REVIEW

Laboratory automation in clinical bacteriology: what system to choose?

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Abstract

Automation was introduced many years ago in several diagnostic disciplines such as chemistry, haematology and molecular biology. The first laboratory automation system for clinical bacteriology was released in 2006, and it rapidly proved its value by increasing productivity, allowing a continuous increase in sample volumes despite limited budgets and personnel shortages. Today, two major manufacturers, BD Kiestra and Copan, are commercializing partial or complete laboratory automation systems for bacteriology. The laboratory automation systems are rapidly evolving to provide improved hardware and software solutions to optimize laboratory efficiency. However, the complex parameters of the laboratory and automation systems must be considered to determine the best system for each given laboratory. We address several topics on laboratory automation that may help clinical bacteriologists to understand the particularities and operative modalities of the different systems. We present (a) a comparison of the engineering and technical features of the various elements composing the two different automated systems currently available, (b) the system workflows of partial and complete laboratory automation, which define the basis for laboratory reorganization required to optimize system efficiency, (c) the concept of digital imaging and telebacteriology, (d) the connectivity of laboratory automation to the laboratory information system, (e) the general advantages and disadvantages as well as the expected impacts provided by laboratory automation and (f) the laboratory data required to conduct a workflow assessment to determine the best configuration of an automated system for the laboratory activities and specificities.

Keywords: Automation, bacteriology, diagnostic, digital imaging, inoculation, smart incubators, specimen processor, telebacteriology
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Introduction

Diagnostic tests greatly affect healthcare, with approximately 70% of medical decisions dependent on laboratory results [1,2]. During the last decade, most laboratories have encountered several difficulties resulting from the gradual and continuous increase in sample volume with limited budgets and personnel shortages. Thus, laboratories have been forced to optimize their workflow to gain productivity while maintaining analytical quality. Automation was introduced many years ago in several diagnostic disciplines such as chemistry, haematology and molecular biology to increase laboratory productivity and quality. However, the introduction of automation was not considered to be applicable in microbiology for several reasons, including the complexity and variability of sample types, the many different analytical processes and the insufficient volume of samples. Recently the availability of new technologies such as identification by matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF), the utilization of liquid-based transport devices and laboratory consolidation have triggered the development of automated solutions designed for microbiology [3]. The first automated modules to be launched on the market were automated specimen processors. The first generations were developed more than 20 years ago, but only third-generation instruments allowing high-throughput and accurate inoculation were successfully introduced into routine diagnostic laboratories. Nowadays, several automated inoculation instruments are available,

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including the Autoplak (NTE-SENER), the InoqulA (BD Kiestra), the Innova (BD), the PreLUD (I2A), the Previ-Isola (bioMérieux) and the WASP (Copan). However, only two main manufacturers, BD Kiestra and Copan, currently provide extended automated systems including specimen processors, conveyors, incubators and digital imaging (Fig. 1).

These extended automated systems include two level of automation: partial lab automation (including the Work Cell Automation (WCA) of BD Kiestra and the WASPLab of Copan) and complete lab automation (Total Lab Automation (TLA) of BD Kiestra). Both partial and complete lab automation are composed of specimen processors and incubators with digital imaging that are connected by a conveyor system, but only the BD Kiestra's TLA provides integrated workbenches with a two-way track system for plate delivery (Fig. 2). BD Kiestra reports that 105 specimen processors and 68 lab automation systems (WCA + TLA) have been installed in routine laboratories; Copan, on the other hand, have installed 325 WASP specimen processors and 23 WASPLabs (Table 1).

The manufacturer I2A is currently developing a partial lab automation system called Recitals that contains a specimen processor (PreLud) and an incubator (Maestro). This system will not be discussed in this review because of insufficient information regarding its implementation in routine clinical laboratories. Over the last few years, bioMérieux also developed a partial lab-automation system called Full Microbiology Lab Automation (FMLA), but the system was never released on the market and the project was recently abandoned.

Here we provide an overview of the BD Kiestra and Copan lab automation systems, including a comparison between the technical features of the different systems, general advantages and disadvantages and impacts on laboratory productivity that may be expected after an implementation of laboratory automation. In addition, we provide an overview of the laboratory parameters and activities that should be considered when choosing an adapted automated system according to laboratories' specific requirements, organization and analytical volumes.

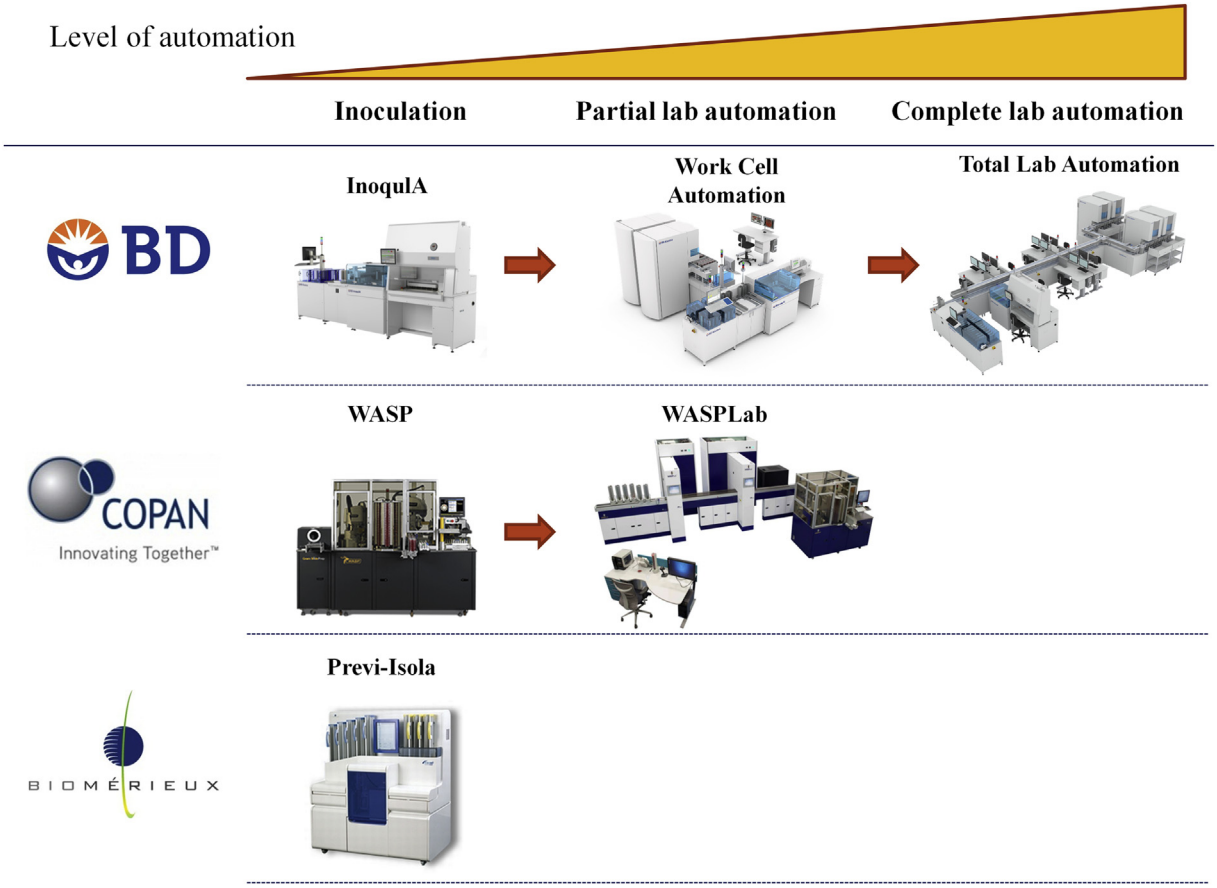

FIG. 1. Levels of automation in bacteriology. Different levels of automation are available from inoculation to partial and complete lab automation solutions. Two manufacturers, BD Kiestra and Copan, provide partial lab automation with WCA (BD Kiestra) and WASPLab (Copan) systems. Complete lab automation is only manufactured by BD Kiestra. Images courtesy of BD Kiestra, Copan and bioMérieux.

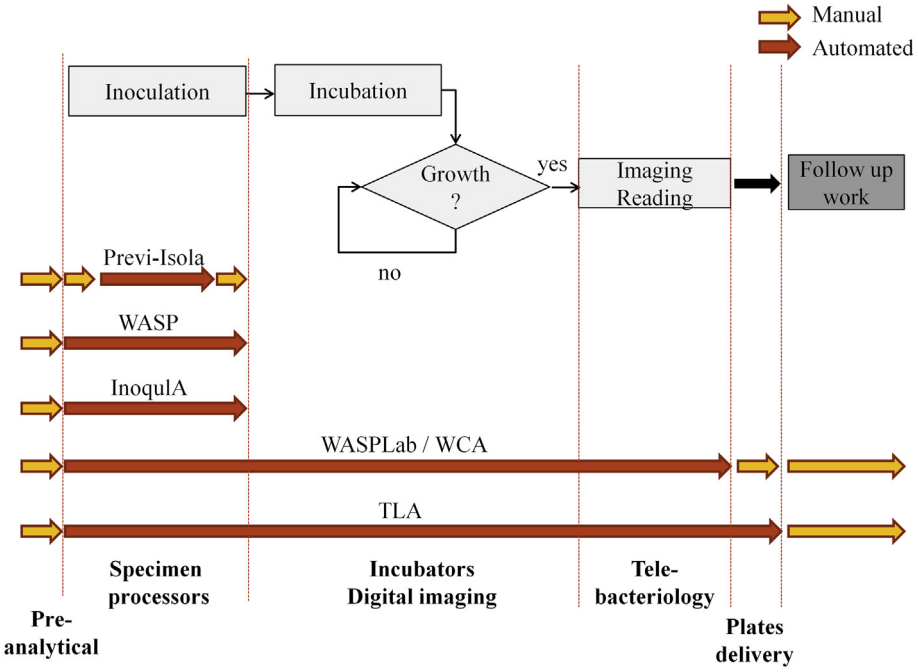

FIG. 2. System workflows. Both partial (WCA, WASPLab) and complete (TLA) automation systems are composed of specimen processors, conveyors and incubators with integrated digital imaging allowing digital reading of plates on computer screens. However, plates delivery directly to workbenches for follow-up work through two-way conveyors is only available with the complete lab automation TLA system (BD Kiestra). In partial automation, plates requiring downstream analysis are delivered to output stackers or carousels and are manually collected by technicians to process at independent workbenches.

Technical features

Systems composition and workflow

The BD Kiestra TLA system is composed of distinct modules including the SorterA (media storage with a capacity of up to 48 different media types and distribution), the BarcodA (barcoding), the InoqulA (specimen processing and inoculation), the ReadA compact (normal atmosphere and CO_2 incubators with digital imaging system) and the ErgonomicA (workbenches). All these modules are linked together by a two-way ProceedA conveyor system (Fig. 3). The number of SorterA/BarcodA (maximum 2/TLA), InoqulA specimen processors (maximum 2/TLA), ReadA compact incubators (maximum 6/TLA) and ErgonomicA workbenches (maximum 12/TLA) can be adapted to the laboratory requirements (Table 2). The specificity of the TLA compared to other laboratory automation systems is that plates can be directly delivered to the technician at the workbench in about 30 seconds and sent back to the system from the workbench through the two-way ProceedA track system (Fig. 3).

TABLE 1. Number of installed systems, August 2015

System	BD Kiestra	Copan
Specimen processors	105	325
Lab automation systems	68	23 (34)[a]
No. laboratories	173	243

Data validated by manufacturers.
[a]Eleven WASPLab pending installations.

The partial automation WCA from BD Kiestra is composed of the same elements but without integrated ErgonomicA workbenches and with a one-way ProceedA track system (Fig. 4). However, the WCA system includes independent software-integrated stations for plate image reading and follow-up work. The plates are delivered to output stacks and picked up manually by the technician for follow-up work. The distribution of the plates to the different output stacks can be organized according to user-defined protocols such as specimen types and downstream applications (e.g. identification (ID), antibiotic susceptibility testing (AST), incubation in external incubators, archives). The WCA is provided as a fixed factory-designed system including one to three ReadA compact incubators, thus exhibiting reduced flexibility for laboratory integration compared to the TLA system, and with a maximum storage capacity of 12 media types. However, the choice of two WCA systems instead of one TLA could be a cost-efficient

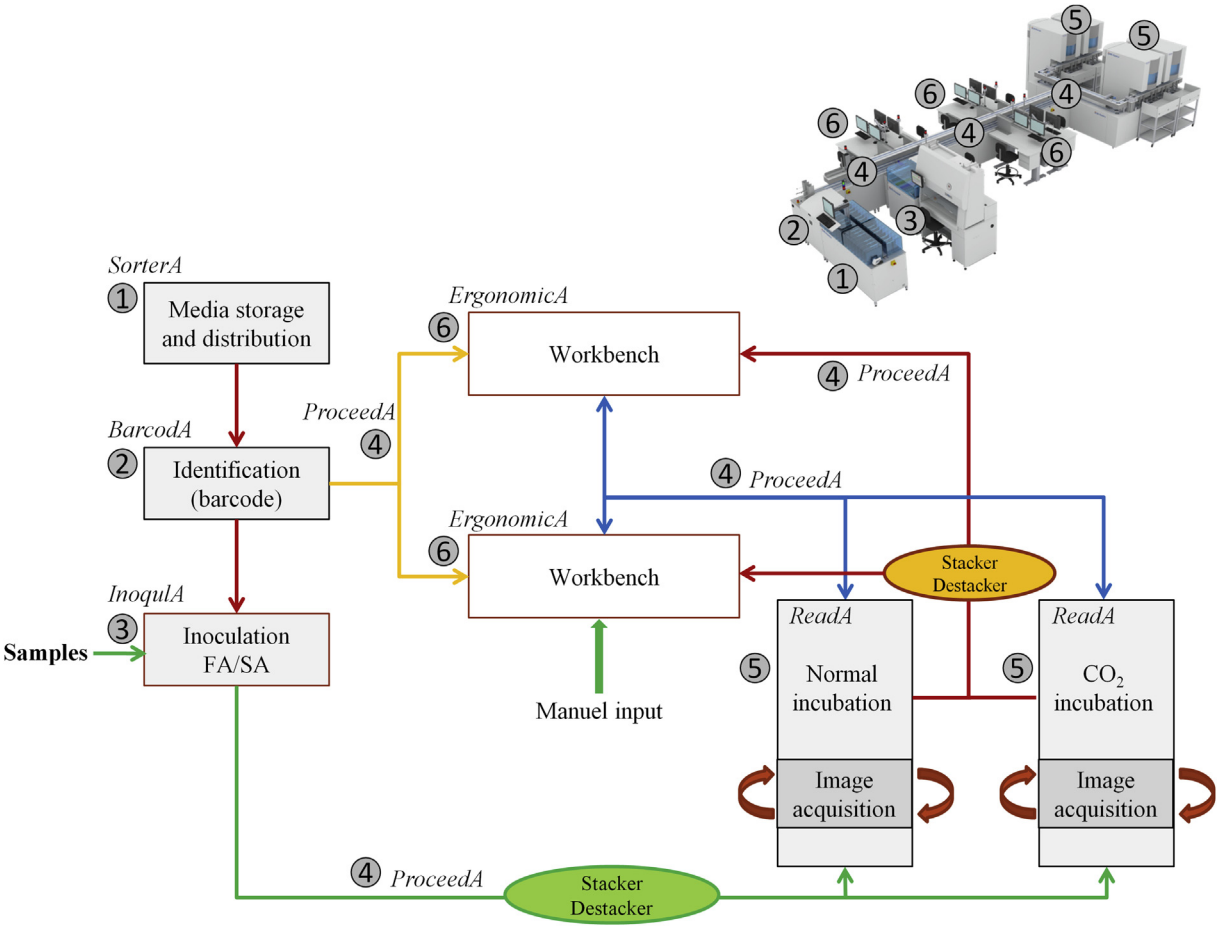

FIG. 3. TLA system workflows. The TLA system is composed of several modules including (1) SorterA (media storage and distribution), (2) BarcodA (barcoding for plate identification), (3) InoqulA (specimen processing and inoculation), (4) ProceedA (two-way modular conveyor system), (5) ReadA compact (incubators with integrated digital imaging system) and (6) ErgonomicA workbenches. All components of TLA are linked by a two-way ProceedA conveyor system. ProceedA delivers barcoded plates from SorterA/BarcodA modules to InoqulA for fully automated (FA) or semi-automated (SA) inoculation or to workbenches for manual inoculation of specific specimens or for subculture of growing microbial colonies. The ProceedA conveyor system connects InoqulA and ErgonomicA workbenches to ReadA compact incubators for plate incubation and imaging. Plates that require downstream follow-up work are directly delivered via the ProceedA conveyor system to workbenches in about 30 seconds for downstream applications such as ID and/or AST. These plates can be sent back to incubators for additional incubation and imaging with the conveyor system. Similarly, plates incubated in external incubators such as anaerobic cultures can be inserted into the system for plate imaging. The ProceedA conveyor system includes stacker/destacker hubs that regulate workflow of plates to avoid system congestion. ProceedA is composed of modular elements that allow flexible configuration of the system to adapt it to laboratory specific surfaces. Incubators exhibit a separated input, output and imaging three-layer track system. Image courtesy of BD Kiestra.

option, with the possibility of a backup solution in case of failure of one of the two systems. However, this option needs to use two independent ReadA browser softwares, which likely increases the complexity of the sample workflow.

The WASPLab is composed of the WASP (Walk Away Specimen Processor for specimen processing and inoculation) and incubators (normal atmosphere and CO_2) that are linked by a one-way conveyor system (Fig. 5). Similar to the WCA, plates are delivered to output stacks (or a carousel) within 20 seconds and are picked up manually for follow-up work. Moreover, the WASPLab system also includes independent software-integrated workbenches for plate image reading and follow-up work, including a colony picking station. Similar to the BD Kiestra WCA, the distribution of the plates to the different output stacks (or carousel) can be organized according to several parameters, such as specimen types and/or downstream applications. The maximum different media types capacity of the WASPLab is nine media types per WASP specimen

TABLE 2. Laboratory automation configurations

System	BD Kiestra TLA	BD Kiestra WCA	Copan WASPLab
Specimen processors	1–2 (SorterA, BarcodA, InoqulA)	1 (SorterA, BarcodA, InoqulA)	1–2 WASP
Incubators	1–6	1–3	1–3 (single or double capacity)
Integrated workbenches	1–12	NA[a]	NA[a]
No. media types	Up to 48	12	9–18

Data validated by manufacturers.
NA, not applicable.
[a]Several types of workbench can be software integrated with the BD Kiestra WCA and the Copan WASPLab, such as interpretation or reading bench, follow-up workbench and picking bench.

processor. Like the TLA BD Kiestra, the number of WASP specimen processors and the number and/or capacity of incubators can be adapted to the laboratory's needs (Table 2). In addition, an optional return conveyor can be added to the WASPLab to deliver plates from downstream input stackers and/or adjacent workbenches back to the incubators. However, the added value of this return conveyor compared to a conventional input carousel located upstream of the incubators remains to be determined. Moreover, the WASPLab can be connected to an Inpeco sorting system that will sort microbiology, chemistry and haematology tubes according to the requested analysis and deliver *via* a tracking system the specimen tube to the laboratory automation module.

Finally, plates incubated in external incubators such as anaerobic cultures can be inserted into the BD Kiestra or the WASPLab laboratory automation systems for plate imaging and subsequent screen reading. Similarly, plates inoculated by automated specimen processors can be directed to output stacks or a carousel for external incubation such as anaerobic and/or fungus cultures.

Future developments

The two manufacturers are planning to release in the near future automated colony-picking modules with the ability to process the sample for both ID (by MALDI-TOF) and AST.

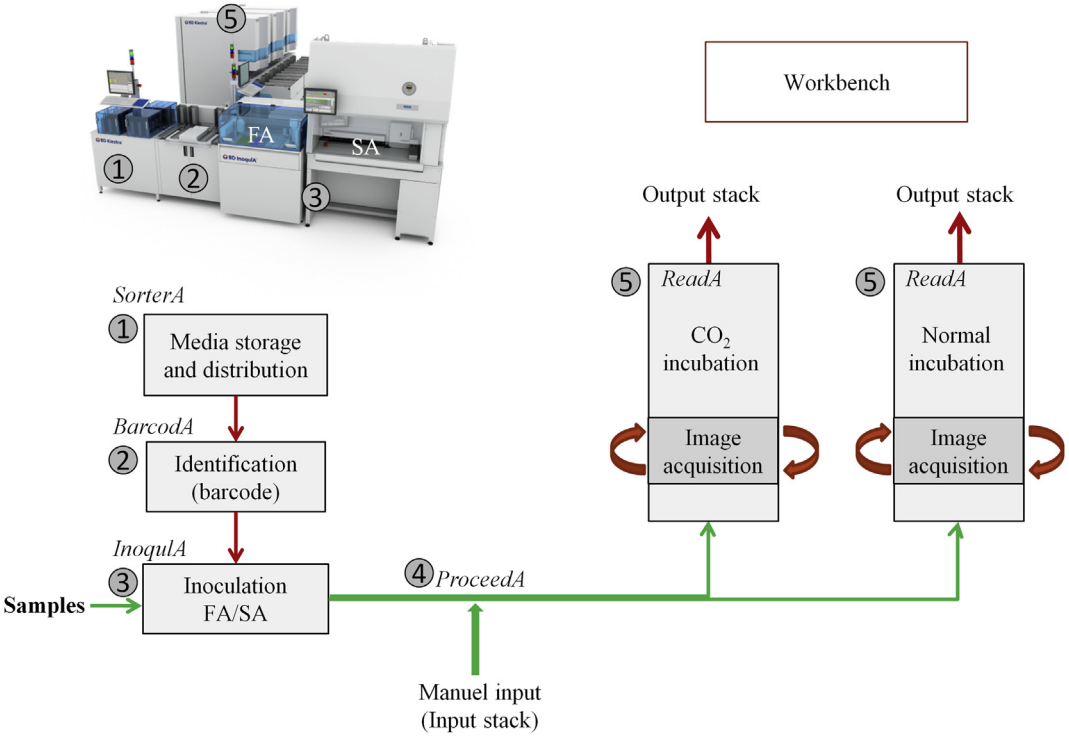

FIG. 4. WCA system workflow. Similar to TLA, the WCA system is composed of several modules including (1) SorterA (media storage and distribution), (2) BarcodA (barcoding identification), (3) InoqulA (specimen processing and inoculation), (4) ProceedA (conveyor system) and (5) ReadA compact (incubators with integrated digital imaging system). However, unlike TLA, WCA is not including integrated workbenches, is composed of one-way ProceedA conveyor system and is only provided with one SorterA/BarcodA/InoqulA module with maximum capacity of 12 different media types. Plates exiting incubators are distributed to output stacks according to user-defined features such as specimen type or according to downstream applications. Plates that have been manually inoculated are inserted into the system via an input stack for automated incubation and digital imaging. Similarly, plates incubated in external incubators such as anaerobic cultures can be inserted into the system for plate imaging. This system is less flexible than TLA and only exists in one configuration with one to three incubators. FA, full automation; SA, semiautomation. Image courtesy of BD Kiestra.

Such automated colony-picking modules will have a major beneficial impact on laboratory workflow and will improve the quality by allowing standardized sample applications on MALDI plates and by largely reducing the risk of sample inversion, estimated to occur in up to 3% of the applications [4]. The Copan prototype module (Colibri) streaks a direct smear of the selected colony on a MALDI plate and prepares a bacterial suspension from other sister colonies for subsequent disk diffusion AST assays. Unlike Copan, the BD Kiestra module will prepare a bacterial suspension from the picked colony or colonies which will be used as template for both the application of the sample on a MALDI plate (Mantlo *et al.*, paper presented at 115th General Meeting American Society for Microbiology, 2015, abstract P-1045) and for AST assays.

Both BD Kiestra and Copan are developing fully automated disk diffusion AST. The WASP, equipped with an antimicrobial disk application element, is able to inoculate agar plates from bacterial suspensions (prepared manually or, in the future, with the automated colony-picking module) and to dispense antimicrobial disks. A study performed with an automated

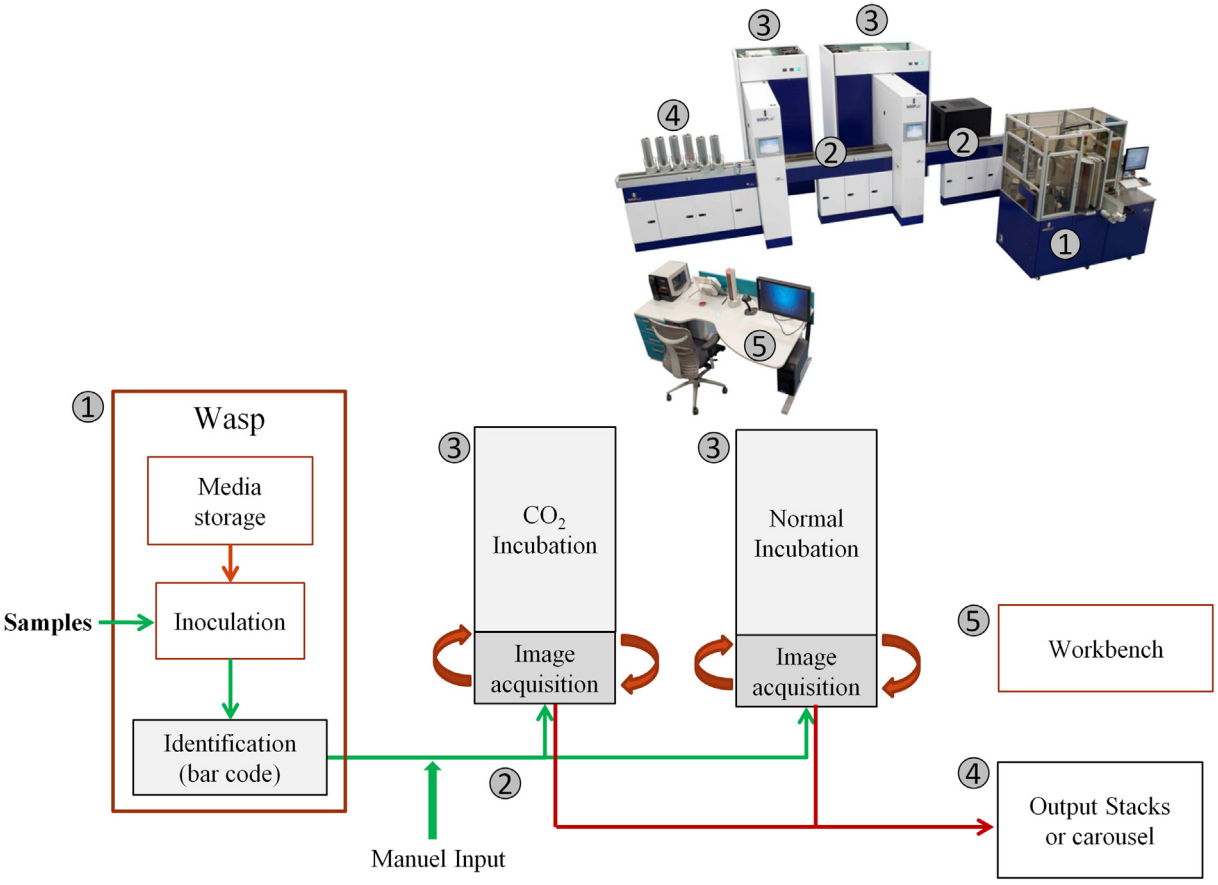

FIG. 5. WASPLab system workflow. WASPLab is composed of (1) the WASP, (2) a one-way conveyor system and (3) incubators with single (882 plates) or double capacity (1764 plates). Similar to WCA, workbenches are not integrated to the automated system, and plates requiring follow-up work are distributed to (4) output stacks (or to an output carousel) according to user-defined features such as specimen type or according to downstream applications. WASPLab includes independent software integrated workbenches (5) for plate image reading and follow-up work. The WASP is a multiple-task specimen processor and inoculation module that integrates a media plate storage carousel with a maximum of nine different media types, a barcode reading and labelling system and a loop-based streaking system. Inoculated plates are delivered to incubators for incubation and plate imaging. Unlike BD Kiestra incubators, WASPLab incubators exhibit a single input/output/imaging lane system but with two robotic arms and a tray allowing the system to perform three simultaneous processes. The conveyor is a one-way track system by default, and plates that are manually inoculated or that require additional incubation and imaging are introduced into the system by simple deposition on the conveyor. Similarly, plates incubated in external incubators such as anaerobic cultures can be inserted into the system for plate imaging. Copan is currently working on an input carousel module for increased efficiency and capacity. The system can integrate a second WASP for increased productivity, allowing processing of larger sample volumes and increased maximum capacity, to 18 different media types. Image courtesy of Copan.

WASPLab disk diffusion AST showed that the system exhibited an increased precision and reproducibility of AST measurement compared to manual testing, thus improving the accuracy of AST interpretation while reducing both the hands-on time and the time to results (Hombach, paper presented at the Copan workshop at the 25th European Congress of Clinical Microbiology and Infectious Disease, 2015). Copan is also planning to offer the possibility of inoculating agar plates and directly dispensing microbial disks with the automated colony-picking Colibri module. BD Kiestra is currently developing a dedicated automated disk diffusion AST module for the preparation of bacterial inoculums, plate inoculation and application of antimicrobial disks on agar plates. These systems should be supported by automated zone measurements and advanced expert systems for AST interpretation.

Inoculation systems

The technical features of specimen processors and inoculation systems have been reviewed in two recent publications [3,5]. An update of the InoqulA and the WASP as well as the workflows of specimen processing and inoculation are discussed in this review. The updated technical features of the InoqulA and the WASP are summarized in Table 3. The InoqulA has significantly evolved compared to the previous commercial semiautomated version. The current InoqulA provides full automation (FA) and semiautomation (SA) for manual interaction required for nonliquid specimens such as dry swabs and catheters. In addition, the SA module can be equipped with a microbiologic biosafety cabinet for increased security. The WASP technical features are similar to those previously described [3,5], with no significant changes except internal upgrades of hardware and software to correct errors and weaknesses of the first released specimen processors. The workflow of the specimen processing and inoculation processes are characterized by several differences between the WASP and the InoqulA (Fig. 6). The WASP is designed for continuous sample processing. Additional samples can be added to the WASP without interrupting or pausing the inoculation process, which permits great system flexibility in terms of varying sample volumes delivered to the laboratory throughout the day. On the other hand, adding new samples to the InoqulA FA system requires the inoculation process to be paused. Thus, the InoqulA FA is more adapted to batch-processing samples, whereas the InoqulA SA module can process samples continuously. However, the FA and SA cannot work simultaneously. The SA module has priority over the FA module and thus induces some delay in the FA process when it is used. An integrated automated centrifugation, which is essential for laboratories processing containers that require centrifugation, such as UriSwabs (Copan), is only available with the WASP. The inoculation of enrichment broth can be performed with both the InoqulA and the WASP. However, the InoqulA can inoculate high volumes—up to 250 µL—providing an increased analytical sensitivity similar to the manual procedure, whereas the WASP can only inoculate a maximum volume of 30 µL (Table 3). A study performed in Lausanne comparing manual and WASP

TABLE 3. Technical comparison between InoqulA (BD Kiestra) and WASP (Copan)

Feature	InoqulA	WASP
Method of inoculation	Pipette	Loop (1 µL, 10 µL, 30 µL)
Streaking method	Rolling bead	Loop, spreaders
Consumable/waste	Pipette tip, bead	Reusable loops (30 000 inoculations/loop)
Automatic decapping/recapping	Yes	Yes
No. different media at once[a]	12 (up to 48 TLA)	9 (with easy carousel configuration change)
No. samples at once	Up to 270	72
Continuous loading/unloading of system with specimens	No for FA, yes for SA[b]	Yes
No. plates streaked at once	1 to 5	1
Nonliquid samples	Yes (SA mode)	Yes
Automatic gram slide processing	Yes (optional module)	Yes (optional module)
Automatic broth inoculation	Yes (open platform)	Yes (optional module; Copan tubes 5 mL and 10 mL)
Throughput[c]	Up to 235 inoculations per hour	~130 inoculations per hour (up to 180)
Inoculation volume	10–250 µL	1, 10 and 30 µL[d]
Image inoculum on plate	Yes	Yes (loop)
Sample vortex	Yes	Yes
Sample centrifugation	No	Yes
Possibility to change loop/bead between quadrants[e]	No	Yes
Possibility of using biplates	Yes	Yes
Manual interaction[f]	Yes (SA mode)	No
HEPA filter	Yes	Yes

Data validated by manufacturers.
CFU, colony-forming unit; FA, full automation; SA, semiautomation.
[a]WCA BD Kiestra has capacity of 12 different media types, whereas TLA has capacity of up to 48 media types.
[b]System pause required for FA but not SA module.
[c]Throughput is dependent on number of streaked media types per specimen and on streaking protocols.
[d]Possibility to double inoculum and to sterilize loop between inoculums and/or quadrants.
[e]Inability of InoqulA to use new beads between quadrants does not affect streaking quality as a result of the capacity of this technology to generate single colonies even with high loads of bacteria of 10^{10} CFU/mL and higher.
[f]Sample can be applied on agar plate before streaking in SA module that can integrate a biosafety cabinet. This application is required for nonliquid specimens such as dry swabs and catheters and is coupled to automatic plate selection and barcoding as well as sample barcode scanning.

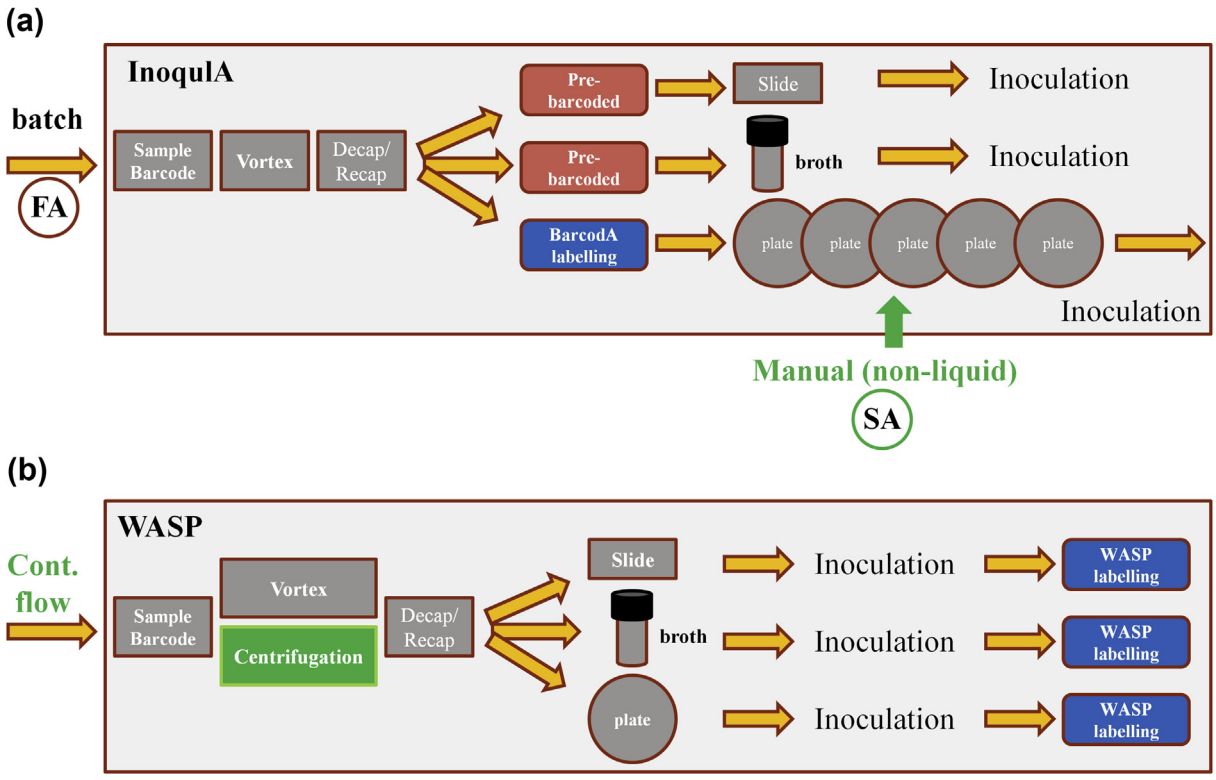

FIG. 6. Workflow of the InoqulA and WASP inoculation systems. (A) The BD Kiestra inoculation system is composed of SorterA/BarcodA/InoqulA modules. InoqulA contains both fully automated (FA) and semiautomated (SA) stations. Specimens are recognized by a barcode reading system and can be vortexed before decapping. Plates labeled by the BarcodA module (blue) and prebarcoded enrichment broth and slides (red) are introduced into the system before inoculation/application with by a pipetting system with liquid-level sensing. InoqulA uses magnetic rolling beads to streak samples on different media types with closed-lid plates for prevention of aerosolization. Five plates maximum can be streaked simultaneously for increased throughput. The SA station (with or without integrated biosafety cabinet) is used to apply nonliquid specimen on media plates before streaking with a rolling magnetic bead. The FA system needs to be paused for insertion of new specimens and is thus more adapted to processing samples in batches. The SA mode is performed in continuous flow. (B) WASP contains a barcode reading system allowing specimen recognition that can be either vortexed or centrifuged before decapping. Samples are inoculated and streaked on media plates with a loop or spreader that reproduces manual streaking with an accurate and fast robotic arm. The loop is also used to inoculate enrichment broth and to apply samples on glass slides for subsequent Gram staining. Unlike SorterA/BarcodA/InoqulA, the WASP labels all samples with an integrated printer after inoculation and streaking (blue). Samples can be continuously inserted into the WASP without pausing the system, which allows great flexibility for continuous processing of varying sample volumes during a workday.

broth inoculation with 300 µL and 10 µL of clinical samples, respectively, showed a 20% reduction of positive enrichment broth with an inoculation of 10 µL (Masciulli *et al.*, paper presented at 70th Annual Meeting and Assembly of the Swiss Society for Microbiology, 2012, abstract P-072). The media plates, enrichment broth and slides are labeled before inoculation and streaking with the InoqulA and after sample processing with the WASP. The difference has no real impact on the workflow, but failure to properly label the sample initiates an interruption of the streaking process of the WASP and requires reinoculation of the sample, which may be problematic for some samples, such as low-volume specimens. However, the WASP labels or prints (i.e. barcode, media type, patient name, sample type) media plates, enrichment broth and slides, whereas manually prebarcoded enrichment broth and slides are required with the InoqulA. Finally, between one and five plates can be streaked simultaneously with the InoqulA, providing an increased throughput for specimens that are streaked on different media plates, compared to the WASP, which processes the plates sequentially. Even though both specimen processors are equipped with HEPA filters, the InoqulA magnetic bead streaking is performed with a closed-lid plate for increased prevention of aerosolization.

Smart incubators

Media plates are automatically delivered to the incubators for storage and incubation, ensuring optimal plate traceability, with barcode reading and indexing as well as improved laboratory workflow, by suppressing manual plate transporting. The ReadA compact and WASPLab incubators are composed of fixed or mobile plate storage carousels, respectively, where each plate is stored in a unique location for rapid imaging and plate delivery upon request for follow-up work (e.g. MALDI-TOF identification, AST, small tests). Compared to conventional incubators, the smart incubators offer constant and uniform T° (laminar flow), which should increase microbial growth efficiency and thus reduce turnaround time (TAT) for microbial detection and identification. Each incubator includes internal automated digital imaging systems that capture plate images with a high-resolution camera using several light sources (front, back, side lights) and imaging conditions (exposure time, brightness). Various imaging incubation times can be processed and defined by the user. However, imaging at time 0 is absolutely required to perform automated algorithmic detection of growth. The resolution of the BD Kiestra ReadA compact high-speed camera is 5 megapixels (Mp), whereas the WASPLab incubator's camera is 48 Mp (three-color CCD). The difference of resolution affects the imaging quality and thus the zoom-in potential for colony observation by telebacteriology, but the added value of high-resolution images has to be counterbalanced by the significant difference in the size of the image files (Table 4), which greatly affects the file-transfer rate and the storage management in the servers of the laboratory automation system and/or of the laboratory. The WASPLab thus requires physical proximity (maximum 80 m cables) to the IT server from the laboratory automation modules to ensure an optimal transfer rate for the large file sizes obtained with a high-resolution camera. Overall, the best resolution and image quality required for on-screen reading by telebacteriology should be defined by the user, but a resolution of 5 Mp appears to be sufficient for the reading of most of routinely analysed plates. Finally, high-definition monitors are required for optimal reading performance of high-resolution plate images.

The incubators exhibit different technical features (Table 4) and architectures (Figs. 7 and 8) which affect workflow and plate management. The ReadA compact incubator is composed of a mobile robotic arm (rotation, up and down) with a static carousel for plate storage (Fig. 7). The WASPLab incubator is composed of a mobile robotic arm (rotation, up and down) and one or two mobile (rotation) carousels for plate storage (Fig. 8). The ReadA compact is characterized by a separated three-layer track system including an input, an output and an imaging track. On the other hand, the WASPLab incubator is characterized by a single bidirectional track system for plate input, output and imaging. However, the WASPLab incubator contains two robotic pitchers and one mobile tray, allowing the system to perform multiple simultaneous operations in the single bidirectional track system, thus limiting the bottleneck that may be expected from such an architecture. Moreover, the ReadA compact contains only one robotic arm, which is likely the major element limiting the throughput of the incubators, independent of the design of a triple-layer track system for plate input, output and imaging. Regarding the WASPLab incubator, the rotation speed of the carousel or carousels, the imaging system and the robotic arm are the elements of the incubator that likely define the maximum throughput of the incubators. The plates' workflow and throughput are greatly dependent on the definition of priority settings of the different tasks performed by the smart incubators. The priority settings for optimal throughput are suggested by the manufacturers but can be user defined according to specific laboratory workflows and local requirements (Table 4). A modification of the priority

TABLE 4. Technical features of ReadA compact and WASPLab incubators

Feature	ReadA compact (BD Kiestra)	WASPLab incubator (Copan)
Capacity (single incubator)	1152 plates	882/1764 plates[a]
Plate loading	600 plates per hour	360 plates per hour
Plate unloading	600 plates per hour	250 plates per hour
Plate loading + picture	300 plates per hour	250 plates per hour
Plate unloading + picture	300 plates per hour	ND[b]
Plate unloading + picture + plate loading (*plates incubated in lab automation incubators*)	150 plates per hour	120 plates per hour
Plate loading + picture + plate unloading (*plates incubated in external incubators*)	163 plates per hour	100 plates per hour
Maximal days of plate incubation[c]	ND	6
Imaging time 0[d]	Yes	Yes
Definition of camera	5 Mp	48 Mp
Size of image files	3 Mb	20–25 Mb
Light sources/background	• Front, back, side lights • No or black background	• Front, back lights • No or black background
Priority settings[e]	• Positive unloading • Imaging (recording) • Loading • Negative unloading	• Positive unloading • Loading • Imaging (recording) • Negative unloading

Numbers provided are maximal throughput measured for stand-alone incubators. Efficiency may be greatly reduced upon connection of incubator to other automated modules. Data validated by manufacturers.
Mb, megabytes; Mp, megapixels; ND, not determined.
[a]Copan incubators can be composed of one (882 plates) or two (1764 plates) carousels for individual plate storage.
[b]Pictures are not taken during unloading step but before, at time 0, and at a given time *x* as defined in incubation protocol. Copan device thus does not provide data regarding this action.
[c]Maximum incubation time tested and guaranteed by manufacturer. According to BD Kiestra, maximum time of incubation is user defined and not limited.
[d]User defined; may depend on types of specimen. However, time 0 is absolutely required for automated algorithmic growth detection.
[e]Suggested by manufacturers for optimal throughput but can be defined by user depending on laboratory specificities.

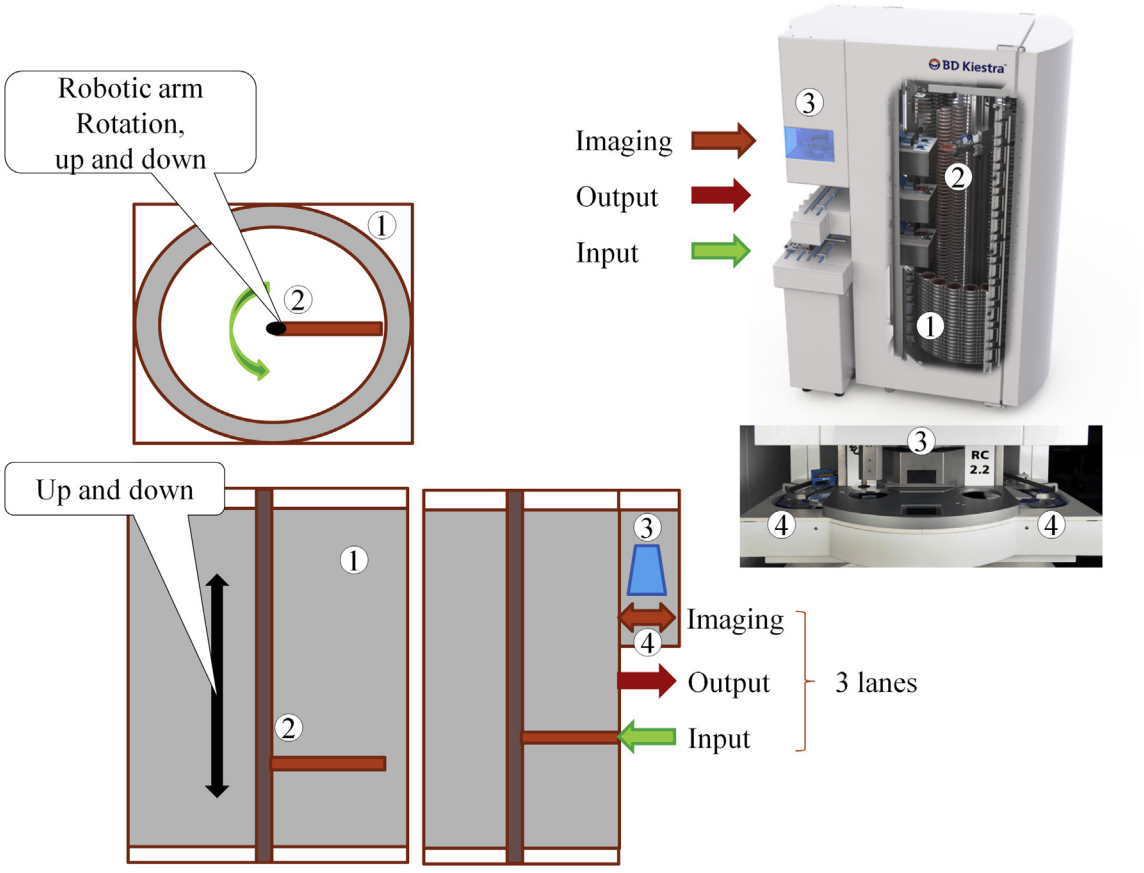

FIG. 7. ReadA compact incubator (BD Kiestra). The incubator is composed of a static carousel for individual plate storage (1), a rotating robotic arm (2) for automated plate sorting and management and an integrated compact imaging system with high-speed camera (3). The incubator exhibits a three-layer track system with input (green arrow), output (red arrow) and imaging (orange two-headed arrow) tracks. The imaging track is composed of a circular conveyor allowing plate queuing before and after imaging for increased throughput (4). The robotic arm is thus the central element that defines maximum throughput of the incubator. Image courtesy of BD Kiestra.

settings can be applied at any time for a quick adaptation of the system upon unexpected changes of laboratory workflow and activity.

Telebacteriology

Telebacteriology is the use of digital imaging and file storage for on-screen reading and decision making. The laboratory has access to a library of digitally recorded images that can be electronically shared between consultants located at different sites; they may also be used as an educational tool. Thus, diagnostic laboratories can create 'reading rooms,' which may offer a comfortable working environment for the reading of the digitalized images. However, such an organization requires a separation of the reading and the downstream applications (i.e. subculture, ID, AST), which should be performed by different technicians for optimized laboratory workflows. Thus, the use of reading rooms requires thorough laboratory organization and communication between technicians to guarantee proper follow-up of microbiologic analyses after reading the plates in a separate room. The images can also be integrated in the patient's files, together with other data, including Gram staining images and clinical information, for improved interpretation of results. Technicians can read the recorded images on high-definition screens and can use several software-based imaging conditions to detect, for instance, bacterial haemolysis (bottom light source) or to improve microbial growth detection (i.e. zoom in, contrast optimization, x-ray output) (Fig. 9). The technician can assign specific follow-up work for each colony by indicating *via* touch screen technology or conventional mouse selection the colonies to use for downstream applications such as MALDI-TOF identification, AST and small enzymatic tests (i.e. oxidase, indole). BD Kiestra and WASPLab have each developed specific software that can provide a sorting of positive and negative plates (BD Kiestra), a growth level classification from high to no growth, allowing efficient plate screening (WASPLab), and measurement of an inhibition zone of disk

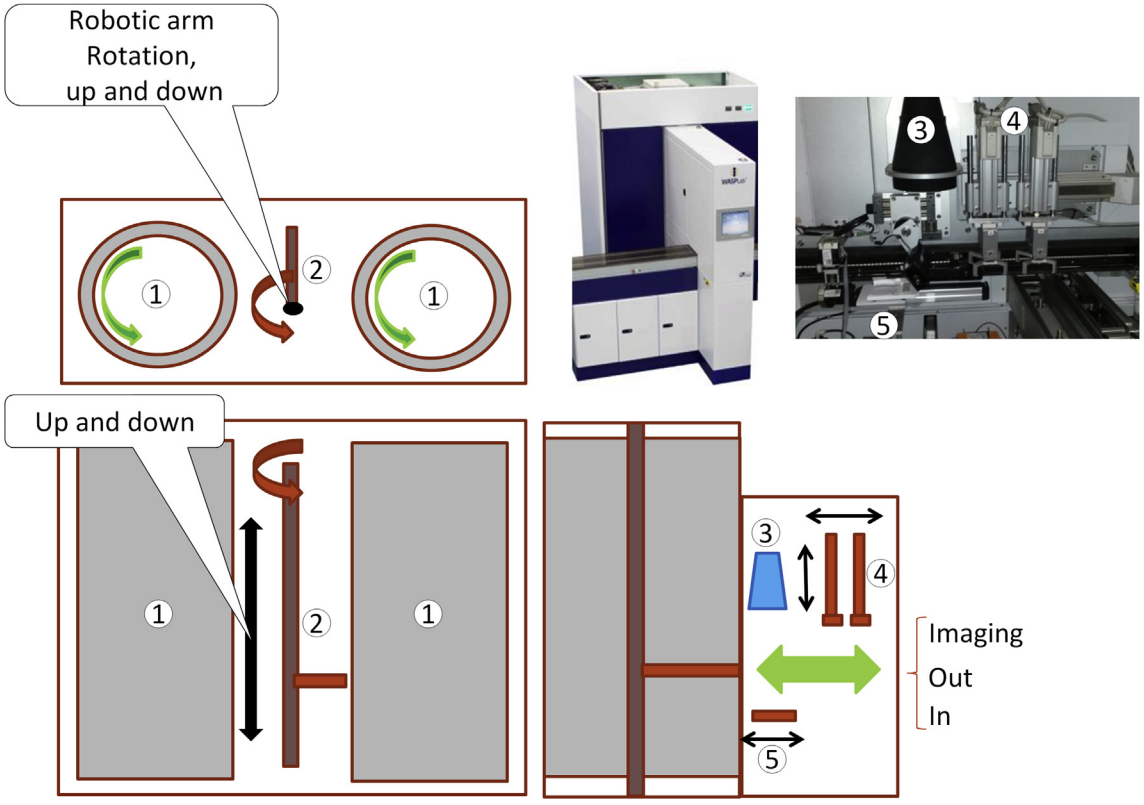

FIG. 8. WASPLab incubator (Copan). The incubator is composed of one or two rotating carousels (1) for individual plate storage and a rotating robotic arm (2) for automated plate sorting and management. The incubator has a one-layer track system for input, output and imaging with a high-resolution camera (3). The single track is composed of multiple elements including two robotic pitchers with lateral and vertical movements (4) and one automated tray (5) used to support plates during imaging and to deliver plates to the internal robotic arm (1). Several actions are thus operated simultaneously in the single input/output track, avoiding plate congestion in this incubator's area. The rotation speed of carousels, the imaging system and the robotic arm are elements that likely define maximum throughput of the incubator. Images courtesy of Copan.

diffusion assays (BD Kiestra and WASPLab softwares). The 'growth–no growth' and chromogenic classification algorithmic engines of the WASPLab have three applications: (a) 'bioactive order' for growth-level classification, (b) 'segregation' for plate image classification according to user-defined bacterial loads thresholds and (c) 'early growth positive notification' for rapid detection of microbial growth from sensitive samples such as cerebrospinal fluid and blood culture specimens. Both manufacturers are currently working on the development of new solutions such as imaging acquisition technologies (Supervised High Quality Imaging (SQHI), BD Kiestra) and image-analysis intelligent algorithms with different future applications such as automated recognition of sister colonies from both chromogenic and nonchromogenic agar, microbial growth quantification and presumptive identification of bacteria species growing on chromogenic agar (Croxatto *et al.* presented at 115th General Meeting American Society for Microbiology 2015; Abstract P-1494. Lacchini *et al.* presented at 25th European Congress of Clinical Microbiology and Infectious Disease 2015; Abstract EP121.). Finally, Copan has developed a 3-D reconstruction image of the recorded plates that will first mainly be used to allow accurate automated colony picking by a module that is under development (Colibri).

Engineering, technology and maintenance

Each supplier has conceived a different interesting engineering solution, depending on the year of conception and the historical release of the different automated systems on the market. The first automated system was launched by Kiestra (now BD Kiestra) in 2006, followed a couple of years later by Copan and then bioMérieux (Table 5). The different elements composing an automated system in bacteriology are divided into three main technical parts: the inoculation system, the incubator or incubators with an integrated digital imaging system and the conveyor.

The BD Kiestra inoculation module is based on a simple engineering solution using a magnetic feature. Thus, the sample is applied with a calibrated pipette (10–250 µL) with liquid level

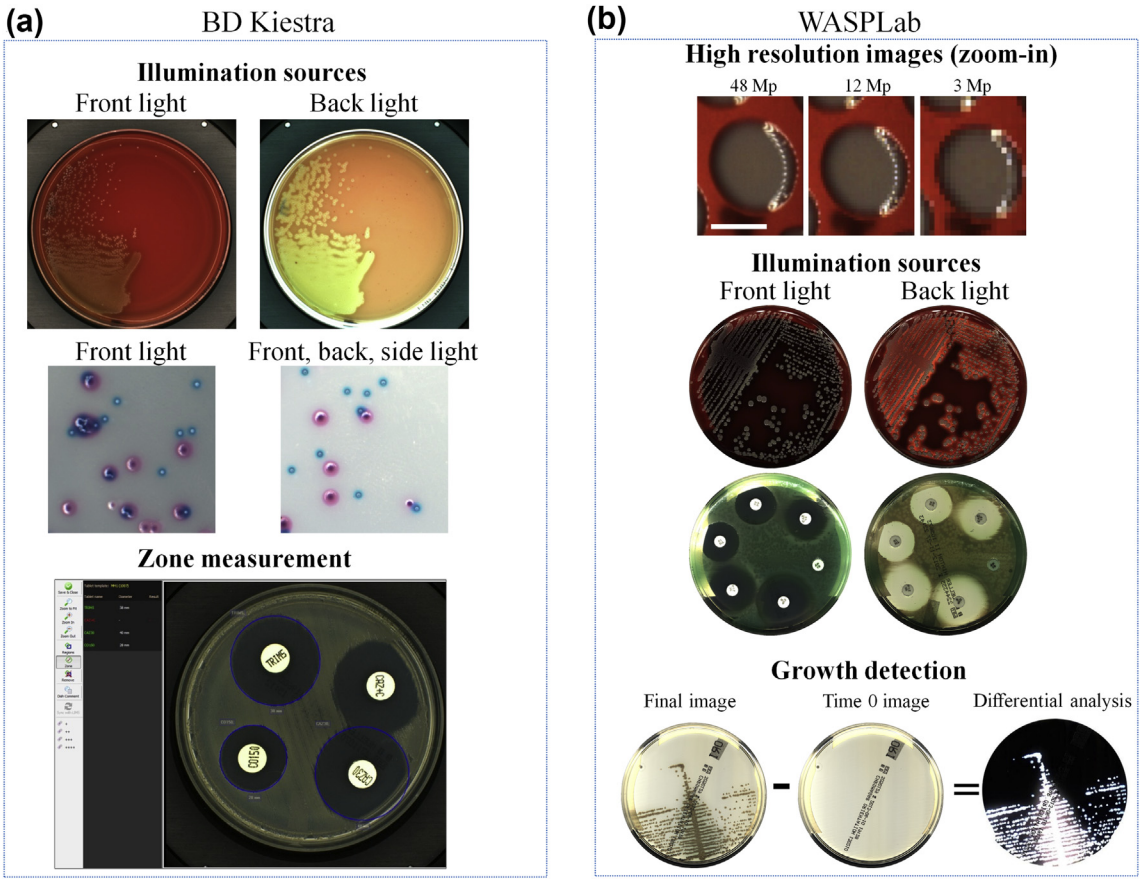

FIG. 9. Plate digital imaging with BD Kiestra and WASPLab. Several light sources and exposure times are used to record plate images for subsequent telebacteriology reading. The two manufacturers dispose of software for zone measurement of disk diffusion assays and growth detection. (A) Examples of plate digital imaging obtained with the BD Kiestra system. Different illumination sources can be used to bring out phenotypic features such as haemolysis on blood agar or colors of colonies on chromogenic agar. Zone measurement of disk diffusion assays (on screen measurement by user-defined or automated measurement) can be performed with the Read Browser interface of BD Kiestra. Similar applications can be performed with the WASPLab software. (B) Examples of plate digital imaging obtained with the WASPLab system. High resolution of the WASPLab imaging system allows sharp images to be obtained upon zooming in on bacterial colonies (scale bar = 1 mm). Several illumination sources can be used to bring out phenotypic features such as haemolysis on blood agar or to facilitate zone measurements of disk diffusion assays. Growth detection is accomplished by an algorithm performing differential analysis between final and time 0 images. A similar approach is used by the BD Kiestra system. Image courtesy of BD and Copan.

sensing and streaked with a single rolling magnetic bead driven by a magnet, allowing simple configuration of multiple streaking patterns. Copan has designed a more complex robotic solution that reproduces the conventional manual loop streaking approach with more restricted volumes (1–30 µL). The WASP solution is more complex than the BD Kiestra InoqulA, but the industrial robotic components provide both high reliability and great flexibility, including multiple streaking patterns, loop sterilization between the streaking on plates, broth inoculation and sample application on glass slides.

Both manufacturers propose automated incubators with an integrated high-definition camera for plate imaging. Copan has designed an incubator in two parts; the first part is dedicated to plate sorting and management, and the second part is largely dedicated to imaging. The various light sources and the camera, with the high-quality optical system (telecentric objective) and three linear sensors of the WASPLab incubators, occupy significant space in the single bidirectional track system for plate input, output and imaging module located at the entrance/exit of the incubator. BD Kiestra has designed a more compact solution with an integrated imaging system with a high-speed camera in the incubator. The different technical characteristics of the BD Kiestra and Copan incubators results in a difference in the plates' workflow, which may lead to definitions of

TABLE 5. Robustness and maintenance

Characteristic	BD Kiestra		Copan
	TLA	WCA	WASPLab
First installation in routine diagnostic laboratory	2006	2012	2012
No. of preventive maintenance per year	2	2	2
Approximate time of preventive maintenance	2–4 days[a]	2–4 days[a]	4–7 hours[b]
MTBF[c]	~100 days	~100 days	~95 days
Cost of full maintenance contract	Variable/customer specific[d]	Variable/customer specific[d]	8–12% of system's cost[e]

Data validated by manufacturers.
MTBF, mean time between failures.
[a]BD Kiestra services the full automation solution at each preventive maintenance (about 2 days for InoqulA and 3–4 days for WCA/TLA, depending on system configuration).
[b]Copan services the full automation solution at each preventive maintenance (2.5 hours per WASP, 1.5 hours per incubator).
[c]MTBF is difficult to provide because it depends greatly on system configuration, system complexity, number and variety of samples processed and user induced factors.
[d]For service/maintenance contract, pricing is customer and site specific (dependent on instrument configuration, options and service level agreement).
[e]Depends on system configuration.

different priority settings for optimal throughput. In addition, the different conceptions of the incubators may lead to different future evolutions. For instance, the WASPLab incubator imaging system is located in an area offering more space for future development compared to the integrated compact BD Kiestra imaging system. This may offer more flexibility to Copan for the development of their imaging system and for the optical features of the camera that may be required for the future development of intelligent algorithms and/or to provide additional features allowing simplified reading of the plates. Finally, the two incubators are equipped with HEPA filters for laboratory security.

The conveyor is the component that will transport the plates between the different modules of the system and to the workbench for the BD Kiestra TLA system. Kiestra was the first company to propose full automation with a two-way conveyor system based on plastic ribbon, pulleys, electric motors and pneumatic elements. The system includes stacker/destacker elements for the regulation and management of the plate on the conveyor. The WASPLab solution is technically simpler, with a one-way conveyor, which is an industrial solution applied to diagnostic laboratory purposes. The conception of BD Kiestra's two-way conveyor system offers more flexibility in plate management without human intervention. WASPLab's conveyor system offers a unidirectional plate transfer from inoculation to output stackers and is thus likely less adapted to the development of a complete lab automation with a two-way track systems, which is not the concept of laboratory automation developed by Copan.

BD Kiestra's conception is mechanically efficient but may require more maintenance than the WASPLab system. Even though the number of preventive maintenances per year is similar between the two manufacturers (Table 5), the time required to perform preventive maintenance may be important because it will define the unavailability of the system, which will affect the productivity of the lab during maintenance. The two manufacturers service the full-automation solution at each preventive maintenance in about 2 to 4 days, depending on the system configuration, for BD Kiestra (about 2 days for the InoqulA and 3 to 4 days for the WCA/TLA) and in about 4 to 7 hours, depending on the system configuration, for Copan (2.5 hours per WASP, 1.5 hours per incubator). For both manufacturers, service maintenance is performed per module, allowing continuous work. Moreover, service maintenance can be performed at night or, in cases of 24/7 laboratories, during quiet times. The complexity of the conception may also affect the system's regular maintenance that will need to be performed by the user. Finally, the mean time between failures (MTBF) is determined by several factors, including the complexity of the conception, the configuration of the system, the number and variety of daily processed samples and user-induced factors. Several backup procedures, implemented either by the manufacturer or by the user, can be conducted upon system failure of one or multiple elements composing a laboratory automation system to reduce the negative impact on laboratory workflow (Table 6).

Connectivity

The successful introduction of an automated/robotic system in a diagnostic laboratory greatly depends on its integration with the laboratory information system (LIS). Unfortunately, the connectivity of the laboratory automation systems to the LIS and/or to other automated modules is not a service automatically provided by manufacturers and LIS providers. It is thus essential to include in the budget the significant additional costs that will be generated for the connection of the laboratory automation system to the LIS.

The laboratory automation systems are managed by a central computer system, the automation management software, that drives the system and that is connected to the laboratory LIS or to a facultative middleware (Fig. 10). The middleware is a software that allows other softwares (automation management software, LIS or other software) to interact. The middleware is optional and is required when the laboratory LIS does not support all the functionalities, such as the management of analytical protocols, connection to other automates and laboratory statistics. The users interact with the automation management software to read the plates and to manage the laboratory automation system. The interaction is performed either in a client–server mode with BD Kiestra or in a Web mode with the WASPLab (Fig. 10). The client–server mode

TABLE 6. Backup procedures in case of system failure as proposed by manufacturers

	BD Kiestra	Copan
Failure	**WCA/TLA**	**WASPLab**
Software	• Backup server available. In case of breakdown, BD Kiestra will use the backup server. • Automatic backups to another server of program software including configuration file of BD Kiestra applications. • Database recovery system; database backup or recovery possible within 1 hour.	• WASP is supplied with internal removable backup CF card containing main database of WASPCore and instrument settings. Stored data can thus be easily transferred to new PC in case of PC replacement. • Control unit for each WASPLab is supplied with two servers, one for routine use and another for continuous mirroring of main server. In case of breakdown, second server can be used to avoid data loss.
Specimen processor	• In case of breakdown of FA mode, InoqulA can still be used in SA mode. • Upon complete breakdown, manual inoculation can be performed and system can be loaded manually for plate incubation and imaging.	• Manual inoculation can be performed and system loaded manually for plate incubation and imaging.
Incubator	• Incubators with same incubation types can be used temporarily as redundant incubator. • Plates can be removed manually or automatically by software application solution and incubated in external incubators. • Imaging can still be processed if it is functional.	
Imaging	• No imaging, but incubators can be used as conventional incubators. • Camera system of other incubators can be used for imaging in case of camera breakdown.	
Conveyor	• Incubators or other modules can be loaded and unloaded manually for imaging and incubation.	
LIS	• System can be used with primary sample plating protocols that can be set up on InoqulA system and reading stations as temporary solution. User selects type of inoculation and incubation protocols for each specimen. • Depending on configuration, sample export messages can be buffered until connection is running again.	• System can be used in a specific modality called "Protocol Section Mode by Technologist." User selects type of inoculation and incubation protocols for each specimen.

FA, full automation; SA, semiautomation.

requires the installation of a client software on the laboratory computers, whereas the Web mode functions without requiring any additional software.

Two modes of connectivity can be implemented, depending on the capacity and flexibility of the LIS and/or depending on the presence of a middleware.

If the LIS is able to manage the inoculation and analytical protocols, the LIS can interact and pilot the laboratory automation system in a master real-time mode. Thus, automation system's client software interacts directly with the client software of the LIS. In the master real-time mode, two screens can be used at the reading station. The first screen exhibits the information of the automated system, such as plate images, and the second screen contains the LIS information of the corresponding analysis, which is automatically synchronized with the data entered into the laboratory automation software. Thus, the analytical steps of the LIS can be directly triggered upon data entry from the automation system.

If the LIS is unable to manage the inoculation and analytical protocols, a middleware or a connection of the LIS in a slave mode is required. When a middleware solution is used, the LIS sends analytical requests to the middleware, which manages the analytical protocols and pilots the laboratory automation system in a master real-time mode. Without middleware, the LIS is connected in a slave mode. In that mode, all the inoculation and analytical protocols must be set in the laboratory automation software, and the LIS only sends analytical requests to the lab automation system's software, which manages the steps of the analytical procedure.

Management of multiple microbiologic protocols, including sample inoculation, incubation and imaging, is defined in the automation management software. Thus, each protocol applied to specific samples needs to be defined in the automation management software, including the type of inoculations (automated, manual, quadrants, semiquantitative, volume, media plates, broth), incubation parameters (internal, external, normal atmosphere, CO_2, time of incubation) and imaging (time of imaging, type of imaging). It is thus possible to manage multiple configurations of microbiologic processes with samples that are fully automated or only partially automated, such as anaerobic cultures (automated inoculation and imaging but incubation in external incubators). It is also possible to manage

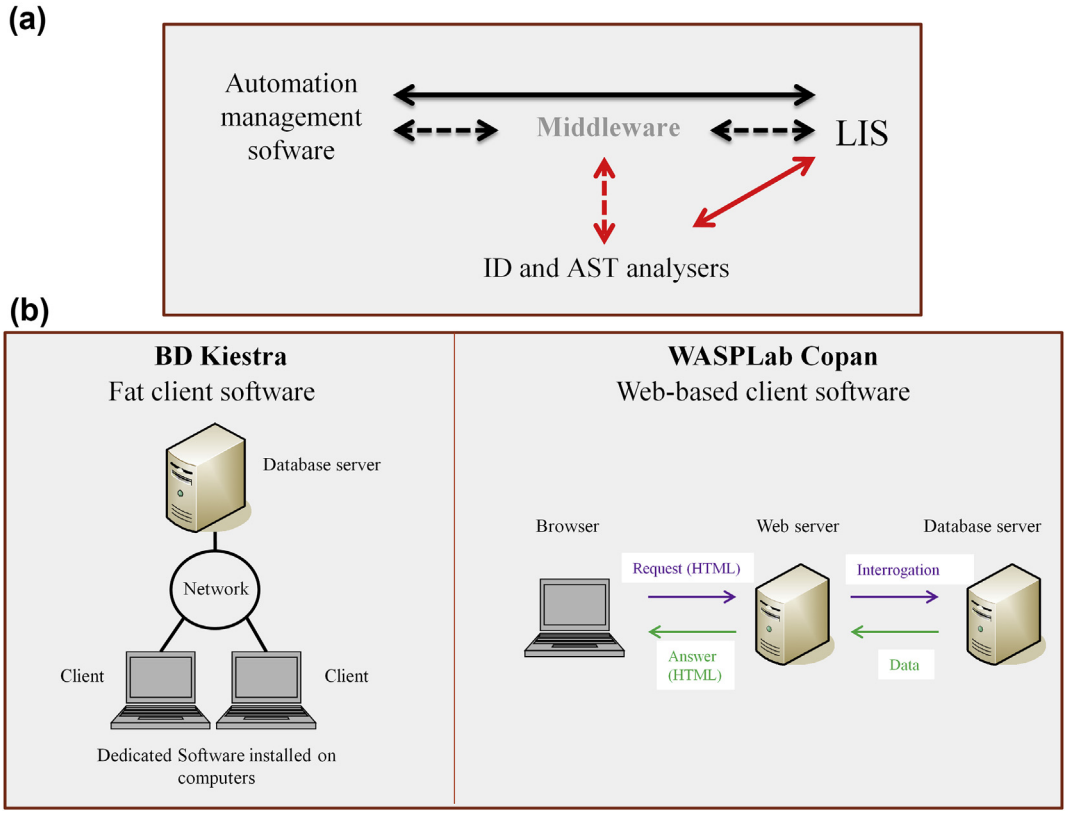

FIG. 10. Connectivity. (A) The user interacts with the lab automation system through automation management software that is directly connected to the LIS or indirectly via a middleware, either in master or slave mode. Other systems, such as ID and AST automated systems, are also integrated into the LIS by direct connection or via a middleware. (B) Interaction of the user with the automation management software is performed either in client–server mode with BD Kiestra or in Web mode with WASPLab.

microbiologic processes which include both fully automated steps (plate inoculation, incubation, imaging) and partially automated steps (automated broth inoculation and subculture, manual broth incubation). However, as a result of the complexity and significant variability of the microbiologic processes, setting the multiple protocols in the automation management software is complex and time-consuming. Thus, the full implementation of the laboratory automation system in the diagnostic laboratory workflow usually requires several months to years and is performed by most laboratories in a stepwise approach to test and validate each microbiologic protocol in the lab automation system. This is probably the most complex and time-consuming step of the lab automation project, and it is critical for optimization of the overall laboratory workflow.

General advantages and disadvantages of automation

Both manufacturers claim that the introduction of partial or total lab automation positively affects a laboratory's activities, which results in reduced time to results and thus putatively in better patient treatment with decreased hospitalization time and lower costs for the hospital. However, the advantages after implementation of laboratory automation are mainly inferred from manufacturers' marketing operations (Table 7). The disadvantages may be extrapolated from personal communications from laboratory managers who have experienced the implementation of laboratory automation and from other expected drawbacks that automation may introduce into a diagnostic laboratory. Thus, the real benefits of lab automation remain to be demonstrated in objective, comparative and prospective clinical studies performed by independent laboratories and published in peer-reviewed journals. Several studies have demonstrated that specimen processors produce more isolated colonies, exhibit enhanced reproducibility and provide decreased hands-on plating time compared to manual streaking [6–9]. One study showed that the higher yield of isolated colonies obtained with the InoqulA system compared to manual inoculation greatly decreased the requirement for subculturing and resulted in a significant decrease in time to result, laboratory workload and laboratory costs [7]. The

TABLE 7. Advantages and disadvantages of laboratory automation

Advantages
Activity/productivity (increase processing of diagnostic samples).

- Improvement of laboratory workflow (dashboards).
- Management reports.
- Cost savings.

Quality and reproducibility.

- Inoculation: Improved yield of isolated colonies.
- Incubation: Improved bacterial growth.

Reduced time to results (ID and AST).

- Decrease hospitalization time, decrease risks of nosocomial infections, treatment improvements.
- Cost savings.

Traceability (barcodes).

- Decrease errors (e.g. sample, media plates, broth switching).

Security.

- Decrease plate transportation.

Labor saving.

- Decrease fastidious and repetitive tasks (e.g. inoculation, plates incubation).
- Release expert staff for added value tasks (e.g. pre- and postanalytic phase, reading, interpretation, troubleshooting, R&D, microscopy).
- Reduce overtime payments.

Disadvantages
No laboratory adaptation to automation (e.g. staff shifts, training, 24/7)

- Misuse of tools
- Expectations for increased productivity not achieved

Crash of automat (backup needed).

- Good support and maintenance essential.
- Expensive maintenance budget.

Staff turnover (boring and lonely work?).

- Lab automation needs to be a project that includes everybody.
- Aim is not to replace experienced laboratory technicians but to assist them in their daily tasks.

Only eye is used.

- Smelling or other sensing of colony consistency disappears.
- More difficult to identify unusual/new species.

Security.

- Inoculation of sensitive samples (e.g. sputum, blood culture).
- Contamination of specimen processors and incubators (e.g. fungus spores, biosafety class 3 microorganisms).

Loss of microbiologic knowledge.

- Decrease in analytical variability.
- Standardized microbiologic factory (you find what you are looking for).

implementation of laboratory automation combined with MALDI-TOF allowed the TAT to significantly decrease for microbial identification of positive blood cultures, allowing adjustment of the antibiotic regimen in 12% of patients [10]. Similarly, laboratory automation allowed a reduction of the TAT for urine specimens from 24 hours' to 16 hours' incubation, with a 99.7% clinical interpretation agreement (Bielli *et al*., paper presented at 25th European Congress of Clinical Microbiology and Infectious Disease, 2015, abstract EVO535). Two laboratories reported that introduction of laboratory automation positively affected the activity by allowing a significant increase in the laboratory productivity index (number of samples per staff member per day) from 2.03- to 2.6-fold (Bentley *et al*. and Humphrey *et al*., papers presented at 21st European Congress of Clinical Microbiology and Infectious Disease, 2011, abstracts P-1792 and P-1793). Thus, several unpublished works as well as peer-reviewed published reports suggest that laboratory automation has a direct positive impact on laboratory productivity, with reduced time to results and laboratory costs, but the true challenge remains to assess the real clinical impact and benefits that may be obtained from faster test results and improved laboratory efficiency.

Workflow assessment

A workflow assessment of the diagnostic laboratory activity is required to determine the laboratory automation requirements, including the number of specimen processors and the number and capacity of the incubators (Table 2). A workflow assessment is a service provided by the two manufacturers, which can also be conducted by independent consulting agencies. Similar laboratory data and information are requested by the two manufactures to perform a workflow assessment (Table 8). The provided data are essential to accurately determine the automated laboratory workflow and to characterize the best configuration of the laboratory automation (number of specimen processors, incubators and workbenches) to avoid any bottlenecks or congestion resulting from the inability of the system to absorb peaks of sample workflow that may occur at certain hours or days during a working week (Fig. 11). A delay will thus occur each time the demand exceeds the throughput. In addition, the laboratory should take into consideration the average increase in sample volume per year to ensure that the demand will not exceed the throughput and that the capacity of the

TABLE 8. Laboratory data and information requested to perform workflow assessment

Item	Information requested

General lab data	• Staff (FTE).
	• Job duties (FTEs/job duty).
	  • Management.
	  • Senior laboratory technician, laboratory technicians and assistants.
	• Task overview.
	  • Sample reception and processing.
	  • Reading.
	  • Sample workup, ID, AST.
	  • Result verification, quality control.

Sample types and volumes	• Total no. samples per year. • Specimen types and average daily volumes. • Weekly distribution. • Hourly distribution.
Hourly sample arrivals	• Hourly sample arrivals for each specimen type.

Sample inoculation and incubation requirements for each specimen type	• Inoculation type (automated or manual).
	• Streaking pattern.
	• Tubes (enrichment broth).
	• Slides.
	• No. plates per incubation type.
	• Incubation types.
	  • Normal atmosphere.
	  • CO_2.
	  • External to lab automation (e.g. anaerobic incubation, fungi).
	• Time of reading (e.g. first read, second read).
	• Follow-up work.
	  • Percentage of follow-up work.
	  • Subculture (no. plates, incubation type, reading).
	  • Average no. IDs and ASTs.

Materials and off-line processes	• Blood culture. • ID/AST (e.g. MALDI-TOF, automated AST and ID cards). • Media/swabs (e.g. solid, liquid). • LIS. • Middleware.

AST, antibiotic susceptibility testing; FTE, full-time equivalent; ID, identification; LIS, laboratory information system; MALDI-TOF, matrix-assisted laser desorption/ionization time-of-flight mass spectrometry.

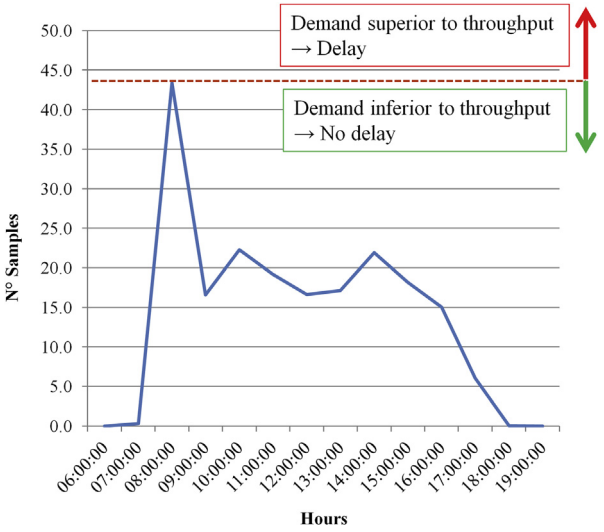

FIG. 11. Average sample arrival in diagnostic laboratory. Shown is average hourly distribution of samples arriving in diagnostic laboratory of Lausanne University Hospital Center, Lausanne, Switzerland. The throughput of an automated system need to be better than the highest demand during a workday to avoid system congestion and sample processing delay.

incubators can tolerate the expected increase in the number of incubated plates.

Expected impacts of automation

An inferred advantage of full laboratory automation is an increased efficiency due to the reduction of repetitive low-value-added tasks and an opportunity to modify the laboratory workflow. For instance, smart incubators with digital imaging reduce the number of manipulation of plates up to 90% according to the type of samples and facilitate reorganization of the laboratory workflow with dedicated workstations, such as identification of bacteria using MALDI-TOF. The precise impact of automation is difficult to assess because (a) concomitant acquisition of new equipment such as MALDI-TOF and/or rapid PCR-based tests and (b) modification of guidelines for sample processing may significantly modify the workload for specific activities, thus representing confounding factors. Unfortunately, only a few reports on the impact of lab automation are available. Bentley *et al.* (paper presented at 21st European Congress of Clinical Microbiology and Infectious Disease, 2011, abstract P-1792) reported an increased laboratory productivity index of 2.06 by comparing the staffing and laboratory productivity before and 2 years after the implementation of full laboratory automation. Staffing was reduced by 30% after automation despite an increase in average workload per day of 27%. The impact may vary dramatically according to the respective proportions of the different laboratory activities. Indeed, a 100% reduction in staff activity was observed for plate sorting, labelling and incubation. Some other activities were significantly affected, with a 30 to 60% reduction of staff activities involved in inoculation, plate reading, identification and antibiotic susceptibility testing. Finally, laboratory activities linked to sample reception, data entry and waste management were moderately impacted, with a 10 to 20% reduction of staff dedicated to these activities.

We have used a categorization of the laboratory activities similar to those defined by Bentley *et al.* to estimate the putative impact of automation for our laboratory. Medical

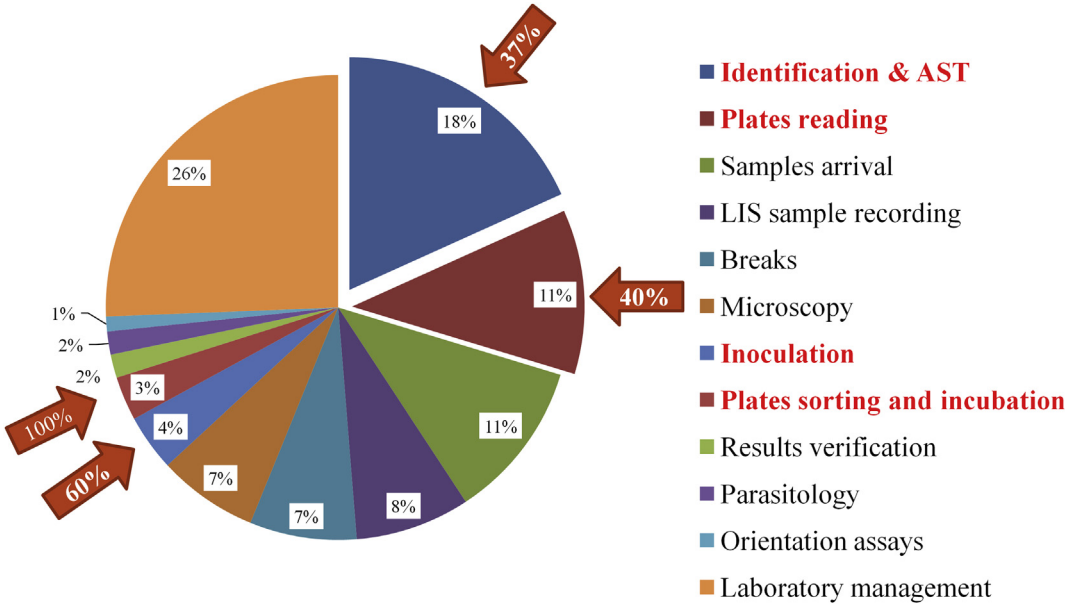

FIG. 12. Impact of implementation of laboratory automation. Workflow assessment and detailed analysis of laboratory activities were performed in the diagnostic laboratory of Lausanne University Hospital Center, Lausanne, Switzerland. Reduction from 37 to 100% of staff working time for activities highlighted in red (plate sorting and incubation, inoculation, plate reading and identification, AST) is expected after implementation of laboratory automation. Estimated impact of laboratory automation from our model corresponds to a total reduction of 2.4 FTE (16.5% of 14.5 FTE). Our laboratory is already equipped with automated specimen processor, two MALDI-TOF systems and two automated ID and AST modules; results shown here may be different for laboratories with different preexisting equipment.

technicians were asked to report on standardized forms the time spent accomplishing different activities during 5 working days. The data were compiled, and the reduction of staff activity was extrapolated from the data reported by Bentley *et al.* and corrected according to the specificities of our laboratory, as an automated inoculation system (WASP Copan) and a MALDI-TOF for bacterial identification (Bruker) had already been introduced in our laboratory (Fig. 12). All together, the impact of laboratory automation estimated using our model corresponded to a total reduction of 2.4 full-time equivalents (FTE) (16.5% of 14.5 FTE) for our laboratory, with a reduction of 1.0 FTE (37%) in identification and AST, 0.6 FTE (40%) in plates reading, 0.4 FTE (60%) in inoculation and 0.4 FTE (100%) in plate sorting and incubation.

Conclusions

The two manufacturers proposing automated solutions for bacteriology have similar structural hardware and software, with specimen processors, smart incubators, conveyors, digital imaging and software-integrated workbenches. However, significant differences in system workflow are observed between the different automated systems. This may affect the laboratory organization required to optimize system efficiency. However, a similar increase in productivity will likely be obtained with the different systems, providing an optimal implementation of the automated systems into the laboratories can be conducted. A failure to properly reorganize laboratory activities for optimization of the automated tool and its connection to the laboratory LIS will likely have a much higher negative impact on the efficiency of the system than the detailed characteristics of a given chosen automated system. Indeed, even a well-designed, high-throughput automated system may exhibit poor performance with inappropriate usage and/or inefficient bidirectional connection with laboratory LIS. Laboratory reorganizations must be conducted in every activity of the laboratory that may affect the system's efficiency, but an extension of opening hours to a 24/7 service is likely one of the major changes that has to be completed to obtain maximal efficiency in order to get increased productivity and quality, reduced TAT and reduced laboratory costs, and thus a positive impact on patient management and hospital costs.

The real benefits that may be obtained with laboratory automation remain to be investigated and demonstrated in peer-reviewed publications. Some publications have shown that specimen processors, and to some extent partial and complete laboratory automation, positively affect TAT, and likely patient

treatment [7,10]. However, more extensive studies focussing on both the diagnostic laboratory and sensitive hospital units such as intensive care units should be conducted in the future to demonstrate the real added value of these systems.

The rapid development of new technologies in diagnostic microbiology, such as high-throughput sequencing, rapid PCR-based assays, single-cell-level assays and miniaturization of bacteriology, may rapidly render laboratory automation less attractive in the future. Even though the commercialization of new, efficient technological solutions is hard to predict, the recent example of MALDI-TOF and its major impact on laboratory activities has demonstrated that analytical processes may rapidly change and that current laboratory automation solutions may rapidly become obsolete with new technologies. Thus, manufacturers need to be vigilant in order to rapidly adapt the proposed tools and engineer open and flexible systems that may be easily adapted to new technological solutions.

Laboratory automation may also represent an interesting tool for research and development in addition to routine diagnostic purposes. The high-throughput potential of automated systems could be used in culturomics approaches for the detection and isolation of multiple microorganisms from both medical and environmental samples using a large variety of selective and nonselective media and broth [11]. The availability of specimen processors, smart incubators with digital imaging and, in the future, automated colony-picking tools may provide the required basis to conduct large-scale bacteriologic studies focussing on a better understanding of human and environmental microbial composition.

The use of a central automated system may represent a major challenge for laboratories if that system should fail. Support and maintenance contracts are thus essential, and each laboratory manager should carefully analyse and discus manufacturers' support efficiency. Manufacturers should be able to quickly fix technical failures and guarantee the presence of a qualified technician on site within a couple of hours (ideally 2–3 hours). They should also be able to provide spare parts quickly, with a maximum delay of 24 hours. Laboratory managers should also consider retaining a minimal backup laboratory setup, such as conventional incubators, in order to maintain a laboratory activity in case of major failure of the automated system or contamination of the smart incubators.

In conclusion, the automated solutions currently available on the market for bacteriology laboratories are interesting in terms of the possible benefits on quality, time to results and productivity. Thus, the question is not whether a new automated system should be considered but rather the minimal sample volume required to start considering automation; the best time to move to an automated system (because we may always be tempted to wait for the next improvement); how to implement the automation system to maximize productivity; and how to obtain the money required to purchase a system. The answer to the last question should not be based only on cost savings but should also include the added value of automation for patient care provided by increased reproducibility and productivity, reduced contamination and reduced time to results.

Transparency Declaration

All authors report no conflicts of interest relevant to this article.

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