Anaesthesia 2019, 74, 1138–1146 doi:10.1111/anae.14707

Original Article

The effects of an aviation-style computerised pre-induction anaesthesia checklist on pre-anaesthetic set-up and non-routine events

S. Jelacic,[1] **A. Bowdle,**[2] **B. G. Nair,**[3] **K. Togashi,**[4] **C. Wu,**[5] **D. J. Boorman,**[6] **K. C. Cain,**[7] **J. D. Lang**[8] and **E. P. Dellinger**[9]

1 Assistant Professor, 2 Professor, 3 Associate Professor, 4 Assistant Professor, 5 Research Assistant, 8 Associate Professor, Department of Anaesthesiology and Pain Medicine, University of Washington, Seattle, WA, USA
6 Production Test Pilot, Boeing Test and Evaluation, The Boeing Company, Seattle, WA, USA
7 Research and Statistical Consultant, Office of Nursing Research and Department of Biostatistics, University of Washington, Seattle, WA, USA
9 Professor, Department of Surgery, University of Washington, Seattle, WA, USA

Summary

This prospective, observational study compared the proportion of cases with missing critical pre-induction items before and after the implementation of an aviation-style computerised pre-induction anaesthesia checklist. Trained observers recorded the availability of critical pre-induction items and evaluated the characteristics of the pre-induction anaesthesia checklist performance including provider participation and distraction level, resistance to the use of the checklist and the time required for completion. Surgical cases that met the criteria for inclusion in the National Surgical Quality Improvement Program at a single academic hospital were selected for observation. A total of 853 cases were observed before and 717 after implementation of the checklist. The proportion of cases with failure to perform all pre-induction steps decreased from 10.0% to 6.4% ($p = 0.012$). There was also a significant decrease in the proportion of cases with non-routine events from 1.2% cases before to none after checklist implementation ($p = 0.003$). In 17 cases, the checklist alerted the anaesthesia provider to correct a mistake in pre-induction preparation.

Correspondence to: S. Jelacic
Email: sjelacic@uw.edu
Accepted: 3 May 2019
Keywords: AIMS:EMR; anaesthesia: checklist; quality measures: patient care
Twitter: @srdjanjelacic; @AndrewBowdle

Introduction

Actions in preparation for anaesthesia can be accidently missed [1]. Checklists are important cognitive aids that have been used in high-risk industries, such as aviation, for decades in an effort to reduce human error [2], and are increasingly being used in medical practice to improve patient care and safety. Haynes et al. demonstrated that a 19-item surgical safety checklist based on the World Health Organization (WHO) guidelines was associated with a significant decrease in postoperative complications and mortality [3]. A systematic review of studies evaluating the use of the original or modified WHO surgical safety checklist further supported the association between fewer postoperative surgical complications and checklist use [4]. Although this checklist addressed some anaesthesia-related items, it did not comprehensively address the critical steps before induction of anaesthesia.

This study tested the hypothesis that the use of an aviation-style computerised version of the Anaesthesia Patient Safety Foundation (APSF) pre-anaesthetic induction

patient safety checklist would be associated with a reduction in missing critical pre-induction items and non-routine events.

Methods

We performed a prospective, observational study over a 10-month period before (October 2014–July 2015) and a 10-month period after (September 2015–June 2016) implementation of an aviation-style computerised pre-induction anaesthesia checklist. Surgical cases meeting the criteria for inclusion in the National Surgical Quality Improvement Program (NSQIP) database were selected for direct observation which facilitated the collection of surgical outcome data. NSQIP cases included general, gynaecological, vascular and otolaryngology procedures. The study was determined to be a quality improvement project by the Institutional Review Board.

Before data collection, two observers, each experienced research coordinators familiar with the operating room environment, received comprehensive training by the investigators. This involved general information about the operating room environment, details of the anaesthetic set-up and familiarity with non-routine events such as anaesthesia equipment malfunction and intravenous (i.v.) catheter failure. The observers shadowed one of the anaesthetist investigators in the operating room before data collection and received additional simulation training and reading materials. Each observer simultaneously collected data with an anaesthetist investigator in 10 cases resulting in average data concordance of 98% between them. The data collected in these 10 cases were for training purposes only and not included in the study analysis.

All anaesthetising locations at our institution use real-time decision support software called Smart Anesthesia Manager, which is an add-on software module on the Anaesthesia Information Management System (AIMS) computer [5]. A new computerised checklist system called Checklist Navigator was developed for this study as a standalone application which interfaced with the Smart Anesthesia Manager to display the checklist items on the AIMS computer monitor and a large centrally located screen mounted on the wall of the operating room. We adapted the APSF pre-anaesthetic induction patient safety checklist for this study and translated it into a computerised aviation-style format (Fig. 1 and Table 1). The checklist was

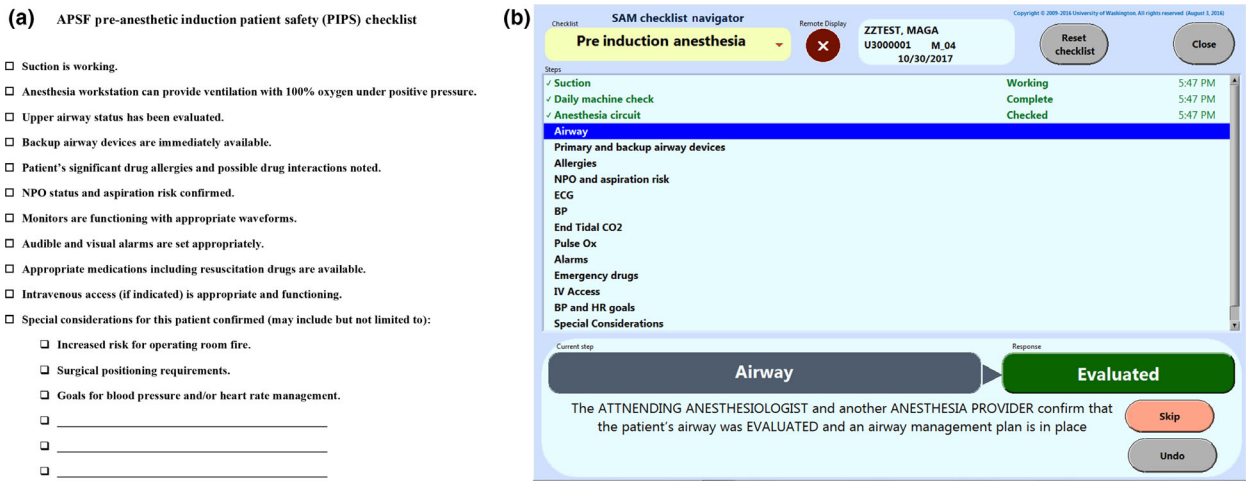

Figure 1 Modifications made to the Anesthesia Patient Safety Foundation (APSF) pre-anaesthetic induction patient safety checklist to create computerised version used for this study. The APSF pre-anaesthetic induction patient safety checklist is shown on the left (a). This checklist was modified by translating each item into 'challenge-verify-respond' format and by separating items that contained several parts into individual components. The item 'Anaesthesia workstation can provide ventilation with 100% oxygen under positive pressure' was translated into 'Daily machine check' and 'Anaesthesia circuit'. The 'Monitors are functioning with appropriate waveforms' item was separated into 'electrocardiography, blood pressure, capnography and pulse oximetry'. The 'Goals for blood pressure and/or heart rate management' item was moved out of 'Special considerations' and into the main checklist, and an item 'Special considerations' was added to the main checklist. A screenshot of the computerised pre-induction anaesthesia checklist is shown on the right (b). Functionality of Checklist Navigator includes a checklist pull down menu, 'Remote Display' button, a case information window, 'Reset Checklist', 'Close', 'Skip' and 'Undo' button. The current checklist item is highlighted by the place-keeper and also displayed on the bottom of the screen in a large font along with the corresponding action or response and a more detailed description of the item. The font colour of completed items changes from black to green.

Table 1 Pre-induction anaesthesia checklist items with short and full description.

Short description	Full description	Action
Suction	The suction is verified to be connected and WORKING by the ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER	WORKING
Daily machine check	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that the daily internal machine check was performed and is COMPLETE	COMPLETE
Anaesthesia circuit	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that the anaesthesia breathing circuit is present and has been manually CHECKED for proper operation	CHECKED
Airway	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that the patient's airway was EVALUATED and an airway management plan is in place	EVALUATED
Primary and backup airway devices	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that required primary and backup airway devices are AVAILABLE. There is at least one supraglottic airway, at least two working laryngoscopes and an intubating stylet	AVAILABLE
Allergies	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER recite and CONFIRM any clinically-relevant allergies (deliberate repetition of SCOAP 1[a])	CONFIRMED
Fasting and aspiration risk	The patient's fasting status and aspiration risk is CONFIRMED by the ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER	CONFIRMED
Electrocardiography	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that there is an appropriate ECG tracing ON the monitor	ON
Blood pressure	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that a blood pressure cuff is on the patient and the monitor is set to take a BP at an appropriate interval. There is at least one BP measurement ON the monitor	ON
Capnography	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that there is an end-tidal CO_2 tracing ON the monitor	ON
Pulse oximetry	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that there is a pulse oximetry signal ON the monitor	ON
Alarms	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that the monitor alarms are ON and alarm limits are SET	SET
Emergency drugs	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that at least adrenaline, ephedrine, atropine, and phenylephrine are AVAILABLE	AVAILABLE
i.v. access	The ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER confirm that the i.v. access is in place and FUNCTIONAL	FUNCTIONAL
Blood pressure and heart rate goals	BP and HR goals if any have been discussed and SET by the ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER. If no specific goals have been discussed, the BP and HR goals may be SET by default at 'routine' levels	SET
Special considerations	Any special considerations not already discussed should be DISCUSSED now by the ATTENDING ANAESTHESIOLOGIST and another ANAESTHESIA PROVIDER	DISCUSSED

[a]SCOAP 1, Surgical Care and Assessment Program checklist part 1 (modified World Health Organization surgical safety checklist performed before induction of anaesthesia at our institution); i.v., intravenous.

incorporated into the Checklist Navigator and displayed by pressing a hotkey on the AIMS computer keyboard. The pre-induction anaesthesia checklist was performed by two anaesthesia providers (e.g. an attending anaesthetist and a resident or certified registered nurse anaesthetist) or, on rare occasions, by an anaesthesia provider and a nurse. The checklist was read from the screen by one provider while the second provider confirmed the presence or correctness of each item. The provider reading the checklist completed each item by clicking on the response button with a mouse or by touching the screen. Before implementation, the Checklist Navigator system was introduced in multiple forums (grand rounds, staff meetings, etc.) to all anaesthesia providers who were also required to view a training video (available at https://youtu.be/gthHVU1i4Ks). For each instance of using a pre-induction anaesthesia checklist, the performed actions and the documented responses were time stamped. These audit data were automatically associated with the corresponding AIMS anaesthesia record of each procedure and stored in an encrypted Checklist Navigator database.

The primary outcome was defined as missing one or more pre-induction items in each observed case. The secondary outcome was the presence of a non-routine event [6] related to pre-induction items (either anaesthesia equipment malfunction or i.v. catheter failure) from the

time that the patient entered the operating room until induction was completed. Potential cases were identified the day before surgery by reviewing the surgical schedule. Anaesthesia providers were notified by e-mail of the study procedures and the presence of observers in advance. Once the case was identified, one of the observers entered the operating room before the patient's arrival while the anaesthesia provider was performing the pre-operative assessment and transporting the patient to the operating theatre. The observer remained in the operating theatre until 15 min after the anaesthesia ready time (defined as the time at which the anaesthesia provider handed the patient over to the surgical team). The observers introduced themselves as 'APSF study observers' during the surgical sign-in performed before induction of anaesthesia. The observer checked for the presence of back-up airway devices and resuscitation drugs within the anaesthetic trolley, date and time of the most recent anaesthetic machine leak test displayed on the anaesthetic machine screen and suction functionality before the patient arrived in the operating theatre. The specific backup airway devices (supraglottic airway, bougie, second laryngoscope and bag-valve-mask) and resuscitation drugs (phenylephrine, ephedrine, adrenaline, atropine and succinylcholine) are part of standard set-up per our departmental guidelines. The observer also confirmed that the i.v. was functional when turned on by the anaesthesia provider and for the presence of the electrocardiogram, pulse oximetry and capnograph waveforms before induction (see also Supporting Information, Figure S1). Ensuring the presence and functionality of these pre-induction items is standard practice at our institution. The observers verified the presence and functionality of each pre-induction item which did not require clinical expertise. However, they did not observe if the anaesthesia providers themselves checked for the presence and functionality of these pre-induction items. Observers also recorded non-routine events during their presence in the operating theatre which included anaesthesia equipment malfunction or i.v. catheter failure. It is important to note that 5 out of the 16 pre-induction anaesthesia checklist items could not be independently verified by the observers: 'Airway', 'Allergies', 'nil-by-mouth and aspiration risk', 'Blood pressure and heart rate goals' and 'Special considerations' (Table 1). These items are cognitive tasks performed as part of the pre-operative evaluation and planning, which might not be evident to the observers. Therefore, the primary outcome measure (missing one or more pre-induction items) included 11 of the checklist items but did not include the 5 items representing cognitive tasks.

Following the implementation of the checklist, observers followed the same data collection process as during the pre-checklist data collection period. In addition, the observers recorded descriptive measures including the checklist performance level ('completely' = all checklist items read and verified; 'partially' = some checklist items read and verified; or 'not performed' = none of the checklist items read and verified), participation level ('excellent' = both anaesthesia providers participating; 'fair' = one anaesthesia and one non-anaesthesia provider participating; or 'poor' = only one anaesthesia provider participating) and distraction level (none, 'minimal' = for example, beeper or phone ringing in the background; 'moderate' = for example, provider answering phone call or a question by operating room staff unrelated to checklist; or 'numerous' = more than 1 distraction occurring at the same time). If the anaesthesia provider performed the pre-induction anaesthesia checklist from memory or not at all and marked each item as completed in the Checklist Navigator after induction, the checklist was considered not completed. It was considered partially completed if the item was marked 'skipped', but the anaesthesia provider did not return to the skipped item to ensure that all checklist items were completed before induction. Observers also recorded any resistance to the performance of the checklist, the time required to perform it and whether the use triggered the anaesthesia provider to correct a problem related to a checklist item.

The sample size for this study was determined by the availability of NSQIP cases during the study period. Descriptive statistics are presented as number (%) or mean ± SD unless otherwise specified. The primary outcome measure was binary and defined as missing one or more pre-induction items in each observed case. Baseline characteristics were compared using two-sample Student's t-test with the assumption of unequal variance (Satterthwaite's degrees of freedom) or chi-square, as appropriate. A control (Shewhart) chart was created showing biweekly proportions of cases with one or more missing pre-induction items before and after checklist implementation. Logistic regression was used to compare the proportion of cases with one or more missing pre-induction items before and after checklist implementation. We controlled for potential confounding variables using a more liberal criterion (p value < 0.20) between pre- and post-intervention periods. To account for the clustering effects of surgical cases within the attending anaesthetist, we chose a generalised estimated equation logit model using the exchangeable correlation structure or an equal correlation model. Effects are

presented as OR between groups with 95%CI. Since there were only 10 cases with a non-routine event before, and none after, the checklist implementation, the sample size was too small to use a model including multiple covariates, or to control for clustering. Therefore, Fisher's exact test was used to compare non-routine events (secondary outcome) before and after the checklist implementation. Values of $p < 0.05$ were considered statistically significant. All statistical comparisons were performed using STATA version 11.0 (StataCorp LP, College Station, TX, USA).

Results

A total of 853 cases were directly observed before, and 717 after implementation of the checklist. Patient characteristics were similar before and after implementation except for body mass index (BMI) and anaesthesia team type (Table 2). Using a more liberal criterion ($p < 0.20$) to identify potential confounders, two additional potential confounding variables (age and emergency surgery) were identified. The use of the checklist was associated with a 31% decrease (from 10.0% before to 6.4% after checklist implementation) in the proportion of cases with one or more missing pre-induction items after controlling for age, BMI, emergency surgery and anaesthesia team type (OR 0.60, 95%CI 0.41–0.90, $p = 0.012$, Fig. 2). There were 89 observed missing pre-induction items in 85 out of 853 (10.0%) cases (81 cases with a single missing item and 4 cases with 2 missing items) before, and 50 missing pre-induction items in 46 out of 717 (6.4%) cases (42 cases with a single missing item and 4 cases with 2 missing items) after checklist implementation (Table 3). A post-hoc analysis showed that the decrease in proportion of cases with one or more missing pre-induction items did not significantly differ between anaesthesia team types (anaesthesia attending with certified registered nurse anaesthetist vs. anaesthesia attending with resident, $p = 0.242$).

There was a significant decrease in the proportion of cases with non-routine events from 10 out of 853 (1.2%) cases before, to none after checklist implementation ($p = 0.003$, Table 4). In addition, in 17 cases, the performance of the checklist resulted in the anaesthesia provider correcting a mistake in pre-induction preparation (Table 5). The checklist was completely performed in 569 (79.4%) cases, partially in 24 (3.3%) and not performed at all in 124 (17.3%) cases. In 18% of cases in which the checklist was completed, a single anaesthesia provider performed the checklist alone. The level of distractions during checklist performance was none or minimal in 472 (79.6%) and moderate or numerous in 121 (20.4%) out of 593 cases in which the checklist was completely or partially performed. The participation level was excellent in 423

Table 2 Patient characteristics and case variables before and after pre-induction anaesthesia checklist implementation. 'Other' procedure type includes non-general and non-gynaecological procedure cases as well as cases with combined general and gynaecological procedures. Values are mean (SD) or number (proportion).

	Before pre-induction anaesthesia checklist n = 853	After pre-induction anaesthesia checklist n = 717	p value
Age; years	52.4 (14.3)	53.5 (13.9)	0.12
Sex; male	241 (28.3%)	191 (26.6%)	0.48
BMI; kg/m^2	31.8 (10.4)	33.0 (11.1)	0.04
ASA physical status			
1 and 2	384 (45.0%)	315 (43.9%)	0.67
3 and 4	469 (55.0%)	402 (56.1%)	
Emergency	7 (0.8%)	12 (1.7%)	0.12
Procedure type			
General	510 (59.8%)	452 (63.0%)	0.42
Gynaecological	328 (38.5%)	254 (35.4%)	
Other	15 (1.7%)	11 (1.5%)	
Anaesthesia team type			
Attending with CRNA	519 (60.8%)	406 (56.6%)	0.04
Attending with Resident	324 (38.0%)	292 (40.7%)	
Attending solo	10 (1.2%)	19 (2.7%)	

ASA, American Society of Anesthesiologists; BMI, body mass index; CRNA, Certified Registered Nurse Anaesthetist; i.v., intravenous.

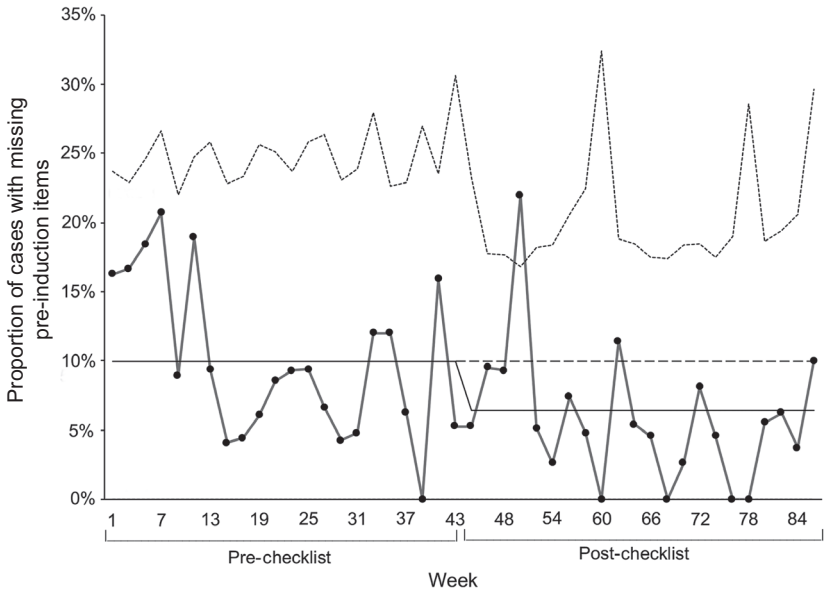

Figure 2 Control (Shewhart) chart showing bi-weekly proportions of cases with missing one or more pre-induction items before and after pre-induction anaesthesia checklist implementation. Solid centre line represents mean, whereas the top dashed line represents upper control limit. The dashed centre line in the post-checklist period represents pre-checklist period mean. Control limits were calculated for each bi-weekly period by adding or subtracting 3 SD to and from the mean. The single data-point outside of the upper control limit is due to much lower number of cases during that particular bi-weekly period.

Table 3 Observed missing pre-induction items before and after pre-induction anaesthesia checklist implementation. There were 81 cases with a single missing item and 4 with 2 missing items before, and 42 with a single missing item and 4 with 2 missing items after pre-induction anaesthesia checklist implementation. Values are number (proportion).

	Before pre-induction anaesthesia checklist n = 853	**After pre-induction anaesthesia checklist n = 717**	**p value**
Second laryngoscope	27 (3.2%)	15 (2.1%)	
Bag valve mask	21 (2.5%)	11 (1.5%)	
Suction	11 (1.3%)	4 (0.6%)	
Machine leak test	7 (0.8%)	0	
Bougie	6 (0.7%)	5 (0.7%)	
Capnography	5 (0.6%)	7 (1.0%)	
Phenylephrine	3 (0.4%)	0	
i.v. catheter	3 (0.4%)	0	
Supraglottic airway	2 (0.2%)	2 (0.3%)	
Blood pressure	2 (0.2%)	2 (0.3%)	
Ephedrine	1 (0.1%)	0	
Pulse oximetry	1 (0.1%)	0	
Succinylcholine	0	0	
Electrocardiogram	0	0	
Adrenaline	0	1 (0.1%)	
Atropine	0	3 (0.4%)	
Total missing items	89	50	
Total cases with missing pre-induction items	85 (10.0%)	46 (6.4%)	0.012

i.v., intravenous.

(71.3%), fair in 135 (22.8%) and poor in 35 (5.9%) out of 593 cases. There were only 5 out of 593 (0.8%) cases in which the anaesthesia provider was resistant to performing the checklist. The mean time to perform the pre-induction anaesthesia checklist was 38 (29) s.

Table 4 Non-routine events before pre-induction anaesthesia checklist implementation.

	Non-routine event description
1.	i.v. catheter failure: i.v. misplaced during induction requiring replacement
2.	Anaesthesia equipment malfunction: oxygen sensor failure alarm on anaesthesia machine screen noted after tracheal intubation requiring oxygen sensor replacement
3.	Anaesthesia equipment malfunction: pulse oximetry not working properly during induction due to poor waveform requiring sensor and cable replacement after induction
4.	i.v. catheter failure: i.v. not functioning properly during induction requiring manipulation and replacement after induction
5.	i.v. catheter failure: i.v. misplaced during induction requiring replacement before induction; additional i.v. placed after induction
6.	Anaesthesia equipment malfunction: poor pulse oximetry waveform requiring sensor and cable replacement after induction
7.	i.v. catheter failure: i.v. misplaced If so state after induction requiring replacement and additional i.v. catheter placement
8.	i.v. catheter failure: i.v. catheter fell out immediately after induction as it was not secured properly, requiring replacement
9.	i.v. catheter failure: Second i.v. catheter fell out before induction requiring replacement by 3rd i.v. catheter after induction
10.	i.v. catheter failure: i.v. misplaced shortly after induction requiring replacement

i.v., intravenous.

Table 5 Pre-induction issues corrected by anaesthesia provider while performing pre-induction anaesthesia checklist.

Pre-induction issue	Number of cases n = 17
Capnograph (not functional – lack of waveform)	4
Blood pressure (not set to automatic mode)	3
i.v. catheter (not functional)	3
Suction (not functional)	3
Machine leak test (not performed)	2
Pulse oximetry (not functional – lack of waveform)	1
Pulse oximetry (low reading – oxygen flow off)	1

i.v., intravenous.

Discussion

Our results strongly argue for the routine use of a pre-induction anaesthesia checklist, especially when the mean time to complete the checklist was only 38 s. Although the anaesthesia machine check process has evolved from being paper and memory based [7, 8] to an automated checkout procedure built into modern anaesthesia machines, the rest of the pre-induction preparation is highly reliant on the anaesthesia provider's memory. There were previous proposals for the development of a more comprehensive pre-induction checklist that would address deficiencies in set-up [1, 9]. A survey-based APSF pre-anaesthetic induction patient safety checklist improved the performance of the pre-induction set-up in a simulation environment [10]. Our study has now demonstrated the utility of similar checklist in a clinical environment.

We chose to implement the pre-induction anaesthesia checklist in computerised rather than paper form and to apply aviation checklist design principles. Our Checklist Navigator software facilitated the availability of the checklist on the AIMS computers at all of our anaesthetising locations, eliminating potential problems such as misplacing a paper card. Using a paper card or poster to perform the checklist may have yielded similar results, but we did not test this. Computerised checklists have been shown to reduce specific errors associated with paper checklists in aviation [11]. Computerised anaesthesia checklists have been described but only studied in a simulation environment [10, 12, 13].

There are important features of an aviation-style computerised checklist which distinguish it from simply placing a static image of a checklist on a computer screen. The key features are an automated cursor that helps to prevent missed checklist items ('place-keeping') and font colour change that distinguishes between complete and incomplete items. Place-keeping also promotes resuming the checklist at the correct place if the checklist performance process is interrupted. Another advantage is access to multiple checklists including routine, emergency and specialty-specific checklists. Our version of the WHO surgical safety checklist operates within Checklist Navigator [14]. We also developed checklists specific to transcatheter aortic valve replacement that can be easily accessed via Checklist Navigator (see also Supporting Information, Figure S2). Others have proposed checklists specific to cardiac procedures which could be computerised in a similar manner [15–17].

There were seven i.v. catheter malfunctions out of 10 non-routine events before the implementation of the checklist. Following implementation of the checklist, in which there is a specific item calling for verification of i.v. catheter function, there were no non-routine events. In US hospitals, the majority of i.v. catheters are placed in the pre-operative holding area by nurses rather than by anaesthesia providers. Our results clearly show the need for anaesthesia providers to carefully check the function of the i.v. catheter immediately before induction of anaesthesia, especially if they did not place the i.v. catheter themselves.

This study has several limitations. There was a decrease in the proportion of cases with missing pre-induction items that occurred several months before the implementation of the pre-induction anaesthesia checklist, as shown in Fig. 2. We do not know why but one possibility is a Hawthorne effect caused by the anaesthesia providers recognising the type of data being collected by the observers. Another is a specific change in anaesthetic practice, staffing or some seasonal effect. A barcode-based drug safety system [18] was introduced at all anaesthetising sites two months after the start of the study and half of our first-year anaesthesia resident class began rotations at our hospital for the first time four months after the start of the study. The implementation of the drug safety system might have increased vigilance among anaesthesia providers. Any impact of first-year residents would likely be minor since they staffed only a few of the study cases. Despite this decline, all of the non-routine events occurred before the checklist, whereas no non-routine events occurred following introduction. Other limitations include observer bias, lack of randomisation and performance of the study in a single centre. The presence of observer bias after checklist implementation is a possibility and could have contributed to the improvement in study outcomes since the observers might favour under-reporting missing pre-induction items and non-routine events. Randomisation was not feasible because the checklists were made available at all anaesthetising locations simultaneously and restricting the use to particular cases was not practical. The effects of having the same anaesthesia providers use the checklist in some cases, but not in other cases could have confounded the results.

In conclusion, an aviation-style computerised pre-induction anaesthesia checklist, based on a modified version of the APSF pre-anaesthesia checklist, resulted in the correction of mistakes during pre-anaesthetic preparation and was associated with a reduced incidence of missing pre-induction items and non-routine events.

Acknowledgements

The authors wish to extend their gratitude and appreciation to L. Sissons-Ross for her assistance with data collection and database management. This study was supported by a grant from Anesthesia Patient Safety Foundation. BN holds equity and serves as a technology advisor for Perimatics LLC (Bellevue, WA) which licenses Smart Anesthesia Manager software. Checklist Navigator is a separate application from Smart Anesthesia Manager that functions on its own. Checklist Navigator software is not a commercial product and is not licensed to any commercial entity. No external funding or other competing interests declared.

References

1. DeMaria S, Blasius K, Neustein SM. Missed steps in the preanesthetic set-up. *Anesthesia and Analgesia* 2011; **113**: 84–8.
2. Helmreich RL. On error management: lessons from aviation. *British Medical Journal* 2000; **320**: 781–5.
3. Haynes AB, Weiser TG, Berry WR, et al. A surgical safety checklist to reduce morbidity and mortality in a global population. *New England Journal of Medicine* 2009; **360**: 491–9.
4. Gillespie BM, Chaboyer W, Thalib L, John M, Fairweather N, Slater K. Effect of using a safety checklist on patient complications after surgery. *Anesthesiology* 2014; **120**: 1380–9.
5. Nair BG, Newman S-F, Peterson GN, Schwid HA. Smart Anesthesia Manager™ (SAM)–a real-time decision support system for anesthesia care during surgery. *IEEE Transactions on Biomedical Engineering* 2013; **60**: 207–10.
6. Weinger MB. Human factors research in anesthesia patient safety: techniques to elucidate factors affecting clinical task performance and decision making. *Journal of American Medical Informatics Association* 2002; **9**: 58S–63.
7. Auerbach AD, Murff HJ, Islam SD. Chapter 23. Pre-anesthesia checklists to improve patient safety. 2001. http://archive.ahrq.gov/research/findings/evidence-based-reports/services/quality/er43/ptsafety/chapter23.html (accessed 19/04/2019).
8. Sub-Committee of ASA Committee on Equipment and Facilities. Recommendations for pre-anesthesia checkout procedures. 2008. https://www.asahq.org/resources/clinical-information/2008-asa-recommendations-for-pre-anesthesia-checkout (accessed 19/04/2019).
9. Thomassen Ø, Brattebø G, Søfteland E, Lossius HM, Heltne J-K. The effect of a simple checklist on frequent pre-induction deficiencies. *Acta Anaesthesiologica Scandinavica* 2010; **54**: 1179–84.
10. Wetmore D, Goldberg A, Gandhi N, Spivack J, McCormick P, DeMaria S. An embedded checklist in the Anesthesia Information Management System improves pre-anaesthetic induction setup: a randomised controlled trial in a simulation setting. *British Medical Journal Quality and Safety* 2015; **25**: 739–46.
11. Boorman D. Today's electronic checklist reduce likelihood of crew errors and help prevent mishaps. *International Civil Aviation Organization Journal* 2001; **1**: 17–22.
12. Krombach JW, Marks JD, Dubowitz G, Radke OC. Development and implementation of checklists for routine anesthesia care: a proposal for improving patient safety. *Anesthesia and Analgesia* 2015; **121**: 1097–103.
13. Blike G, Biddle C. Preanesthesia detection of equipment faults by anesthesia providers at an academic hospital: comparison

of standard practice and a new electronic checklist. *American Association of Nurse Anesthetists Journal* 2000; **68**: 497–505.
14. Dellinger EP, Bowdle A, Jelacic S. Modifying the checklist – it needs to be done, but carefully. *Journal of Surgical Research* 2018; **122**: e24–e26.
15. Fernandes P, Cleland A, Bainbridge D, Jones PM, Chu MWA, Kiaii B. Development of our TAVI protocol for emergency initiation of cardiopulmonary bypass. *Perfusion* 2015; **30**: 34–9.
16. Loor G, Vivacqua A, Sabik JF, et al. Process improvement in cardiac surgery: development and implementation of a reoperation for bleeding checklist. *Journal of Thoracic and Cardiovascular Surgery* 2013; **146**: 1028–32.
17. Vakamudi M. Weaning from cardiopulmonary bypass: problems and remedies. *Annals of Cardiac Anaesthesia* 2004; **7**: 178–85.
18. Jelacic S, Bowdle A, Nair BG, Kusulos D, Bower L, Togashi K. A system for anesthesia drug administration using barcode technology: the codonics safe label system and smart anesthesia manager. *Anesthesia and Analgesia*. 2015; **121**: 410–21.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Data collection form used by observers to record missing pre-induction items before and after pre-induction anaesthesia checklist implementation.

Figure S2. Screenshots of three checklists specific to transcatheter aortic valve replacement procedure performed before anaesthesia induction, before incision/puncture and prior valve deployment.