and diagnostic accuracy, as AI tools are not yet sufficiently developed or integrated into routine practice. In contrast to radiology, digitising pathology is an additional step in the process and does not lead to material savings, as blocks and glass slides are still necessary and legally they must be stored for many years (from 10–30 years depending on the country; 10 years in the United States of America, India and Australia, and 30 years or even more in France, the United Kingdom and Belgium; and type of sample).^{26–30}

4.2 The main impacting factors: storage and desktop tools

The most efficient way to reduce the CF is to limit storage duration and avoid unnecessary replication. Data replication involves copying and storing data in multiple locations (between two and six), ensuring availability and accessibility while protecting against system failures, cybersecurity breaches, or other disasters. In surgical pathology, however, WSI replication is unnecessary, as the original glass slides are preserved and can be re-scanned at any time. For these reasons, the duration of WSI storage should be minimised. While most French laboratories have opted for a storage period of three months, in routine practice, most cases could be deleted as soon as the report is validated. The second most significant factor impacting the CF is the desktop tools. This is not surprising, as such items are associated with capital equipment, which has a high CF due to the manufacturing process and the need for precious

metals.³¹ Reducing their impact involves extending their lifespan. Ecodesigning such tools could be the next step in the future.

4.3 Digitisation and carbon footprint of a SP laboratory

When comparing the evaluation of French surgical pathology laboratories,⁶ implementing digital pathology could lead to a 4–8% increase in a laboratory's CF. This is at odds with the reduction targets needed to meet the ambitions of the Paris Agreement, which calls for a 5% annual decrease in emissions until 2050 to limit global warming to below 1.5°C.³² The potential for remote work that digitisation offers could reduce the CF of a digitised surgical pathology laboratory. However, many uncertainties remain regarding the energy savings associated with remote work. According to Hook *et al.*, in many cases, the balance may be negative or neutral: non-work-related travel, home energy consumption, and the use of home-based digital equipment could offset the benefits of reduced work-related travel.³³

4.4 Impact of AI tools

Associated with digitisation, AI is the next step in surgical pathology for developing diagnostic tools. Our CF assessment did not include AI, since recent data have been published in this field.²³ Indeed, a recent modelling study on the GHG emissions concluded that the widespread use of deep learning (excluding the tool training phase) could have a significant global warming potential of around 16 megatons (Mt) CO₂eq, requiring up to 86,590 km² of global forest to sequester these CO₂eq emissions.²³

4.5 Reflections and proposals to mitigate the CF of digitisation

It is now time for medical communities, policymakers, and patients to confront this new challenge and take action together by developing national and international guidelines for the sustainable use of digital pathology and associated AI tools. There are significant economic stakes behind the use of these digital technologies, which must not overshadow their environmental impacts, particularly in terms of climate deregulation, which has well-documented consequences for human health.³⁴

The surgical pathology community must collectively address three key questions:

- (1) Is it necessary to digitise all glass slides? It is clear that not all slides, but only a select portion (likely a minority depending on the laboratory's activity and location), could benefit from digitisation with AI tool assistance, or for teleconsultation and education purposes. This consideration aligns with current healthcare discussions on the relevance of certain healthcare practices. However, the consequences of the implementation of a double slide workflow (physical and WSI) must be anticipated by the staff to limit disorganisation.
- (2) What ecodesign measures can be implemented to limit the impact of digitisation? Based on this study, several evaluations and recommendations have already been proposed to mitigate the environmental impact of digitisation, which are summarised in **Tables 2 and 3**.
- (3) Beyond environmental concerns, how do we ensure resilience and continuity of care? How can we maintain surgical pathology activities in the event of a cyberattack or resource shortages? Microscopes must remain in surgical pathology laboratories to address these challenges.

This innovative study is one of the first to be published in this field, but it has several limitations. The first limitation is not having a comprehensive LCA of the main equipment used for digitisation in surgical pathology (e.g., scanners), which could lead to inaccurate evaluations.

The second limitation is related to the methodology we employed and the assumptions made, such as the number of scanners per laboratory or the number of WSI analyses per slide (counted as only one time). These assumptions could result in an underestimation of the final CF. The third limitation stems from the evaluation of the IMS (three different voluntary viewers), which was conducted using a national tool under development, designed for smartphone apps and not for computers.

5. Conclusion

Digital pathology is the inevitable sociocultural evolution of surgical pathology: it is anchored in the changes of our societies and culture over time, and nobody can stop it. However, it comes with environmental costs. While we await the diagnostic benefits that AI may offer, we present, for the first time, recommendations to assist the surgical pathology community in France and beyond in ecodesigning digitisation within their pathology laboratories.

Declaration of generative AI and AI-assisted technologies in the writing process

Generative AI or AI assisted technology was not used to write the manuscript.

Data availability

The data that support the findings of this study are available on request from the corresponding author, CT.

Author contributions

CT, LGD and AR designed the study, conducted the pathology analyses, and wrote the manuscript. NP, CM. and CB contributed to the study design. BS provided original design and analysis of the carbon footprint of imaging management systems. AT contributed to manuscript writing. All authors participated in editing the last manuscript version.

Conflicts of interest and sources of funding

The authors state that there are no conflicts of interest or sources of funding to disclose.

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Figure captions

Fig. 1: Study design of the 100% digital pathology scenario in France.

Fig. 2: Carbon footprint of the elements of one scanner.

The carbon footprint of the main elements constituting one scanner are given in kg CO₂eq and in percentage.

*GPU: graphic processing unit

Fig. 3: Carbon footprint of components of 500 scanners for the 100% digital pathology scenario in France.

The carbon footprint is dominated by transport (97 tons of CO₂eq), followed by manufacturing (31.5 t CO₂eq), end-of-life (16.5 t CO₂eq) and energy (16 t CO₂eq).

Fig. 4: Data storage is the dominant contributor to carbon footprint of implementing the 100% digital pathology scenario in France.

For 3-months local storage (**A**) the carbon footprint was dominated by storage (549 t CO₂eq; 44%), followed by desktop tools (482 t CO₂eq; 38%), scanners (161 t CO₂eq; 13%) and IMS (67 t CO₂eq 5%). For one-year local storage (**B**) the storage still dominating reaching 2,214 t CO₂eq; 76%) far away from desktop tools (482 t CO₂eq;16%), scanners (6%) and IMS (2%). For 3-months external storage (**C**) the carbon footprint was dominated by desktop tools (482 t CO₂eq; 44%), followed by storage (393 t CO₂eq; 15%), scanners (161 t CO₂eq;15%) and IMS (67 t CO₂eq; 6%). For one-year external storage (**D**) the storage represented 1,406 t CO₂eq (66%) of the carbon footprint followed by desktop tools (23%), scanners (8%) and IMS (3%). IMS: imaging management system.

Fig. 5: Equivalence of carbon footprint of implementing digitisation for the 100% digital pathology scenario in France according to type and duration storage.

(**A**) carbon footprint of implementing digitisation according to type (local and external) and duration (3 months and 1 year) storage: (**B**) equivalence of carbon footprint number of tours around the world by thermal car, (**C**) number of European inhabitants annual carbon footprint, (**D**) number of freezers (-80°C) over one year, and (**E**) surface of forest required to sequester the emitted CO₂.

Table 1: Details of the annual carbon footprint of desktop tools necessary for the 100% digital pathology scenario in France.

Tools	Number of items	Emission factor (kg CO₂ eq/item)	Carbon footprint (t CO₂eq)	Share of emissions (%)
Computer	1,672	104	174	36
HD* screen (24-31 inches)	3,344	92	308	64
Total	/	/	482	100

*HD: high definition

Table 2: Assessment of the impact of the main recommendations compared to the reference scenario (1,259 t CO₂eq for three months of storage with local storage)

Main items	Ecodesign option	Reference CF*	Ecodesigned CF	CF reduction (%)
Storage	1 month duration	549	183	366 (67)
Desktop tools	Lifespan (x 1.5)	482	332	150 (31)
Scanner	Lifespan (x 1.5)	161	110	51 (32)
	Pooling usage (58 scanners 24 hours/working day)	161	21	140 (87)
	WSI size (1GB)	549	364	185 (34)

*CF= carbon footprint expressed in tons of CO₂eq.

Table 3: Recommendations for ecodesigning the implementation of digitisation in current surgical laboratories.

Categories	Recommendations	
	Users	Manufacturers
Digitisation activity	Full or partial digitisation Limit scan magnification (x20)	
Equipment (desktop tools, scanner, etc.)	Sizing consistent with activity Increase lifespan Scanner mutualisation Reconditioned equipment Sustainable purchasing policy	Increase lifespan Increase reparability Life cycle assessment to ecodesign equipment Reconditioned equipment catalogue Reduce WSI size (GB)
Storage (and data centre)	No replication Decrease time storage duration except special cases (education, teleconsultation, publication or research) Discard most WSI immediately after report validated Favour pooling storage in case of geographic proximity	Ecodesign data centre (recovery of waste heat, PUE ~1, geographic proximity, etc.) Add possibility to discard most WSI immediately after report validated Ecodesign storage (higher-latency cold data storage) Favour mutualisation storage for several laboratories

PUE: Power Usage Effectiveness; WSI: whole-slide image; Cold data storage: type of archival storage of data that needs long-term preservation but does not require ongoing or readily available access.

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Fig. 1: Study design of the 100% digital pathology scenario in France.

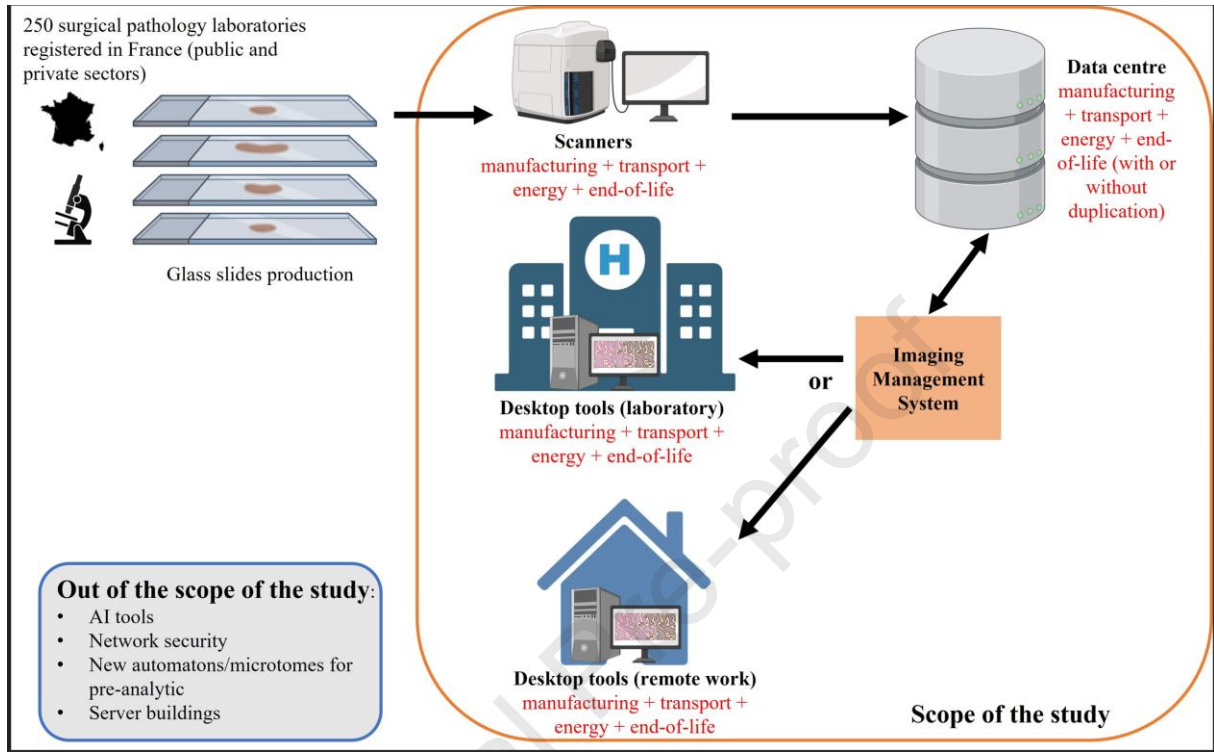


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The carbon footprint of the main elements constituting one scanner are given in kg CO₂eq and in percentage.

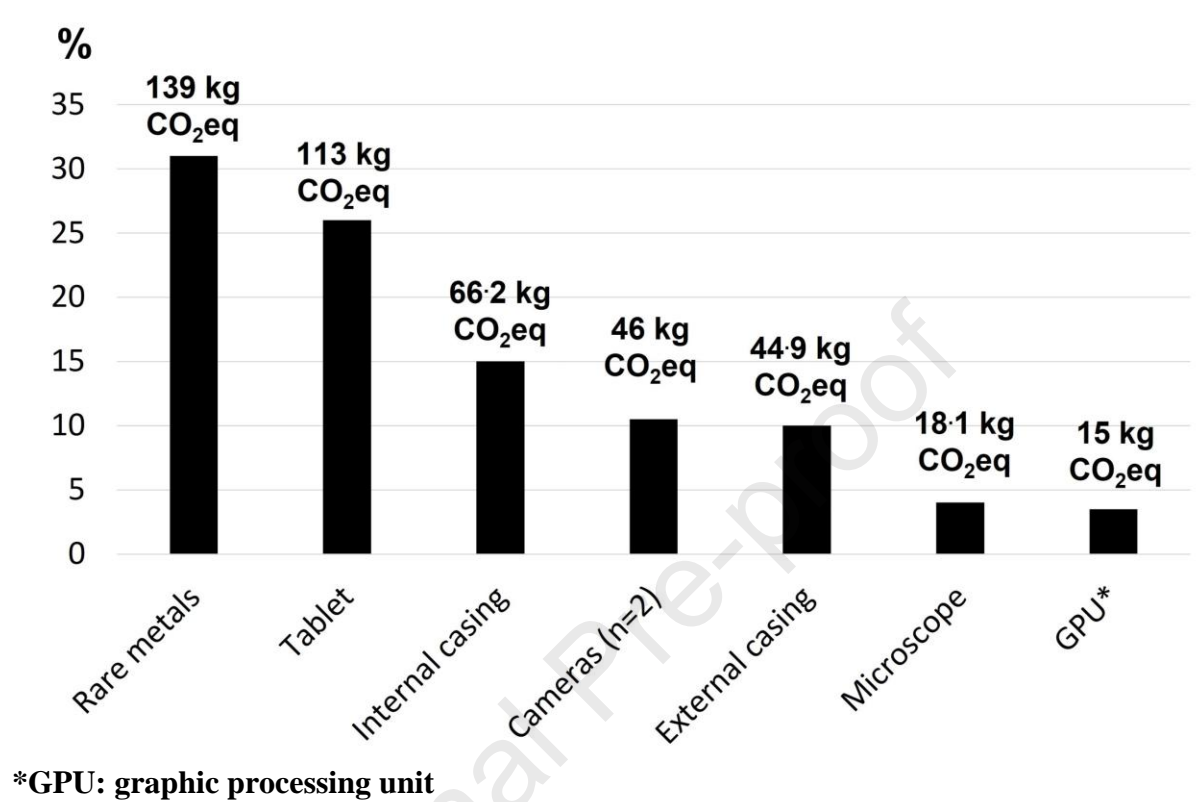
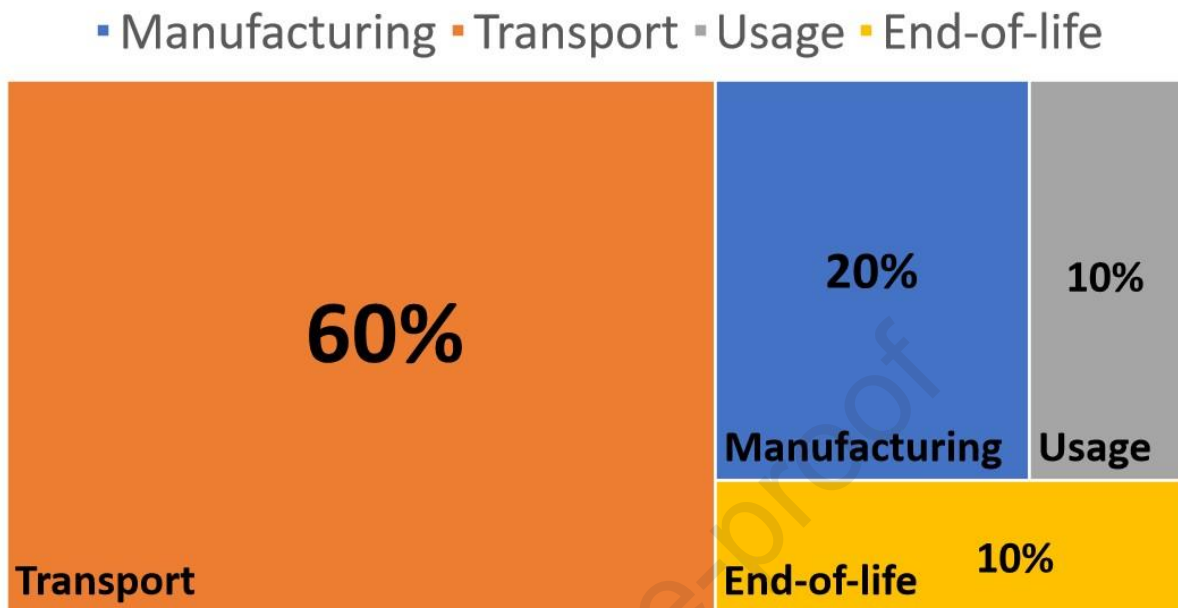


Fig. 3: Carbon footprint of components of 500 scanners for the 100% digital pathology scenario in France.



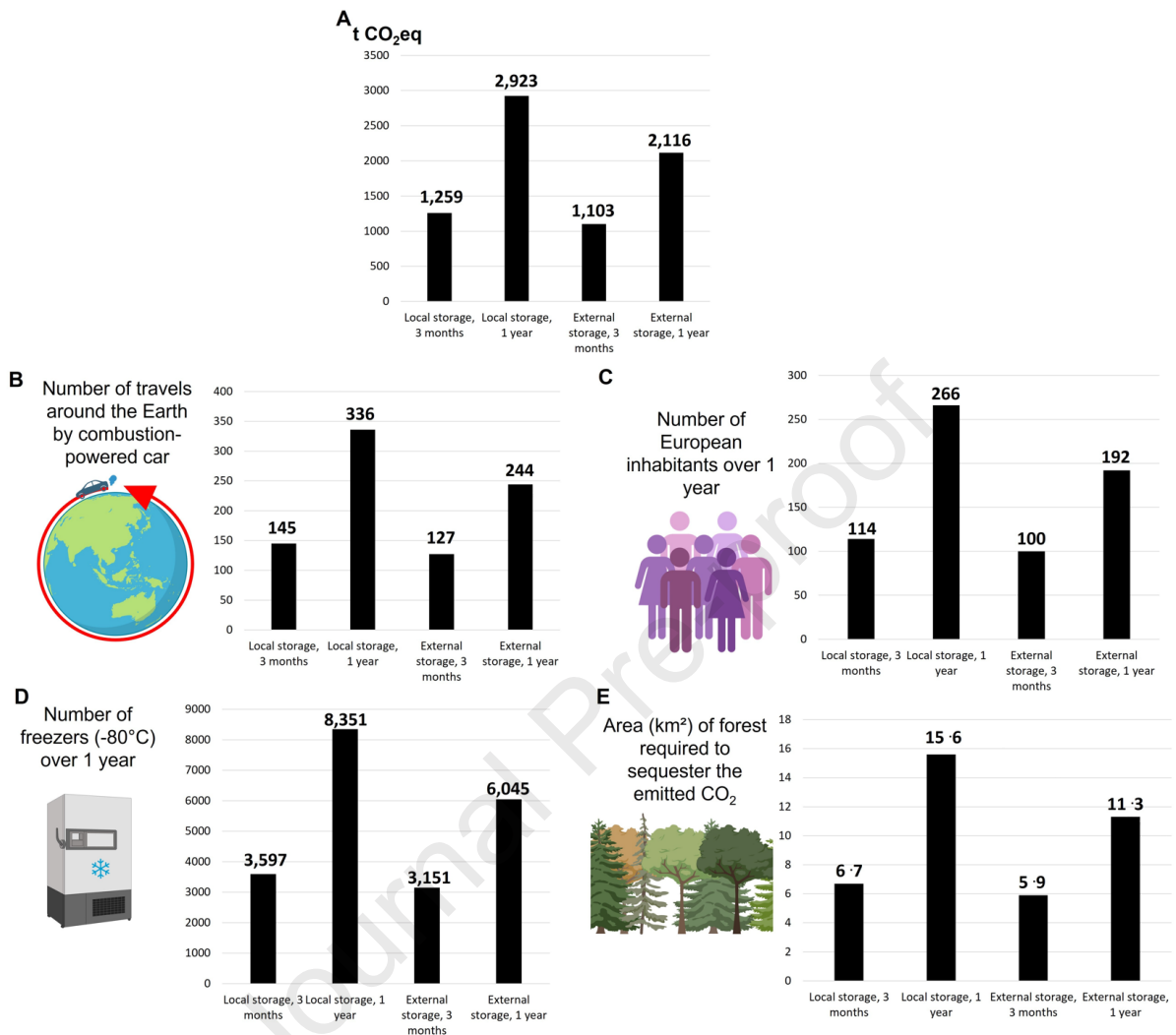
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