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INTRODUCTION

Flap monitoring is as important to a plastic surgeon as flaps are in reconstruction. Optimal blood supply to deliver oxygen is essential for any tissue to survive, and compromised supply, if detected early, can help correct the causative factor and salvage a dying flap.
Direct clinical observation is still the gold standard monitoring system but is not objective and requires an experienced/trained staff. Although various methods are available to objectively monitor flap survival, all have a common drawback of being highly expensive and not available routinely to a surgeon.

In this study, we have used simple syringes and blood gas analyser, routinely available in any hospital, to get partial pressure of oxygen (pO$_2$) in a flap and calculated a cut-off value to objectively predict the chances of flap survival in post-operative period.

These cut-off values can further be used with implantable microcatheter oxygen sensors, where no such cut-off values are present, because of small number of flaps studied in literature.

**METHODS**

This prospective observational study was carried out from November 2014 to April 2016 on 75 patients having total of 84 flaps. Approval by the local Institutional Ethics Committee was taken for the study.

Thirty-minute post-elevation and inset of skin flaps, capillary blood is collected from the bleeding edges in 1-ml heparinised insulin syringes after spraying 0.1 ml of heparin (5000 µ/ml) to minimise clotting, intraoperatively from the proximal, middle and distal third of the flap. The fraction of inspired oxygen (FiO$_2$) was kept constant at 0.5% or 50% to minimise the confounding due to changes in oxygen level, as dissolved oxygen increases with increase in FiO$_2$. Samples were immediately analysed for pO$_2$. At the same time, sample of capillary blood was collected in similar manner from the fingertip as control and to compare the difference in the tissue oxygen levels.[Figure 1] If the sample collected was clotted or insufficient, that point was excluded from the study.

These points were marked and closely monitored clinically in post-operative period for a week to note for viability of the flap by assessing the skin colour, capillary refill, oozing on pinprick and comparison of flap temperature with normal adjacent skin. These 235 points were divided into two groups depending on the post-operative viability at each point: Group 1 – points those were clinically ischemic in post-operative period (34/235) and Group 2 – all points that remained healthy in post-operative period (201/235).

Values of the pO$_2$ in dead flap points and alive flap points were compared with their corresponding control (fingertips) to see for any significant difference in levels of pO$_2$ in two groups. Difference of mean of pO$_2$(diff-pO$_2$) was calculated for each of these 235 points by subtracting pO$_2$ of fingertip of the same patient. This value showed the change in pO$_2$ levels in the flap compared to the body (fingertip).

We analysed the data for obtaining the prediction values of partial pressures which can determine the flap survival using receiver operating characteristic (ROC) analysis. [Figure 2].

**RESULTS**

Seven of 75 patients in study underwent two flaps while one had three skin flaps making 84 flaps in 75 patients. Table 1 shows the different types of surgically elevated flaps, along with their frequency. A total of 252 (84 × 3) flap points were there in 84 flaps from which blood was analysed of which 17 samples were inadequate and thus excluded.[Figure 3] Of these, 17 inadequate samples 7 were from distal, 6 from middle and 4 from proximal points of flap, thus leaving 77 distal, 78 middle and 80
Sixty out of 84 flaps remained healthy while 24 developed variable degrees of necrosis. Two flaps showed necrosis of more than two-thirds of the flap; six showed one-third to two-thirds flap necrosis while 16 showed less than one-third flap necrosis.

Descriptive statistics of \( pO_2 \) from these fingertip samples is given in Table 2. Data were checked for distribution using Shapiro–Wilk test and were not found to be normally distributed, so \( pO_2 \) at fingertip in both groups was analysed using non-parametric independent samples Mann–Whitney U-test. We observed no difference between \( pO_2 \) of both the groups with mean (SD) finger \( pO_2 \) of 158.6 (30.06) mmHg in the dead and 167.9 (29.81) mmHg in the alive group [Figure 4] with \((P = 0.56)\). Thus, both the groups were comparable, and there was no confounding based on the patient’s oxygen levels, as assessed from the fingertip \( pO_2 \).

### Oxygen levels

\( pO_2 \) in flap points (flap \( pO_2 \)) half an hour after elevation was found to be lower in the dead/ischemic flaps points, compared to the flap points which remained healthy in proximal flap points to be evaluated making a total of 235 flap points. Mean (standard deviation [SD]) \( pO_2 \) of distal, middle and proximal points of flaps was 100.5 (45.59), 126.6 (47.22) and 143.1 (38.57) mmHg, respectively. Mean (SD) \( pO_2 \) from finger was 166.6 (29.96) mmHg.

### Table 2: Type of surgically elevated flaps

| Flaps                              | Frequency |
|------------------------------------|-----------|
| Abdominal                          | 2         |
| Cross leg                          | 2         |
| Gluteal rotation advancement       | 2         |
| Reverse sural                      | 12        |
| Deltoperctoral                     | 5         |
| Free flaps                         | 2         |
| Post-expander                      | 10        |
| Leg fasciocutaneous                | 4         |
| Flag flap                          | 1         |
| Forehead flap                      | 3         |
| Musculocutaneous gastrocnemius    | 1         |
| Groin                              | 15        |
| Hypogastric                        | 1         |
| Latissimus dorsi flap              | 2         |
| Lateral calcaneal artery           | 1         |
| Perforator                         | 9         |
| Paravertebral flap                 | 1         |
| Rotation flap back                 | 2         |
| Nasolabial flap                    | 1         |
| Preputial flap                     | 1         |
| Scalp rotation                     | 2         |
| Post-auricular flap                | 1         |
| Tensor Fasia Lata flap             | 1         |
| Pedicled tram                      | 1         |
| Tube flap for auricle              | 2         |
| Total                              | 84        |
the post-operative period. Mean (SD) of flap pO\textsubscript{2} for the dead flap points was 49.4 mmHg (SD: 14.61) as compared to 134.9 mmHg (SD: 38.99) for the alive flap point group.

Independent samples t-test (normally distributed data for flap pO\textsubscript{2}) showed that the two groups had significantly different pO\textsubscript{2} in the flap points when comparing the two groups with \( P = 0.005 \). ROC curve was plotted [Figure 2] and was used to find the sensitivity and specificity at different levels of pO\textsubscript{2} as shown in Table 3. Applying the Youden index, a cut-off value of pO\textsubscript{2} <86.3 mmHg was calculated with a sensitivity of 100% and specificity of 89.05%. Table 4 shows a 2 × 2 table taking cut-off value of pO\textsubscript{2} <86.3 mmHg. The positive predictive value at this level is 60.71 and the negative predictive value is 100%. We infer from the above that if capillary blood drawn from the flap points shows pO\textsubscript{2} <86.3 mmHg, it would mean that there is a 60.71% chance that the flap will show evidence of necrosis. If the value obtained is >86.3, there is a 100% chance that the flap points will be healthy as negative predictive value is 100%. From the various other cut-offs on ROC curve, as shown in Table 3, we can see that at a value of <49.78, there is a 100% chance of flap failure, as at this value, the specificity of the test is 100%.

**Difference of oxygen level from fingertip (difference of mean of partial pressure of oxygen)**

The difference/fall in pO\textsubscript{2} was calculated by subtracting flap pO\textsubscript{2} from finger pO\textsubscript{2}. These values were found to be normally distributed and were compared statistically and \( P \) value was calculated to see for any statistical difference.

Diff-pO\textsubscript{2} was found to be higher in the Group 1 (dead/ischemic flap points) compared to Group 2 (alive/healthy flap points).

Mean (SD) value of diff-pO\textsubscript{2} from the dead flap points was 109.3 mmHg (SD: 28.03) compared to 33.1 mmHg (SD: 41.02) in the alive/healthy flap point group [Figure 4].

Independent samples t-test was used (normal distribution) to see for any difference which showed that the two groups were significantly different with \( P = 0.000 \).

ROC curve was plotted for diff-pO\textsubscript{2} [Figure 2] and was used to calculate sensitivity and specificity at different levels of diff-pO\textsubscript{2} as shown in Table 3. Applying the Youden index, a cut-off value of >68.5 was calculated with a sensitivity of 94.12% and a specificity of 79.60%. Table 4 shows a 2 × 2 table taking cut-off value of drop of oxygen >68.5 mmHg.

This implies that if diff-pO\textsubscript{2} is >68.5 mmHg, there is a 43.84% chance that the flap points will show evidence of necrosis, whereas if fall is ≤68.5 mmHg, it means that there is a 98.77% chance of healthy flap.

If the drop is ≤54.0 mmHg, then the chance of survival of flap is 100% as sensitivity and negative predictive value will be 100%, and for a drop of >127.6 mmHg, chance of flap ischemia is 100% as specificity and positive predictive value will be 100% as shown in Table 3.

**DISCUSSION**

pO\textsubscript{2} has been used in various studies to monitor the blood flow to a flap. Various methods such as Clark-type microcatheter,[1] modified Clark electrode,[2] transcutaneous polarographic measurements of oxygen developed by Huch and Lubbers,[3] Licox catheter pO\textsubscript{2} micropore instrument,[4] optochemical and oxygen-sensing electrode (oxygen optode inner space),[5] dynamic phosphorescence imaging using luminescence lifetime imaging,[6] and many more have been used in

![Figure 4: Similar values of mean pO\textsubscript{2} of finger but significantly different values of flap pO\textsubscript{2} when compared between dead and alive groups (a); diff-pO\textsubscript{2} between finger and flap is much higher if flap points necrose verses if it survives (b). Diff-pO\textsubscript{2}: Difference of mean of partial pressure of oxygen, pO\textsubscript{2}: Partial pressure of oxygen](image-url)
Gupta, et al.: Intra-OP pO\textsubscript{2} for flap survival prediction

In this study, we have used commonly available 1-ml syringes and blood gas analyser to find the pO\textsubscript{2} of a flap. We calculated a cut-off value of flap pO\textsubscript{2} with high sensitivity and specificity, which allows us to predict the outcome of the flap. This study is unique in many ways; it can predict the outcome intraoperatively and thus allows a surgeon to take measures to revise their flap, if needed. It is much cheaper and readily available to a clinician compared to other machines using pO\textsubscript{2} to monitor flap postoperatively. To the best of our knowledge, no study has been done using this method to assess pO\textsubscript{2} and predict flap survival.

Using the pO\textsubscript{2} values obtained in the flaps that survived and underwent necrosis, a cut-off of pO\textsubscript{2} was calculated.

Table 3: Sensitivity and specificity of partial pressure of oxygen and difference of mean of partial pressure of oxygen at different levels

| Levels of pO\textsubscript{2} | Corresponding sensitivity | Corresponding specificity |
|-------------------------------|---------------------------|--------------------------|
| <19.3                         | 0.00                      | 100.00                   |
| ≤49.78                        | 61.76                     | 100.00                   |
| ≤49.8                         | 61.76                     | 99.50                    |
| ≤50.47                        | 64.71                     | 99.50                    |
| ≤50.7                         | 64.71                     | 99.00                    |
| ≤54.64                        | 73.53                     | 99.00                    |
| ≤54.9                         | 73.53                     | 98.51                    |
| ≤54.91                        | 76.47                     | 98.51                    |
| ≤55.9                         | 76.47                     | 98.01                    |
| ≤56.37                        | 79.41                     | 98.01                    |
| ≤56.5                         | 79.41                     | 97.01                    |
| ≤58.3                         | 82.35                     | 97.01                    |
| ≤63.1                         | 82.35                     | 95.52                    |
| ≤63.307                       | 85.29                     | 95.52                    |
| ≤64.9                         | 85.29                     | 94.53                    |
| ≤67.341                       | 88.24                     | 94.53                    |
| ≤67.691                       | 88.24                     | 94.03                    |
| ≤68.494                       | 91.18                     | 94.03                    |
| ≤76.922                       | 91.18                     | 91.54                    |
| ≤79.8                         | 97.06                     | 91.54                    |
| ≤86.253                       | 97.06                     | 89.05                    |
| ≤86.3                         | 100.00                    | 89.05                    |
| ≤250.465                      | 100.00                    | 0.00                     |

| Levels of diff-pO\textsubscript{2} | Corresponding sensitivity | Corresponding specificity |
|-------------------------------------|---------------------------|--------------------------|
| >9.3                               | 100.00                    | 0.00                     |
| >54.011                            | 100.00                    | 69.65                    |
| >54.666                            | 97.06                     | 69.65                    |
| >60.2                               | 97.06                     | 74.63                    |
| >60.5                               | 94.12                     | 74.63                    |
| >68.503                            | 94.12                     | 79.60                    |
| >68.9                               | 91.18                     | 79.60                    |
| >73.3                               | 91.18                     | 82.09                    |
| >75.667                            | 85.29                     | 82.09                    |
| >76.8                               | 85.29                     | 83.08                    |
| >78.3                               | 82.35                     | 83.08                    |
| >85.013                            | 82.35                     | 88.06                    |
| >85.149                            | 79.41                     | 88.06                    |
| >86.5                               | 79.41                     | 88.56                    |
| >86.513                            | 76.47                     | 88.56                    |
| >87.509                            | 76.47                     | 90.55                    |
| >88.369                            | 73.53                     | 90.55                    |
| >91.6                               | 73.53                     | 91.54                    |
| >91.889                            | 70.59                     | 91.54                    |
| >92.2                               | 70.59                     | 92.04                    |
| >92.7                               | 67.65                     | 92.04                    |
| >95.841                            | 67.65                     | 95.02                    |
| >96.484                            | 64.71                     | 95.02                    |
| >97.195                            | 64.71                     | 95.52                    |
| >98.2                               | 61.76                     | 95.52                    |
| >100.25                             | 61.76                     | 96.02                    |
| >100.746                            | 58.82                     | 96.02                    |
| >103.79                             | 58.82                     | 96.52                    |
| >107.7                              | 52.94                     | 96.52                    |
| >107.95                             | 52.94                     | 97.01                    |
| >108.8                              | 50.00                     | 97.01                    |
| >110.7                              | 50.00                     | 97.51                    |
| >111.217                            | 47.06                     | 97.51                    |
| >112.7                              | 47.06                     | 98.51                    |
| >113.612                            | 44.12                     | 98.51                    |
| >113.8                              | 44.12                     | 99.00                    |
| >114.2                              | 41.18                     | 99.00                    |
| >114.6                              | 41.18                     | 99.50                    |
| >119.199                            | 32.35                     | 99.50                    |
| >127.6                              | 32.35                     | 100.00                   |
| >180.116                            | 0.00                      | 100.00                   |

Values highlighted in yellow are the recommended cut-off values. Diff-pO\textsubscript{2}: Difference of mean of partial pressure of oxygen, pO\textsubscript{2}: Partial pressure of oxygen.
Comparing with other studies, values obtained by our study show that mean (SD) \( pO_2 \) of the group comprising healthy flaps is 134.9 (38.99) mmHg, whereas mean (SD) \( pO_2 \) of the group of flaps that did not survive is 49.3 (14.61) mmHg. A study by Geis et al. on nine free flaps showed the mean \( pO_2 \) of surviving flap, 4 h postoperatively to be 53 ± 0.7 mmHg. One flap was re-explored to improve flap perfusion, which had \( pO_2 \) below 10 mmHg. Another study by Schrey et al. assessed tissue oxygen levels of flaps which remained healthy and found a mean of 46.8 mmHg (SD: 17.0).\[8\]

The variation obtained compared to these studies can be explained from the following points:

1. Fraction of FiO\(_2\) in our patients was much higher (50%) which alters the oxygen level at tissue. It was observed that an increase in FiO\(_2\) causes an increase in saturation, as well as in \( pO_2 \). This explains the reason for the higher values of \( pO_2 \) obtained in our study, compared to various other studies in which the measurements were done at room air (FiO\(_2\) of 21%).

2. In our study, samples were collected earlier (after 30 min of flap inset), than other studies, where sampling was done later in post-operative periods, sometimes up to 2–3 days. A study by Kamolz et al. shows how the level of \( pO_2 \) changes with time. Decrease of the ptiO\(_2\) levels was noted in all the patients during the 1st few min, until a more or less constant but reduced level. At the time of weaning off, the ptiO\(_2\) values decreased once again. After approximately 30 min, an almost stable but reduced ptiO\(_2\) level was re-established (34.6 ± 10.9 mmHg). During the next days, Kamolz et al. observed a more or less constant but reduced level. These values from the 2nd-day onwards were lower than the mean values of the 1st day. The mean value for all flaps was 23.1 ± 6.5 mmHg.\[9\] It is the maximum initially and then drops to obtain a plateau by days 2–3. In another study by Geis et al. during the first 4 h, almost constant transcutaneous oxygen partial pressure (ptc\(O_2\)) values were detected (53 ± 0.7 mmHg). During the following time intervals, ptc\(O_2\) values decreased and reached a more or less constant level after approximately 12 h. The mean ptc\(O_2\) decreased from 53 ± 0.7 mmHg to 39 ± 1.0 mmHg.\[9\]

3. Most studies in literature are on free flaps whereas bulk of our samples was pedicled flaps. In free flaps, due to complete absence of blood flow, the \( pO_2 \) is found to be much lower compared to pedicled, as in later, there is only a decreased flow and very rarely a complete absence of blood flow. It was seen in a study that the value of oxygen gradually decreased from base to periphery of a pedicled flap.\[10\] This can be a reason for higher mean value obtained in our study of the necrosed flaps which might be having low blood flow initially at 30 min postoperatively, instead of absent blood flow seen in other studies with free flaps.\[6,8\] This explains the difference of values obtained, as in our study, sample was taken intraoperatively after 30 min of flap elevation itself.

In this study, we also took sample from the fingertip as control. We calculated the difference or drop of oxygen level in capillary blood of flap by subtracting flap \( pO_2 \) value from the fingertip \( pO_2 \) value. Using this, we have also calculated a cut-off value for drop of flap \( pO_2 \) level as

### Table 4: Results at cut-off value of partial pressure of oxygen of <86.3 mmHg and difference of partial pressure of oxygen at cut-off of >68.5 mmHg

| Details                     | \( pO_2 <86.3 \text{ mmHg} \) (%) | \( \text{Diff } pO_2 >68.5 \) (%) |
|-----------------------------|----------------------------------|----------------------------------|
| Sensitivity                 | 100                              | 94                               |
| Specificity                 | 89.05                            | 79.60                            |
| AUC                         | 0.95                             | 0.87                             |
| Positive likelihood ratio   | 9.14                             | 4.61                             |
| Negative likelihood ratio   | 0                                | 0.07                             |
| Disease prevalence          | 14.47                            | 14.47                            |
| Positive predictive value   | 60.71                            | 43.84                            |
| Negative predictive value   | 100.00                           | 98.77                            |

AUC: Area under the curve, Diff-\( pO_2 \): Difference of mean of partial pressure of oxygen, \( pO_2 \): Partial pressure of oxygen.
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compared to the fingertip, i.e. diff-pO2, which will predict the flap survival/failure. In this way, we were able to reduce the error due to mixing of oxygen from air in the samples. These values were also found to be significantly different statistically in the two groups, i.e. the dead and the alive flap groups.

While most of the studies have evaluated trends of pO2 to monitor flaps, but we have tried to predict the outcome by intraoperatively analysing single value of pO2. We tested flap’s inherent blood supply or factors affecting it at time of elevation or during movement and not the factors that affect flap survival in post-operative period. Using this study as a guideline, a clinician can take the sample from the edge of a flap intraoperatively after 30 min of flap inset, as shown in materials and methods. It is important to keep the FiO2 at 50% while collecting samples, otherwise values will change as explained above. Similar samples should be taken from the fingertip of the same patient at the same time while flap sample is being collected to act as control and to calculate diff-pO2. The sample should be assessed using a normally available blood gas analyser used in hospitals to obtain arterial blood gases.

The results can be interpreted as discussed above. With this, the surgeon can predict the survival of that part of the flap on the table. Surgeon can take remedial actions if flap pO2 is ≤86.3 mmHg or diff-pO2 is >68.5 mmHg as chances of failure are very high beyond these levels.

Limitations of this study include only two free flaps. FiO2 needs to be fixed at 50% to use this cut-off value, which is difficult in patients of regional anaesthesia. In such cases, venturi mask can be used to deliver FiO2 of nearly 50%. Role of heparin spray is not well established and reference based we are using it by our own experience. Points with insufficient sample from the flap could not be analysed and were excluded from the study. These are points that are most likely to necrose but were excluded from study. Demographic data of coexisting illnesses such as lung disease and smoking were not noted which can be a confounding factor in the study. Further studies are required to get cut-off values at lower FiO2. Method of collection of blood sample needs to further improvise to decrease the erroneous readings. In this study, instead of a whole flap, points are considered as individual reading, whereas in reality, we need the values for a flap, not points, especially in cases of free flaps. In case of pedicled flaps, as in our study, points from where the values are below cut-off might be the areas that might necrose, whereas the places where the pO2 is higher than cut-off most likely will survive.

CONCLUSIONS

From this study, we can conclude that pO2, measured using capillary blood gas analysis in skin flaps, is helpful in predicting the skin flap viability. Similarly, the difference in pO2 measured using capillary blood gas analysis between skin flaps and fingertip can be used to predict the chances of skin flap failure.

The cut-off value calculated in this study can be useful for a surgeon to take actions intraoperatively; in case, the values obtained for flap pO2 are lower than calculated cut-off of <86.3 mmHg or diff-pO2 is >68.5 mmHg.

We thus suggest that, in case any point on flap shows values <86.3 mmHg, measures should be taken immediately to revise the flap as otherwise it has high chances (60.71%) of failure. Similarly, if the difference from fingertip is >68.5 mmHg, measures to improve flap supply need to be taken to save the flap.

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Conflicts of interest

There are no conflicts of interest.

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