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GAS EXCHANGE CHARACTERISTICS AND QUALITY OF APPLES

A thesis presented in partial fulfilment
of the requirements for the degree of
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in Plant Science
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Benjamin Kwesi Dadzie
1992

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ABSTRACT

Atmospheric modification can extend the storage life of harvested fruits and vegetables beyond that which can be achieved with refrigerated air storage alone. Apples are particularly well suited to modified atmosphere (MA) storage and yet the recommended atmospheres for different cultivars of apples vary widely and responses of individual populations of apples to a given treatment can be variable. Part of this variation may be related to the variability in the internal atmosphere composition of individual fruit. This thesis explores the relationships between internal atmosphere composition of apples and factors such as skin resistance to gas diffusion (**R**), respiration, external oxygen concentration ($[O_2]_{ext}$), temperature and artificial barriers, all of which can influence the outcome of a given MA treatment.

Skin resistance to gas diffusion (**R**) values of freshly harvested apples of eight cultivars grown in New Zealand, were obtained using non-steady state and steady state methods at 20±1°C. **R** was cultivar dependent, with freshly harvested Braeburn apples having the highest mean **R** and Royal Gala the lowest. Skin resistance to ethane diffusion ($\mathbf{R}C_2H_6$) was linearly related to skin resistance to ethylene diffusion ($\mathbf{R}C_2H_4$) for individual apples within cultivars. Although there was a large degree of variation in between pairs of **R** values obtained on different apples within each cultivar, individual **R** values within these pairs were very similar to each other. The close relationship between the two independent estimates of **R** confirmed that this was real fruit to fruit variation rather than measurement error. In contrast, estimates of skin resistance to carbon dioxide diffusion ($\mathbf{R}CO_2$) were consistently higher than values for $\mathbf{R}C_2H_4$. There was a curvilinear relationship between $\mathbf{R}CO_2$ and $\mathbf{R}C_2H_6$ in a combined data set for all cultivars, indicating that CO_2 may diffuse through additional routes to those available for O_2, C_2H_4 and ethane (C_2H_6).

Freshly harvested Cox's Orange Pippin apples were respiring nearly twice as fast as Splendour, Granny Smith or Braeburn apples and a third higher than Gala, Royal Gala and Golden Delicious apples. Respiration rate appeared to be independent of $\mathbf{R}C_2H_6$ both within individual cultivars and in a combined data set for all cultivars. On the other hand, there was a declining exponential relationship between $[O_2]_i$ and $\mathbf{R}C_2H_6$ for individual apples and an increasing relationship between $[CO_2]_i$ and $\mathbf{R}C_2H_6$. Thus, the magnitude of **R** affects internal atmosphere composition for a given external atmosphere.

The respiratory and C_2H_4 production responses of Cox's Orange Pippin and Granny Smith apples to reduced O_2 concentrations were characterised by studying the variation in the magnitude of O_2, CO_2 and C_2H_4 concentration differences between the internal and external atmospheres ($\Delta[O_2]$, $\Delta[CO_2]$ and $\Delta[C_2H_4]$) of individual apples maintained in different O_2 atmospheres at 20±1°C. $\Delta[O_2]$ decreased at low O_2 levels, reflecting the decreased rate of O_2 uptake in low O_2 concentrations. Oxygen uptake relative to that in air (***Rel***O_2) approximately followed Michaelis-Menten kinetics, with a half-maximal rate of 2.5% O_2 for $[O_2]_i$ and 7.5% for $[O_2]_{ext}$. A mathematical equation was developed to describe the two physiological processes (ie. anaerobic and aerobic respiration) involved in the relationship between relative rate of CO_2 production (***Rel***CO_2) or internal CO_2 concentration ($[CO_2]_i$) and $[O_2]_{ext}$ or $[O_2]_i$. The equation had two components, each describing one of the two physiological processes.

The relationship between relative rate of C_2H_4 production (***Rel***C_2H_4) or internal C_2H_4 concentration ($[C_2H_4]_i$) and $[O_2]_i$ was more closely described by an exponential rather than a Michaelis-Menten type hyperbolic curve. Nevertheless, the overall shape of the relationship conformed to the expectation that small changes in O_2 concentration would have much greater effect at low $[O_2]_i$ than they do at high $[O_2]_i$. In contrast, the presence of the skin as a diffusion barrier (**R**) resulted in development of an apparent 'lag phase' in the relationship between ***Rel***C_2H_4 or $[C_2H_4]_i$ and $[O_2]_{ext}$ such that it was no longer described by an exponential type curve and became essentially sigmoidal. These differences are attributable to gradients in gas composition between internal and external atmospheres.

Washing of Granny Smith apples in Tween 20 solutions inhibited development of greasiness. This effect was associated with increased **R**, depressed $[O_2]_i$, lower respiration and increased $[CO_2]_i$ and $[C_2H_4]_i$ in the washed fruit compared to controls. The depression of $[O_2]_i$ in Tween 20 treated fruit was greater than the elevation of CO_2, suggesting that the Tween 20 treatment may have affected CO_2 production and O_2 uptake to different extents or alternatively the Tween 20 deposit on the fruit surface was differentially permeable to these two gases. Washed fruit also remained greener and firmer than controls. Pre-treatment by wiping without using Tween 20 solution had none of these effects but did stimulate weight loss. None of the treatments induced internal browning which is often associated with the development of greasiness in Granny Smith apples.

The relationship between temperature and **R**, internal atmosphere compostion, respiration and rate of C_2H_4 production of eight cultivars of apples was ascertained after equilibrating fruit at temperatures ranging from 0 - 30°C for 72h. **R** appeared to be independent of temperature. $[O_2]_i$ decreased, while $[CO_2]_i$ increased, in response to increasing temperatures and varied with cultivar. Braeburn apples consistently had lower $[O_2]_i$ and higher $[CO_2]_i$ than the other cultivars while the converse applied for Splendour apples. Internal C_2H_4 concentrations ($[C_2H_4]_i$) and rate of C_2H_4 production increased with increasing temperatures to a maximum at 25°C, above which internal concentrations and rates of production declined. The magnitude of decline was cultivar dependent. Compared to the other cultivars, Splendour apples had the least capacity to accumulate and produce C_2H_4. There was a

progressive increase in fruit respiration rate with increasing temperatures, which varied with cultivar. Over all the temperature regimes, Splendour had the lowest average respiration rate while Cox's Orange Pippin apples had the highest. The potential for variability in these gas exchange variables being associated with overall storage life and response to MAs is discussed.

Small gas concentration differences were measured between the equator and calyx end, and between the equator and calyx end shoulder within individual fruit in Golden Delicious, Red Delicious, Granny Smith and Splendour apples at 20±1°C. In contrast, large O_2 and CO_2 concentration differences between the same positions were found in Gala, Royal Gala, Braeburn and Cox's Orange Pippin apples. The differences were much greater than those measured between the core cavity and the fruit surface. Similarly, tissues in the calyx region of Braeburn and Granny Smith apples consistently had lower O_2 but higher CO_2 and C_2H_4 concentrations than any other position on the fruit surface, whilst tissues at the equator had higher O_2 and lower CO_2 and C_2H_4 concentrations than other parts of the fruit. These data falsify the notion that the internal atmosphere of individual apples can be regarded as being homogeneous. The heterogeneous distribution of gases within individual fruit would presumably affect the tendency of individual tissues to develop low-O_2 or high CO_2 disorders, particularly for fruit stored in MAs at elevated temperatures.

A conceptual model is presented which summaries the relationships between fruit $[O_2]_i$ and $[O_2]_{ext}$, **R**, respiration, temperature and artificial barriers. The $[O_2]_i$ of apples are always lower than the $[O_2]_{ext}$ used during MA storage, to an extent which is determined by the respiratory O_2 uptake by the tissues coupled with **R**. With everything else being maintained equal, increased **R** or increased respiration rate therefore depresses $[O_2]_i$ which in turn modifies the extent of response of the crop to a given MA treatment. These variables are therefore all important in determining the fruit's response to atmospheric modification.

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LIST OF ABBREVIATIONS.

A = Fruit surface area (cm^2)

AA = Acetaldehyde

$[AA]_{se}$ = Subepidermal acetaldehyde concentration ($\mu l\ l^{-1}$)

ACP = Anaerobic compensation point (% O_2)

$[ACP]_{ext}$ = Anaerobic compensation point for external oxygen (% O_2)

$[ACP]_i$ = Anaerobic compensation point for internal oxygen (% O_2)

CA = Controlled atmosphere

CO_2 = Carbon dioxide

$[CO_2]_i$ = Internal carbon dioxide concentration (%)

$[CO_2]_{initial}$ = Initial carbon dioxide concentration in jar (%)

$[CO_2]_{final}$ = Final carbon dioxide concentration in jar (%)

C_2H_4 = Ethylene

$[C_2H_4]_i$ = Internal ethylene concentration ($\mu l\ l^{-1}$)

$[C_2H_4]_{initial}$ = Initial ethylene concentration in jar ($\mu l\ l^{-1}$)

$[C_2H_4]_{final}$ = Final ethylene concentration in jar ($\mu l\ l^{-1}$)

C_2H_6 = Ethane

$\Delta \boldsymbol{C}_{CA}$ = Difference in gaseous concentration (ie. $\Delta[O_2]$, $\Delta[CO_2]$, $\Delta[C_2H_4]$ etc.) between the external and internal atmospheres of a fruit in CA (%)

$\Delta \boldsymbol{C}_{air}$ = Difference in gaseous concentration (ie. $\Delta[O_2]$, $\Delta[CO_2]$, $\Delta[C_2H_4]$ etc.) between the external and internal atmospheres of a fruit in air (%)

ETOH = Ethanol

$[ETOH]_{se}$ = Subepidermal ethanol concentration ($\mu l\ l^{-1}$)

$\boldsymbol{F}$ = Flux or respiration rate ($cm^3\ s^{-1}$)

$\boldsymbol{F}_{max}$ = Maximum rate of exchange when O_2 is saturating ($cm^3\ O_2\ s^{-1}$)

$\boldsymbol{F}_{air}$ = Flux of gases (ie. O_2, CO_2, C_2H_4 etc) in air ($cm^3\ s^{-1}$)

$\boldsymbol{F}_{CA}$ = Flux of gases (ie. O_2, CO_2, C_2H_4 etc) in CA ($cm^3\ s^{-1}$)

FO_2 = Rate of oxygen uptake ($cm^3\ kg^{-1}\ h^{-1}$)

FCO_2 = Rate of carbon dioxide production ($cm^3\ kg^{-1}\ h^{-1}$)

FC_2H_4 = Rate of ethylene production ($\mu l\ kg^{-1}\ h^{-1}$)

h = Hour

$\mathbf{k'_f}$ = a fruit constant (**A**/**R**) ($cm^3\ s^{-1}$)

$\boldsymbol{K}_m$ = Michaelis-Menten constant (% O_2)

MA = Modified atmosphere

N = Newtons

O_2 = Oxygen

$[O_2]_i$ = Internal oxygen concentration (%)

$[O_2]_{ext}$ = External oxygen concentration (%)

$[O_2]_{initial}$ = Initial oxygen concentration in jar (%)

$[O_2]_{final}$ = Final oxygen concentration in jar (%)

R = Skin resistance to gas diffusion ($s\ cm^{-1}$)

RCO_2 = Skin resistance to carbon dioxide diffusion ($s\ cm^{-1}$)

RC_2H_4 = Skin resistance to ethylene diffusion ($s\ cm^{-1}$)

RC_2H_6 = Skin resistance to ethane diffusion ($s\ cm^{-1}$)

RelE = Relative rate of exchange

RelO_2 = Relative rate of oxygen uptake

RelCO_2 = Relative rate of carbon dioxide production

RelC_2H_4 = Relative rate of ethylene production

RelRQ = Relative respiratory quotient

RQ = Respiratory quotient

$\boldsymbol{rF}_{max}$ = Maximum relative rate of exchange when $[O_2]_i$ is saturating ($cm^3\ O_2\ s^{-1}$)

rK_m = Michaelis-Menten constant for the relative rate (% O_2)

s = Seconds

Π = 3.1416

V_{fruit} = Fruit volume (cm^3)

V_{jar} = Jar volume (cm^3)

W_{fruit} = Fruit weight (kg)

T = Time