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Review

Cadaver models for cardiac arrest: A systematic review and perspectives

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Abstract

Aim: To provide an overview of cadaver models for cardiac arrest and to identify the most appropriate cadaver model to improve cardiopulmonary resuscitation through a systematic review.

Methods: The search strategy included PubMed, Embase, Current contents, Pascal, OpenSIGLE and reference tracking. The search concepts included "heart arrest", "cardiopulmonary resuscitation" and "cadavers". All studies, published until February 2019, in English or French, on research or simulation in the field of cardiac arrest and using cadaver models were eligible for inclusion.

Results: Overall, 29 articles out of the 244 articles located were selected. The characteristics of the studies and the cadaver models were heterogenous. Indeed, 31% of the studies lacked a proper description of the model used and its specificities. Fresh cadavers were used in 55% of the studies and chest compressions were performed in 90%. This model was appreciated for its realism in terms of mechanical properties and tissue conservation. Thiel-embalmed cadavers also showed promising results concerning lung and chest compliance. The lack of circulation stood out as the strongest limitation of all types of human cadaver models.

Conclusion: Four types of cadaver models are used in cardiac arrest research. The great heterogeneity of these models coupled with unequal quality in reporting makes comparisons between studies difficult. There is a need for uniform reporting and standardisation of human cadaver models in cardiac arrest research.

Keywords: Heart arrest, Resuscitation, Cadaver, Cardiac arrest, Cardiopulmonary resuscitation

Introduction

Although progress has been made in cardiac arrest response and management, patients' outcome has barely improved over the last 30 years.[1,2] The fine pathophysiology of cardiac arrest remains unclear, especially the interaction between ventilatory and circulatory support during resuscitation.[3]

Several limits need to be taken into account to explain the complexity of experimental and clinical research in this field.[4] First, cardiac arrest mainly occurs out of hospitals and physiologic parameters change quickly after occurrence, which results in difficulties exploring the pathophysiology of this event. Second, ethical concerns may be an obstacle to research with these patients, who obviously are not able to give their consent prior to the intervention and for whom medical care has to be optimal and efficient.

Abbreviations: CPR, cardiopulmonary resuscitation; HCM, human cadaver model.

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Lastly, the heterogeneity of patients and their precipitating pathologies are also a constraint.

Animal research, mainly on swine models, has provided some translational discoveries but also has several limitations.[5,6] Even if swine, among other animal models, appears to have the most similar thorax shape to humans, the slight differences in chest morphology make it difficult to extrapolate the effect of chest compressions. The differences in global cardiopulmonary physiology also restricts the comparability of the models.[7–9]

Manikin trials are widely used for training purposes in the field of cardiac arrest,[10–12] although the transfer of skills learned on simulation tools into clinical practice is still being discussed.[13,14] Some manikin-based studies also intended to explore cardiopulmonary resuscitation (CPR) pathophysiology.[15] Even if findings obtained on manikin-based studies are sometimes directly extrapolated to clinical practice,[16] this needs to be done cautiously. Manikin models are an approximate representation of physiological observations and measurements made on patients[17] and therefore cannot be used to explore pathophysiology to achieve a better understanding.

Since human cadavers are not typically used for resuscitation training or research, the aim of this review was to reference studies on cardiac arrest or CPR using human cadaver models (HCMs) and to give a complete overview of their characteristics. Potential limiters of an HCM are the condition of the body, how it is stored and prepared, time interval since death and its accessibility. However, HCMs have the potential to provide new information related to the mechanics of CPR, especially when trying to elucidate the mechanisms of interactions between anatomic elements. Additionally, this model allows sophisticated physiologic monitoring that could not be attained in a consistent methodological design in live humans. Finally, HCMs make it possible to explore various resuscitation techniques on the same model, in comparison with animal models which often require a new animal for each test. No systematic review has yet been published on this subject. We therefore aimed to (1) report a precise analysis of the cadaver models used in the field of cardiac arrest research, (2) list the research fields explored in those studies, (3) synthesise the advantages and drawbacks mentioned by the authors of each HCM and finally (4) imagine an ideal HCM based on previous observations.

Methods

Eligibility criteria

Studies concerning the use of a cadaver model to explore cardiac arrest pathophysiology or to assess the effectiveness of a new CPR method, as well as studies using HCMs to simulate cardiac arrest for learning and/or teaching goals, were eligible for this systematic review. Cadaver models used for any fields other than CPR or cardiac arrest and studies on animals were excluded. Cadaver models that could be included in this study were identified through a systematic literature review (Fig. 1). It was conducted in accordance with current guidelines on systematic literature reviews and it complied with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement.[18]

Search strategies and data extraction

Studies were identified through electronic databases. The following key words were used: “heart arrest”, “cardiac arrest”, “cardiopulmonary resuscitation”, “cadaver”. Only articles with the full text available in English or French were selected. No type of document restriction was applied and no methodology filters were used. All studies published until February 2019 were eligible for inclusion. This search was applied to Medline and adapted to Embase, Current Contents and Pascal electronic databases. We also searched the grey literature (Open SIGLE). The precise research approach for identifying potential eligible studies is described in Appendix A. One author (HD) conducted the literature search with the help of a professional librarian (VD) to produce a database of references. Finally, a secondary search was conducted by scanning the reference lists of the original articles retrieved.

Two review authors (HD, GD) independently and blindly screened the titles and abstracts of all the records identified by the search strategy, in accordance with the Cochrane recommendations.[19] For this initial screening, all search results were imported into reference management software and duplicates were removed. The screening process assessed whether the citation: (1) reported data from an original research study using HCMs and (2) focused on cardiac arrest or cardiopulmonary resuscitation. If both criteria were met, the study was considered eligible. The two review authors rated each citation using a “relevant”, “irrelevant” or “unsure” designation. Only full-text articles that received a “relevant” or “unsure” classification from at least one of the two review authors were retrieved for citations. Out of 244 records identified, discrepancies of eligibility assessment between authors were encountered for 14 references. Full-text articles of records identified as being potentially relevant were independently assessed by the two authors for inclusion. Disagreements on eligibility were resolved in discussion between the reviewers. The reasons for excluding studies were recorded. A PRISMA-style flow diagram was drawn to illustrate the process of primary study selection from identification to inclusion in the systematic review (Fig. 1).

The following data were collected for each study eligible when available: the type of cadaver and its characteristics and the intended purpose of the study. We also reported if chest compressions were applied and their modalities, if ventilation was performed, if declotting or perfusion techniques were used and if any other kind of equipment was used on the cadaver. Finally, we looked for any mention of the model’s quality assessment or limitations reported in those studies.

Risk of bias (quality) assessment

To provide an overview of the quality level of the studies included, we used the Cochrane RoB Tool developed by the Cochrane Collaboration[20] to report the risk of bias (Appendix B). This tool evaluates seven different quality domains: (1) random sequence generation, (2) allocation concealment, (3) blinding of participants and personnel, (4) blinding of outcome assessment, (5) incomplete outcome data, (6) selective reporting and (7) other biases. The Cochrane RoB Tool was developed for randomised clinical trials and is not completely adequate for studies on cadaver models which include experimental studies. This means that some aspects of the quality assessment process needed to be adapted to the characteristics of the studies using HCMs. When the risk of bias for a specific domain was considered irrelevant in a given study by the authors, it was graded as “low”. We graded as “unclear risk of other biases” studies lacking a description of the model’s characteristics, preparation or storage conditions in a way resulting in non-reproducible study conditions.

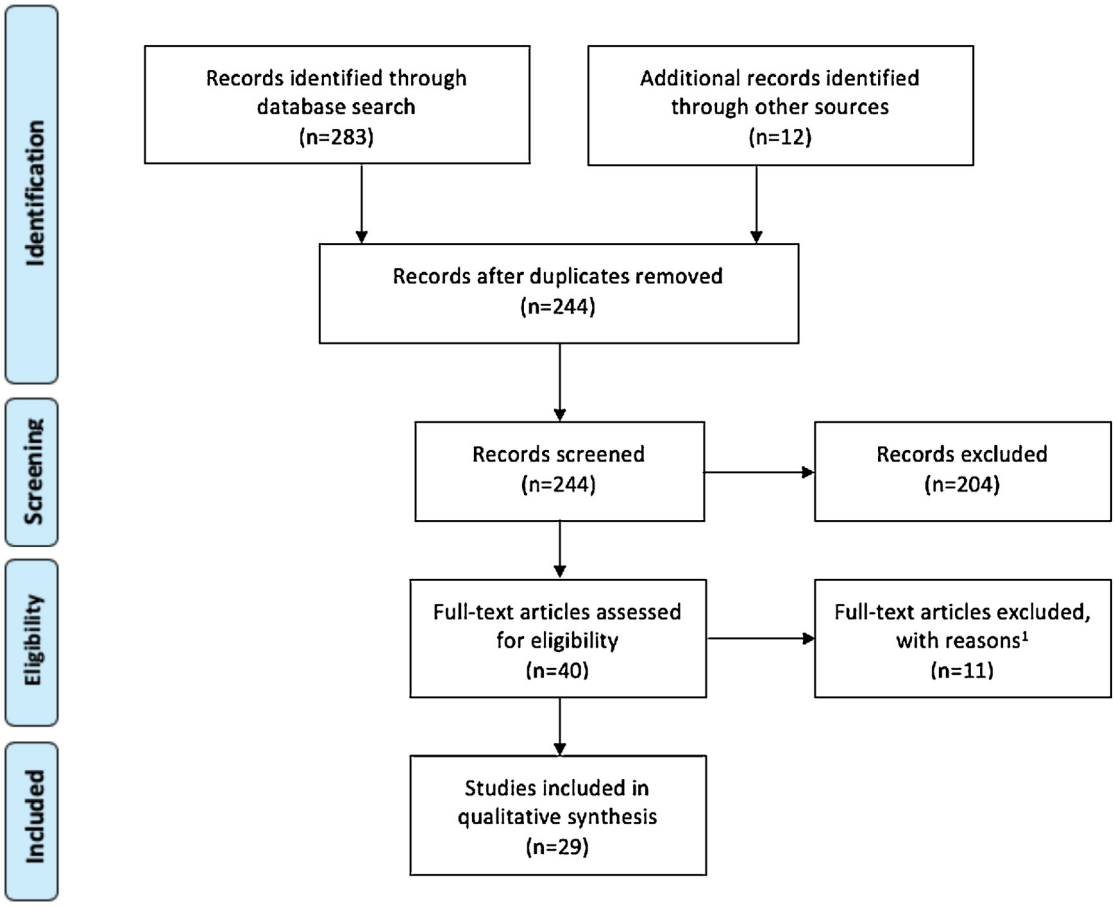

Fig. 1 – PRISMA flow diagram.
[1]Reasons for exclusion: (1) Not about cardiac arrest n = 7.
(2) Not about cadavers n = 1.
(3) References reporting data already included in other studies n = 3.

Statistical analysis

The results were reported as numbers and percentages for categorical variables and means and standard deviations or minimum and maximum values for continuous variables.

Results

Literature search

A total of 283 citations were identified in the database search (Fig. 1). The secondary search yielded 12 additional records, identified from citation and reference tracking. After removing duplicates, a total of 244 studies were screened on the basis of the title and abstract. The full text of 40 articles was retrieved for a more thorough eligibility review. Eleven citations did not fulfil the inclusion criteria and were excluded. Finally, 29 articles were included. Four different cadaver preparation models were used.

Characteristics of the studies included

Sixteen (55%) studies used fresh cadavers, six (21%) used "newly deceased" cadavers, four (14%) used Thiel-embalmed cadavers and three (10%) used fresh-frozen cadavers. No study used formalin-embalmed cadavers. A brief technical description of each model is summarised in Table 1. The number of cadavers used in each study was 12 ± 11. Within studies, interventions were performed several times on the same cadaver with an average number of uses of 6 ± 11 times. The age of cadavers was indicated in 15 (52%) studies, with a mean of 71 years (range, 58–84). Only five studies specified the cadaver storage temperature, four of them used fresh cadavers, not frozen, and cadavers were kept at 4 °C in three of these, one study kept them at 22 °C for a very short time. One study using Thiel-embalmed cadavers mentioned a storage temperature of 20 °C. Ten (34%) studies used automated chest compressions, seven (24%) used manual chest compressions, three (10%) used open chest cardiac massage and four (14%) used a combination of the above. Thirteen (45%) studies used ventilation on cadavers, either manual or mechanical (Table 3).

The studies explored seven main domains: ventilation and airway management, 14 (48%); haemodynamics, five (17%); thoraco(s)tomy, two (7%); mechanical properties of the chest, four (14%); defibrillation safety, two (7%); bispectral index monitoring, one (3%); and intraosseous access, one (3%) (Table 2). All relevant studies were interventional in design.

Table 1 – Models' description.

Type of cadavers	Preservative agents	Time between death and use	Storage	Period of use
Fresh	None	A few hours (less than 72 h usually)	4 °C	Days
Fresh-frozen	None	Days	Ca. −18 °C	Days
Thiel-embalmed	Glycol, various salts, boric acid, chlorocresol, formaldehyde, alcohol	A few months (immersion time)	20 °C	Years
Newly deceased	None	Immediatly after death	None	Hours
Formalin-embalmed	Formaldehyde ± phenol and glycerine	Hours	20 °C	Years

Table 2 – Domains of study.

	Fresh	Fresh-frozen	Thiel-embalmed	Newly deceased
Ventilation and airways' management	Truszewski et al. Truszewski et al. (2) Cho et al. Segal et al. (2) Coats et al. Piegeler et al. Ruetzler et al.	Silvestri et al.	Charbonney et al. Grieco et al. Savary et al.	Davis et al. Langhelle et al. Lufkin et al.
Haemodynamics	Moore et al. Rutty et al.			Wei et al. Rieder et al. Skinner et al.
Thoraco(s)tomy		Hanouz et al.	Puchwein et al.	
Mechanical properties of the chest	Segal et al. Baubin et al. Eichhorn et al.	McKay et al.		
Defibrillation safety	Wampler et al. Lemkin et al.			
Bispectral index monitoring	Fatovich et al.			
Intraosseous access	Szarpak et al.			

Risk of bias within studies

The risk of bias assessment is summarised in Appendix B. The main issue was that considering the main outcome measured, 22 (76%) studies were not able to blind participants to the intervention type. In addition, there was either unclear or no blinding of assessors in 25 (86%) studies. The model description was considered adequate if at least five out of eight of the following criteria were specified in the study: type of cadaver, storage temperature, number of cadavers used, number of uses per cadaver, age, weight, gender and post-mortem time interval. Nine (31%) studies were considered as non-reproducible due to insufficient model description. There was insufficient information on the sequence generation process and/or allocation concealment in five studies (17%). One study[21] seemed to incompletely report its outcomes. Finally, there was substantial (25%) unexplained drop-out in one study[22] and 27% of the data were missing in one of the interventions in a crossover study.[23]

Fresh cadavers

Fresh cadavers entail a human body never frozen or embalmed post-mortem, generally kept for up to 72 h in a refrigerated area and then used for research or teaching. No preparation or declotting is performed. In this systematic review, 16 (55%) studies used fresh cadavers, and these records studied six main research areas: airway management, seven studies (44%);[24–30] mechanical properties of the chest, three studies (19%);[17,31,32] haemodynamics, two studies (12.5%);[33,34] defibrillation safety, two studies (12.5%),[22,35] intraosseous access, one study (6%);[36] and one study explored bispectral index monitoring and used a fresh cadaver for artefact control (6%).[37] The main advantages reported of using fresh cadavers were: its accurate morphology and tissue conservation making it possible, for example, to reflect the conditions of endotracheal intubation, accurately estimate regurgitation risks in humans having CPR, obtain a stable transthoracic impedance over time and characterise thoracic viscoelastic properties. The authors also reported good results in haemodynamic simulations since they were able to measure a pressure rise during chest compressions; one study assessed achievement of venous circulation from a peripheric vessel to pulmonary vessels with automated chest compressions,[34] and another one reported haemodynamic findings similar to pigs during ventricular fibrillation.[33] On the other hand, the limitations of this model were that no right-to-left circulation was achieved, nor left-to-right capillary flow, resulting in blood flow measurement being impossible. Moreover, the authors reported that the loss of vascular tone, the modified biomechanics of the tissues and the modification of lung compliance due to beginning rigor mortis were also limitations to the realism of the model. Finally, one group regretted that human cadavers consisted of elderly patients with a low body mass index, which could reduce the comparability with cardiac arrest patients, and one study decided to use fresh-frozen cadavers because they considered fresh cadavers too expensive.[38]

Table 3 – Studies' characteristics.

References	CC	Ventilation	Perfusion/ declotting	Equipment	Number of cadavers	Age (mean ± SD)	Weight	Post-mortem interval (in hours)
Truszewski et al.	Automated	No	No	ETI	10	18–25[a]	UK	up to 72
Charbonney et al.	Manual + automated	Yes	Yes	ETI	11	81 ± 9	63 ± 13	UK
Szarpak et al.	Automated	No	No	IOD	42	18–65[a]	UK	up to 72
Wampler et al.	Manual + automated	No	No	ECG	2	UK	UK	UK
Rieder et al.	Manual	UK	No	Pressure catheters: ABP, SG	3	UK	UK	0
Truszewski et al. (2)	Automated	No	No	ETI	5	18–65[a]	UK	up to 72
Languelle et al.	Manual	No	No	ETI	12	68 ± 15	80 ± 15	0
Cho et al.	Manual	Yes	No	ETI	1	UK	UK	UK
Fatovich et al.	Manual	No	No	BIS monitor	1	58	UK	48
McKay et al.	Manual	No	No	Sternal plates	6	UK	UK	UK
Segal et al.	Automated + ACD-ITD	No	No	No	9	75 ± 17	66 ± 16	72–96
Baubin et al.	ACD	No	No	No	36	74 ± 24	63 ± 25	22 ± 28
Puchwein et al.	OCM	No	No	No	29	UK	UK	UK
Moore et al.	Automated	Yes	Yes	ETI + pressure catheters: AoP, ICP, ITP	9	84 ± 10	70 ± 14	89 ± 48
Rutty et al.	Automated	No	Yes	No	14	74 ± 17	UK	53 ± 62
Eichhorn et al.	Automated	No	No	No	20	74 ± 13	80 ± 15	70 ± 22
Segal et al. (2)	Automated	Yes	Yes	ETI + pressure catheters : ITP, ABP	7	UK	UK	UK
Coats et al.	Automated	Yes	No	ETI	1	UK	UK	32
Silvestri et al.	No	Yes	No	ETI + IOI + IOD	2	80	UK	36 ± 12[b]
Ruetzler et al.	Automated	Yes	No	Supra-glottic airway device	18	66 ± 12	UK	UK
Piegeler et al.	Manual	Yes	No	Gastric tube	30	69 ± 29	69 ± 26	<3
Hanouz et al.	No	No	No	No	10	UK	UK	UK
Grieco et al.	Automated	Yes	No	ETI + pressure catheter: ITP	3	73 ± 7	68 ± 12	UK
Savary et al.	Yes	Yes	Yes	ETI	2	UK	UK	UK
Wei et al.	Manual	No	No	Pressure catheter: ABP	11	59 ± 11	65 ± 9	0
Lemkin et al.	No	No	No	Defibrillation pads	8	UK	UK	UK
Davis et al.	No	Yes	No	Flow and pressure transducer in ETT	25	63 ± 10	80 ± 15	0
Lufkin et al.	Manual	Yes	No	Radial artery line	10	83	UK	0
Skinner et al.	Manual	Yes	No	ETI	7	UK	UK	0

CC, chest compression; UK, unknown; ACD, active compression-decompression; ITD, impedance threshold device; OCM, open cardiac massage; ETI, endotracheal intubation; IOD, intraosseous device; ECG, electrocardiogram; SG, swan-ganz; BIS, bispectral index; AoP, aortic pressure; ICP, intracranial pressure; ITP, intrathoracic pressure; ABP, arterial blood pressure; IOI, intraesophageal intubation; ETT, endotracheal yube.

[a] Range.

[b] Time between death and freezing was considered.

Fresh-frozen cadavers

Fresh-frozen cadavers consist of human bodies frozen a few hours after death (only one study mentioned the post-mortem interval between death and freezing: 36 h ± 12) and then thawed before use. Like fresh cadavers, no preparation or declotting techniques are used. In this systematic review, three studies used fresh-frozen cadavers (10%), one explored the mechanical properties of the chest (33%),[38] one assessed an open chest cardiac massage device (33%)[39] and one studied ventilation (33%).[40] None of them specified the freezing temperature. One study exploring capnographic waveforms during ventilation pointed out the advantage of the similarity of cadaver models with the low- or no-perfusion state observed in cardiac arrest patients.[40] The authors reported a lack of realism of the lung and chest compliance and the frailty of the cadavers compared to patients or fresh cadavers. Once again, the lack of circulation was found to be a strong limitation of the model since complications

such as bleeding could not be simulated, as well as the lack of a real gas exchange despite ventilation. One study mentioned high cost as a limitation to the number of specimens used and therefore to the power of the study.[38]

Thiel-embalmed cadavers

Thiel-embalmed cadavers are soft-embalmed cadavers using a method described by Thiel in 1992[41] and updated in 2002.[42] It consists in the application of an intravascular injection formula containing glycol, various salts, boric acid, chlorocresol, alcohol and low levels of formaldehyde, and maintaining the corpses submerged for a determinate period of time in the immersion solution in a tank. After immersion, it is possible to maintain the corpses in a hermetically sealed container, thus avoiding dehydration outside the tank. Cadavers embalmed with Thiel methods can be used repeatedly and be preserved for up to 3 years, in contrast with fresh and fresh-frozen cadavers. In this review, four studies used Thiel-embalmed cadavers (14%), three of them were conducted by the same research team and studied ventilation (75%)[43–45] and one studied thoracotomy training (25%).[46] All the studies included using Thiel-embalmed cadavers were published after 2015, even though this embalming method has been known since 1992. The main advantages reported concerning the use of Thiel-embalmed cadavers were the lifelike aspect of the anatomy and mechanical properties, in particular the preserved elasticity and flexibility of the tissues as well as lung and chest wall compliance and resistance that were found to be comparable to values reported in critically ill patients. In addition, this model also had the advantage of being stable over time in terms of resistance and compliance and reproduces the airway opening and collapse phenomenon observed in cardiac arrest patients. Once again, the lack of blood flow and perfusion was reported by the authors as a shortcoming. Charbonney et al.[44] also mentioned that Thiel-embalmed cadavers seemed to be particularly prone to pulmonary derecruitment. The other disadvantage reported was the fact that Thiel-embalmed method requires expertise available in only certain laboratories.

Newly deceased cadavers

Six records used newly deceased cadavers (21%) to study ventilation and airway management[47–49] and haemodynamics.[21,23,50] These studies were carried out in the minutes following death in ICU and emergency departments, or on organ donors. No description of the models was provided, but the authors report that the cadaver population used could differ from cardiac arrest patients given that most of the subjects died of multiorgan failure or had severe pulmonary complications before death. One study noted that the model was found to be unstable over time.[50] As for ethical concerns, four studies reported or implied that informed consent was not required by ethics committees, one study mentioned that permission was obtained with the permit for organ retrieval[50] and consent of the family was obtained in one study.[23] Interestingly enough, all studies using newly deceased cadavers except one[23] were published before the beginning of the 21 st century.

Discussion

To our knowledge, this review is the first to describe the different human cadaver models that have been used to date in cardiac arrest research. We found that four different models were used– newly deceased, fresh cadavers, fresh-frozen cadavers and Thiel-embalmed cadavers with the specific advantage and limitations for each model. The majority of the studies were conducted on fresh cadavers.

Understanding the physiology of cardiopulmonary resuscitation during cardiac arrest has been a challenge for many years. Preclinical research in this field is often long and fastidious. Although animal studies have tried to reflect the clinical scenario, these models fail to properly simulate human cardiopulmonary pathophysiology. Likewise, manikin simulation cannot be extrapolated with certainty to patients in cardiac arrest because it is only a representation of physiological observations and measurements taken on patients. It has been shown that the results obtained on manikins may fail to translate to actual out-of-hospital cardiac arrest patients.[51–53] This might be a root cause for the negative results of many clinical studies with promising experimental findings.[54–57] High-quality post-resuscitation care is the key component to improve survival with good neurological outcome.[58,59] Human cadaver models provide new perspectives in resuscitation research through their ability to enable sophisticated physiologic monitoring that could not be attained in a clinical setting. In addition, their human morphology allows researchers to overcome anatomical differences which might burden animal studies.

The studies included in this review explored two main areas, ventilation and airway management, and haemodynamics. Most studies using Thiel-embalmed cadavers explored ventilation and showed promising results, particularly concerning the similarity of respiratory system behavior with cardiac arrest patients. Haemodynamics was studied using either fresh cadavers or newly deceased cadavers. Three studies measured blood pressure in cadaver models, two of them using newly deceased cadavers were evaluated with a high risk of bias.[23,50] One study with good methodology[33] measured arterial blood pressure in a fresh cadaver model and reported encouraging findings of similar blood pressure curves to those obtained on pigs in ventricular fibrillation. Nevertheless, the lack of circulation was almost systematically reported as a limit to HCM and research in this area should be pursued.

Taking into account the weaknesses and strong points underlined by the authors, we have described an “ideal” cadaver model of cardiac arrest. What seemed important for the realism and accuracy of the model was its lifelike anatomy and tissue conservation as well as similarity with cardiac arrest patients in terms of chest and lung compliance and resistance. Stability over time appeared as another important point to be emphasised given that human cadaver research can be expensive. The lack of circulation was definitely the most common and important limitation of the models described; therefore we suggest that this ideal model should enable left-to-right circulation. To reproduce circulation, the use of a fresh cadaver seemed to be a reasonable option as haemodynamic studies have already reported satisfactory results.[33,34] The drawback of this model, as previously reported, is the lack of embalming, which requires the cadaver to be disposed of after the procedure. Moreover, although it has not been reported in the studies included, prolonged cardiac massage on a perfused cadaver inevitably leads to pulmonary and limb oedema due to the altered vascular permeability of fresh cadavers. An interesting lead to explore could be to try and reproduce circulation on a Thiel-embalmed cadaver since this model shows greater similarities in terms of lung and chest compliance and resistance, with critically ill patients, and is more stable over time compared to fresh cadavers. This has never been done to explore cardiac arrest pathophysiology,

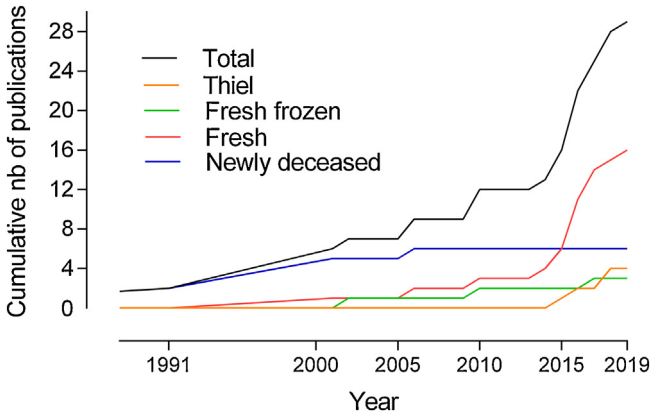

Fig. 2 – Cumulative number of publications related to cadaver studies and cardiac arrest.

but one team has successfully perfused the aorta of a Thiel-embalmed cadaver to simulate aortic endovascular procedures.[60]

Even if human cadavers are not yet traditionally used for resuscitation training or research, it is interesting to note that 60% of the studies included in this review were published in the past 4 years, which confirms a definite trend towards this approach in cardiac arrest research (Fig. 2).

Furthermore, "time for procedure" was found to be the main outcome measured in a fair number of the studies included,[24–26,36,39,46] underscoring the fact that cadaver models are used in feasibility studies to test new medical devices. In extension, this also opens the door to the idea that an HCM could be used for training and education in cardiac arrest management. Indeed, their lifelike features could enable realistic training and simulation of invasive procedures and/or new CPR strategies in a controlled and risk-free environment.

A strong limitation reported by the authors was that cadaver research could be expensive and therefore limits the size of the samples used. We attempted to evaluate the cost of each cadaver model but the literature in this field is poorly documented. We must admit that maintenance of a cadaver lab, storage, technical support, operative equipment and embalming fluids has cost implications that might be too complex to calculate a cost per cadaver. We identified three studies mentioning "preparation" costs of cadaver models, all of them concerning surgical training. Benkhadra et al.[61] estimated the price of a Thiel-embalmed cadaver at about 300 € while Hammer et al.[62] proposed a modified Thiel embalming method which could almost cut the price in half. This modified Thiel method was estimated around 437 €, which is inconsistent with Benkhadra et al.'s findings. Both studies estimated the price of formaldehyde-based cadavers near 30 €. Finally, Mitchell et al.[63] priced a fresh cadaver model between 900 € and 1800 € depending on the presence or absence of the extremities and head, as opposed to a porcine model's cost, which was estimated at 350 € per animal. Comparatively, another study using swine models in burn research estimated the price at 517 € per animal. Once again, this estimation does not include technical support, storage or operative equipment.[64] Cadaver-related costs, however, can be mitigated using the same cadaver for other purposes and by other disciplines. In this way, the Thiel-embalmed cadaver could be the most sustainable model used in these studies because it was found to be reusable after investigation and stable over time.

Finally, an "ideal" cadaver model is probably an unrealistic goal, as no single HCM can encompass the complexity of a cardiac arrest patient. Various models are essential to answer specific research questions. Based on the findings of this systematic review, we consider fresh cadaver models as the most appropriate model to investigate hemodynamic during CPR, even if Thiel-embalmed cadavers have never been tested for this purpose. However, Thiel-embalmed cadavers could represent strong models to study ventilation in cardiac arrest, and it should probably be researchers' first choice for such studies. Investigators should adapt their choice of HCM in accordance with the scientific question at hand, but their methodology must be reported and well documented to enable reproducibility. The lack of uniform reporting limits our ability to compare the results obtained in these studies. Such discrepancy might be further enhanced by the large period of literacy search. Studies that were performed almost 60 years ago substantially differ from the more recent ones, due at least partly to the fact that the methodology of research in this field has greatly improved. Accordingly, comparison might be challenging. Nevertheless, there is a need to standardise cardiac arrest research and reporting on human cadaver models. Ideally, the Utstein-Style Guidelines for Uniform Reporting of Laboratory CPR Research[8] could be adapted to research on cadaver models. These guidelines were published in 1996 with the aim of standardising the reporting of animal cardiac arrest research. Similar guidelines for studies on cadavers might improve comparability and reproducibility of such studies.

Conclusion

Four types of cadaver models were reported, newly deceased, fresh cadavers, fresh-frozen cadavers and Thiel-embalmed cadavers. The majority of the studies used fresh cadavers. Ventilation and airway management was the most common topic explored. The lack of circulation was found to be the main drawback of human cadavers regardless of the type of model. The studies included lacked uniform reporting, which limited our ability to compare the results obtained.

Conflict of interest

The authors declare that they have no conflict of interest in connection with the article.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resuscitation.2019.08.009.

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