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ORIGINAL ARTICLE

Biosafety Cabinet Handling Practices and PCR Laboratory SOPs Compliance among Undergraduate Medical Students: Implications for Laboratory Safety and Biomolecular Training

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ABSTRACT

Background: Biosafety practices and following standard operating procedures (SOPs) are integral parts of molecular diagnostic laboratories. This study assessed the knowledge of biosafety cabinets, compliance to PCR laboratory SOPs, laboratory safety competency among undergraduate medical students and factors associated with better laboratory competency. **Methods:** A cross-sectional analytical study (n=90) used structured questionnaires designed to gather data on biosafety cabinet knowledge, compliance with PCR laboratory SOP, awareness of contamination prevention, and laboratory safety practices. Participant characteristics and competency scores were described in terms of descriptive statistics. Independent-samples t-tests and Pearson correlation analysis were used (p value < 0.05, SPSS v.25.0). **Results:** 84.4% of the participants knew the term biosafety cabinets, but only 54.4% of them recognized the correct functions of a Class II biosafety cabinet. The percentage of students using high level biosafety cabinet was 33.3%. The average laboratory competence score was 27.9 ± 4.8 of 40. Students who have received biosafety training scores significantly higher in their SOP compliance (7.4 ± 1.6) compared to untrained students (5.8 ± 1.9, $p < 0.001$). The overall competency was significantly correlated with SOP compliance ($r = 0.63$, $p < 0.001$), biosafety knowledge with SOP compliance ($r = 0.56$, $p < 0.001$), and laboratory exposure was significantly correlated with biosafety knowledge ($r = 0.44$, $p < 0.001$). **Conclusion:** The competency of undergraduate medical students in biosafety and PCR laboratory practices were moderate, and there were significant deficiencies in the practices of the biosafety cabinets and in the compliance of the PCR workflow.

Keywords: Biosafety; Biosafety Cabinet; PCR Laboratory; Standard Operating Procedures; Laboratory Safety; Medical Students; Molecular Diagnostics; Laboratory Competency.

In the present day, the use of molecular diagnostic techniques has gained importance in healthcare, and it has been observed that laboratory biosafety and the proper implementation of standard operating procedures (SOP) are of great significance [1]. Polymerase chain reaction (PCR) is one of the most commonly applied molecular techniques to detect, characterize and monitor infectious and genetic diseases [2]. The accuracy and reliability of PCR-based testing relies, not only on technical expertise, but also on adherence to biosafety protocols that are in place to minimize cross-contamination, protect individuals and preserve the integrity of the specimen [3].

Biosafety cabinets (BSC's) are one of the most basic components of laboratory safety equipment and are very common in laboratories where there are potentially hazardous biological materials present [4]. Workers in molecular and clinical laboratories need to have a proper understanding of the classifications of biosafety cabinets, airflow systems, personal protective equipment (PPE), and decontamination protocols. In the same way, the use of the PCR laboratory SOPs – such as handling samples properly, segregation of pre and post PCR areas [5], the prevention of aerosol contamination and the management of reagents – is also critical in guaranteeing valid and replicable laboratory results [6].

Medical students are more and more exposed to learning activities in a laboratory throughout their undergraduate studies [7]. As future health care workers, they will become competent in laboratory safety procedures and become familiar with molecular diagnostic procedures [8]. However, even though laboratory training is getting more and more attention, shortcomings regarding biosafety awareness and compliance with SOP of students and laboratory trainees have been reported [9]. Failure to understand how to operate the biosafety cabinet or PCR workflow procedures could lead to laboratory contamination, inaccurate diagnosis and laboratory worker exposure to biological hazards [10].

Assessment of the biosafety knowledge and laboratory practices among undergraduate medical students is hence, important to know the gaps in knowledge and enhance competency-based laboratory training. Greater knowledge about these factors can help institutions to create specific biosafety education programs and improve the practical preparedness in laboratories. So, the present study was to evaluate the knowledge of Biosafety Cabinet, compliance of the SOP for PCR laboratory, laboratory safety competency among undergraduate medical students and to examine the correlation between biosafety training, laboratory practices and overall competency score.

METHODOLOGY

A cross-sectional analytical study was carried out to evaluate biosafety knowledge, the compliance of standard operating procedure (SOP) of PCR laboratory among undergraduate medical students and laboratory safety competency. The study was conducted in a medical college with its laboratory learning facilities for a period of three months (from January to March 2026). All participants signed an informed consent before entering the study. The information collected was kept confidential during this study. The study was carried out in compliance with the ethical principles of the Declaration of Helsinki and institutional research guidelines.

The study population included undergraduate medical students in different academic year. There were 90 students involved in the study. Students currently enrolled in medical program who were willing to provide informed consent were included. Students who did not participate and students who missed the data collection period were not included. To achieve the representation of different academic years, a stratified convenience sampling method was employed. Eligible students were invited to participate voluntarily, and informed consent obtained before data collection. Structured, self-administered questionnaire was designed based on available biosafety and molecular laboratory guidelines to gather data. The questionnaire was divided into four parts. The questions in Section I addresses demographic and educational characteristics. Data on age, gender of students, academic year, prior laboratory experience, and participation in formal biosafety training was gathered in this section. The Student will learn about biosafety cabinets and their usage. The student will learn about the knowledge and practices of biosafety cabinets.

Questions measured biosafety cabinet awareness (categories I, II, III), principles of airflow, use of UV sterilizers, PPE and proper operating procedures. Sample collection for this incident occurred at the PCR Lab. For this incident, samples were taken in the PCR laboratory. This section assessed practices undertaken in the key pre-PCR and post-PCR areas of compliance, sample labelling, handling of filter pipette tips, dedicated use of equipment, contamination control, reagent handling and waste disposal. Participants filled out the questions dealing with laboratory safety, contamination prevention awareness, incident management, and overall competency of the laboratory. A score of one point was given for a correct answer and zero points for an incorrect and/or negative answer. The scores were combined to form composite scores of biosafety cabinet knowledge, PCR SOP compliance, laboratory safety practices and overall laboratory competency. The higher the scores, the better the knowledge and compliance. The overall competency scores were classified as Medium competency: 50-59% of the total score, Competent: 76–90% of total score and Extremely Competent: 75% or more of total score.

To ensure content validity, the questionnaire was pretested by three faculty members working in the field of microbiology, molecular diagnostics and laboratory biosafety. A feasibility and clarity study was done with 10 students with a pilot study. The internal consistency of the instrument was tested by Cronbach's alpha, and the results were quite acceptable with $\alpha = 0.84$. The data were compiled and analyzed by SPSS version 26.0. Frequency, percentage, mean and standard deviations were used to present descriptive statistics. Independent-samples t-tests were used for comparing the scores of PCR SOP compliance based on biosafety training. Pearson correlation analysis was used to assess correlations between biosafety knowledge, SOP compliance, and exposure to the laboratory, academic year, and competency scores. A p value of < 0.05 was deemed to be statistically significant.

RESULTS

The total number of undergraduate medical students involved in the study were 90. The female students (53.3%) outnumbered the males (46.7%) in the sample. Almost half (48.9%) of the participants were between the ages of 21 and 23 years. The distribution with regard to academic years was fairly even, with 26.7% of the study population in third year and 26.7% in their final year. Prior laboratory training of most participants (74.4%) and formal biosafety training sessions of about 2/3 of the participants (64.4%) (**Table I**).

Table I: Demographic and Laboratory Training Characteristics (n = 90)

Variable	Category	n (%)
Gender	Male	42 (46.7)
	Female	48 (53.3)
Age Group (years)	18–20	28 (31.1)
	21–23	44 (48.9)
	>23	18 (20.0)
Academic Year	1st Year	20 (22.2)
	2nd Year	22 (24.4)
	3rd Year	24 (26.7)
	Final Year	24 (26.7)
Prior Lab Training	Yes	67 (74.4)
	No	23 (25.6)
Biosafety Training Attended	Yes	58 (64.4)
	No	32 (35.6)

Most students (84.4%) indicated knowledge of biosafety cabinets, but not so much in detail. The appropriate functions of a Class II biosafety cabinet was correctly identified by only 54.4% and airflow principles were correctly understood by 57.8%. 51.1% reported using appropriate

ultraviolet sterilization procedures (UPS). Students wearing proper PPE during cabinet operation was found in 61.1% of them. The composite assessment revealed that 33.3% had high level of biosafety cabinet practice and 21.1% had low level biosafety cabinet practice, which means there were significant gaps in practical biosafety competency (**Table II**).

Table II: Biosafety Cabinet Knowledge and Practice Patterns

Parameter	Category	n (%)
Awareness of Biosafety Cabinets	Yes	76 (84.4)
	No	14 (15.6)
Correct Identification of Class II Cabinet	Correct	49 (54.4)
	Incorrect	41 (45.6)
Knowledge of Airflow Direction	Correct	52 (57.8)
	Incorrect	38 (42.2)
Proper Use of UV Sterilization	Yes	46 (51.1)
	No	44 (48.9)
Correct PPE Usage Inside Cabinet	Adequate	55 (61.1)
	Inadequate	35 (38.9)
Overall Biosafety Cabinet Practice Level	High	30 (33.3)
	Moderate	41 (45.6)
	Low	19 (21.1)

Table III shows that there were differences in compliance with PCR laboratory standard operating procedures between the measured domains. Labeling of samples for analysis, reagent storage and separation of pre-PCR area for maintenance, had the highest compliance rates, with 78.9%, 73.3% and 68.9% respectively. Aerosol contamination prevention measures and post-PCR handling procedures were comparatively low (54.4% and 50.0% respectively). In conclusion, the overall percentage of students' SOP compliance was 42.2%, indicating that there are opportunities for improvement in the molecular laboratory workflow practices.

Table III: PCR Laboratory SOP Compliance Indicators

SOP Component	Compliance Rate n (%)
Pre-PCR area separation maintained	62 (68.9)
Use of filter pipette tips	58 (64.4)
Dedicated pipettes for PCR steps	53 (58.9)
Proper sample labeling	71 (78.9)
Avoidance of aerosol contamination	49 (54.4)
Post-PCR handling protocol followed	45 (50.0)
Proper reagent storage compliance	66 (73.3)
Overall SOP Compliance (High level)	38 (42.2)

Students achieved the highest mean score in laboratory safety practices (7.4 ± 1.6), followed by biosafety cabinet knowledge (7.1 ± 1.8). Scores for contamination prevention awareness (6.9 ± 1.9) and PCR SOP compliance (6.6 ± 2.0) were comparatively lower. The mean overall laboratory competency score was 27.9 ± 4.8 out of a maximum possible score of 40, reflecting a moderate level of competency in laboratory biosafety and molecular diagnostic procedures among the study participants as presented in **Table IV**.

Table IV: Laboratory Biosafety and PCR Competency Scores

Domain	Mean ± SD	Max Score
Biosafety Cabinet Knowledge Score	7.1 ± 1.8	10
PCR SOP Compliance Score	6.6 ± 2.0	10
Laboratory Safety Practice Score	7.4 ± 1.6	10
Contamination Prevention Awareness	6.9 ± 1.9	10
Overall Laboratory Competency Score	27.9 ± 4.8	40

Students who had received formal biosafety training demonstrated significantly higher PCR SOP compliance scores compared with those who had not received such training (7.4 ± 1.6 vs. 5.8 ± 1.9). Independent-samples t-test analysis revealed a statistically significant difference between the two groups ($t = 4.21$, $p < 0.001$) (**Table V**). These findings suggest that biosafety training plays an important role in improving adherence to molecular laboratory standard operating procedures.

Table V: Comparison of SOP Compliance by Training Status

Training Status	Mean SOP Score ± SD	t-value	p-value
Trained (n=58)	7.4 ± 1.6	4.21	<0.001*
Not Trained (n=32)	5.8 ± 1.9		

Correlation analysis demonstrated significant positive relationships among major laboratory competency indicators is presented in **Table VI**. The strongest correlation was observed between SOP compliance and overall laboratory competency ($r = 0.63$, $p < 0.001$), followed by biosafety knowledge and SOP compliance ($r = 0.56$, $p < 0.001$). Biosafety training was positively associated with SOP compliance ($r = 0.49$, $p < 0.001$), while laboratory exposure was significantly correlated with biosafety knowledge ($r = 0.44$, $p < 0.001$).

Table VI: Correlation between Key Laboratory Variables

Variable Pair	r value	p-value

Biosafety knowledge vs. SOP compliance	0.56	<0.001*
SOP compliance vs. overall competency	0.63	<0.001*
Biosafety training vs. SOP compliance	0.49	<0.001*
Academic year vs. competency score	0.38	0.002*
Lab exposure vs. biosafety knowledge	0.44	<0.001*

Academic year also showed a moderate positive association with competency scores ($r = 0.38$, $p = 0.002$), indicating progressive improvement in laboratory competency with advancing medical education.

DISCUSSION

The present study aimed at assessing the biosafety knowledge, adherence to the standard operating procedures (SOPs) for PCR laboratory and competency of undergraduate medical students. The results showed that structured biosafety education and practical laboratory training are important to enhance competency among future health care professionals. The moderate level of biosafety knowledge found in the present study is similar to that found in previous studies of medical and laboratory science students [11,12]. Similar to the previous studies, the theoretical knowledge of students about the basic concepts of biosafety in the laboratory is good, but the practical knowledge of operating biosafety cabinets and preventing contamination is limited [13]. Lack of knowledge about the mechanisms of airflow, the use of personal protective equipment and cabinet maintenance has also been reported in academic laboratory settings [14,15]. Only 54.4% of the participants correctly identified the functions of a Class II biosafety cabinet, which is consistent with previous reports that show a lack of practical biosafety competency among trainees [16]. These deficiencies are concerning because the use of a biosafety cabinet could affect the safety of the operator and the integrity of the specimens [17].

The present study also revealed moderate compliance with the PCR laboratory SOPs with lower compliance was noted in aerosol contamination prevention and post-PCR handling procedures. A similar situation is observed during molecular diagnostic training programs, where contamination control is often cited as a problematic part of PCR workflow management [18]. Laboratory contamination and reduced diagnostic accuracy are also highlighted concerns due to poor SOPs in previous studies, with an increased risk of false-positive results if SOPs are not followed [19,20]. Increased compliance with sample-labelling and reagent storage seen in the present study may be attributed to increased focus on these procedures in routine laboratory instruction. Similar findings have been reported for laboratory trainees [21], and students in the health sciences where adherence to routine procedures was higher than adherence to contamination control [22]. The observations here indicate that there are potential benefits of dedicated training on contamination prevention as well as dedicated training on workflow segregation, in order to improve the performance of molecular laboratories [23].

A significantly higher compliance was shown by the students who have received formal biosafety training compared to the students who have not received any biosafety training which corroborates earlier findings of the efficacy of structured biosafety education programs. The same positive effects on lab performance after biosafety training have been reported in medical students, lab workers, and health care workers [24,25]. In addition, the high correlation among biosafety knowledge, compliance with SOPs and competency suggest that competency in the laboratory is multifaceted and builds from the combination of knowledge, competence in practice, and frequent exposure to the laboratory [26]. The overall positive trend of competency scores with the academic year further validates previous results showing that performance in the laboratory increases with years of experience and advancement in education [27].

This study has several limitations that should be taken into consideration when interpreting the findings. The cross-sectional design does not allow causal relationships between biosafety training and laboratory competency. Second, the data were obtained by self-report questionnaires, and could be influenced by recall and response errors. Thirdly, the study took place in one institution, which may make the results difficult to generalize. It is recommended that future multicenter studies be conducted, incorporating direct observation of laboratory practices, and longitudinal assessment of competency development, to gain a fuller understanding of biosafety training outcomes among undergraduate medical students.

CONCLUSION

The present study showed the undergraduate medical students had moderate knowledge regarding biosafety, moderate compliance with PCR laboratory SOP and moderate laboratory competency. While awareness of biosafety cabinets was generally good there were gaps in understanding what biosafety cabinets are, how they prevent contamination, and how they are used in critical PCR procedures. Furthermore, laboratory exposure and academic year was associated with higher competency levels. The results highlight the importance of providing integrated biosafety education and experiential training in the molecular laboratory in undergraduate medical education.

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Conflict of Interest

None

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Use of Artificial Intelligence

The corresponding author declared that no other artificial intelligence or AI-assisted tools were used anywhere in this manuscript.

Authors' Contribution

MK, S, KA: conceptualization, data collection, statistical analysis, drafting, critical review and final approval. All Authors contributed equally as per ICMJE.

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