The 6th International Symposium on Jet Propulsion and Power Engineering
October 16-18, 2017, Beijing, China

2017-ISJPPE-0010

Bypass Transition in Separated-Reattached Flows under Elevated Free-Stream Turbulence

Zhiyin Yang

Department of Engineering, College of Engineering and Technology, University of Derby, Derby, UK

Abstract: Laminar-to-turbulent transition is of great practical interest as it occurs in many engineering flows and often plays a critical role in aerodynamics and heat transfer performance of those flow devices. There could be many routes through transition, depending on flow configuration, geometry and the way in which transition is initiated by a wide range of possible background disturbances such as free-stream turbulence, pressure gradient, acoustic noise, wall roughness and obstructions, periodic unsteady disturbance and so on. This paper presents a brief overview of transition in general and focuses more on the transition process in the free shear layer of separated-reattached flows, demonstrating that above certain free-stream turbulence intensity a so called bypass transition could occur.

Keywords: Laminar-to-turbulent transition; Bypass transition; Separated shear layer; Separated-reattached flows; Free-stream turbulence.

Nomenclature and abbreviations

D	flat plate thickness (unit: m)
f	frequency (unit: Hz)
k_{max}	maximum turbulent kinetic energy (unit: m^2/s^2)
U_0	free-stream velocity in the axial direction (unit: m/s)
x_R	mean separation bubble length (unit: m)
x	co-ordinate in the axial direction (unit: m)
y	co-ordinate in the vertical direction (unit: m)
z	co-ordinate in the spanwise direction (unit: m)
DNS	Direct Numerical Simulation
KH	Kelvin-Helmholtz
LES	Large Eddy Simulation
TS	Tollmien-Schlichting
2D	Two-dimensional
3D	Three-dimensional

1. Introduction

Laminar-to-turbulent transition is hugely complex and remains to be one of unsolved problems in fluid dynamics despite enormous efforts by engineers, physicists and mathematicians for more than a century. Transition can be found in many engineering flows and has a significant impact on the aerodynamics and heat transfer characteristics of those flow systems. Transition may take different routes depending on flow configuration and geometry, and transition process is greatly influenced by the presence of many possible flow disturbances such as wall roughness or obstructions, free-stream turbulence, acoustic noise, pressure gradient, surface heating or cooling, suction or blowing of fluid from the wall and so on. Traditionally transition has been classified into the following three main categories:

I. Natural transition

This kind of transition occurs in an attached boundary layer under very low level flow disturbances, e.g., free-stream turbulence intensity less than 0.5%. The transition process is

*Corresponding author: Tel.: +44 (0)1332593588 E-mail address: Z.Yang@derby.ac.uk.

initiated by two-dimensional (2D) instability waves called Tollmien-Schlichting (TS) waves, followed by a three-dimensional (3D) instability leading to significant 3D flows with the formation of streamwise/spanwise vortices. The final stage of such transition process is called the breakdown stage, which involves the breakdown of those large scale vortices into smaller flow structures, leading to the generation of turbulent spots which eventually merge to form a turbulent boundary layer [1 – 6]. Natural transition is the most extensively researched area compared with other two categories of transition (significant amount of work had already been done by the first half of 20th century mainly based on linear stability theory and some experiments) and hence the transition process is relatively much better understood, there are several stages involved in the transition process:

i). Receptivity stage – how the disturbances are projected into growing eigenmodes, or how they enter or otherwise induce disturbances in a boundary layer.

ii). Primary instability – small disturbances are amplified due to a so called primary instability (2D TS waves) of the flow.

iii). Secondary instability – usually once a disturbance reaches a finite amplitude it often saturates and transforms the flow into a kind of new, possibly steady state. Very rarely the primary instability can lead the flow directly into a turbulent state and the new steady or quasi-steady flow becomes a base on which secondary instability can occur (3D flows develop). This secondary instability can be viewed as a new instability of a more complicated flow. The growth rate of disturbances is much larger than that of the primary instability stage.

iv). Breakdown stage – nonlinearities and possibly higher instabilities excite an increasing number of scales and frequencies in the flow. This stage is more rapid than both the linear stage and the secondary instability stage.

II. Bypass transition

For an attached boundary layer under sufficiently high flow disturbances, e.g., a boundary layer on a flat plate without pressure gradient under free-stream turbulence intensity larger than 1%, transition occurs more rapidly and the 2D instability stage of natural transition is bypassed. The term “bypass transition” was first given by Morkovin [7] to this type of transition. Bypass transition was initially regarded as a mystery as turbulent spots seemed to be generated very rapidly out of nowhere compared with natural transition. However, over the past two decades better understanding of bypass transition has been obtained through numerical simulations with stability analysis (especially DNS - Direct Numerical Simulation) [8 – 16]. A general description of bypass transition is as follows:

i). At elevated free-stream turbulence low-frequency disturbances penetrating into the laminar boundary layer may undergo an algebraic growth (called transient growth or nonmodal growth, with the later referring to the fact that this mode is not predicted as one of the eigenmodes of the solution of linearized theories based on Orr-Sommerfeld and Squire equations), leading to the formation of elongated streamwise streaks. Those streaks are termed as boundary layer streaks or Klebanoff distortions (or called Klebanoff modes) after P.S. Klebanoff who investigated this phenomenon first and described them as a periodic thickening/thinning of the boundary layer [17, 18]. They are zones of forward and backward jet-like perturbations (high- and low-speed streaks) in the streamwise direction, alternating in the spanwise direction with a wavelength in the order of boundary layer thickness.

ii). A laminar boundary layer distorted by the streaks is susceptible to instabilities and the streaks grow downstream both in length and amplitude. Transition is usually initiated near the top of the boundary layer via an inflectional type of instability as a result of the interaction between the low-speed streaks lifted from near wall region and high-frequency disturbances in the free-stream which is strongly damped by the laminar shear layer (called shear sheltering) and hence cannot penetrate into the boundary layer.

iii). Turbulent spots are generated initially and further downstream, those turbulent spots merge to form a fully turbulent boundary layer.

III. Separated-flow transition

When a laminar boundary layer separates or when laminar flow separates at a blunt/sharp/rounded leading edge of a flat plate transition may occur in the separated free shear layer of the flows, which is termed separated-flow transition. It is worth noting that in some literatures transition has been classified into four categories and the fourth one is called wake-induced transition [6, 19 - 22] since in turbomachinery flows, the transition process is strongly influenced by impinging wakes coming from the preceding blade rows.

The use of a single category to describe transition in a separated laminar shear layer is too general or too vague as argued by Walker [23] in the early 1990s that some kind of natural and bypass transitions, similar to those in an attached boundary layer, could occur in separated shear layers. Nevertheless specific studies on the topic of “bypass transition in separated shear flows” have been very scarce. Furthermore, separation can be induced in many different ways, e.g., boundary layer separation on a flat plate due to an adverse pressure gradient; separation induced geometrically, and also in some cases separated flows reattach to the surface to form a separation bubble while in other cases they never reattach again.

In the following two sections of this paper a discussion on the transition process in separation bubbles formed due to an adverse pressure gradient will be presented in section 2. Section 3 will focus on the influence of free-stream turbulence on the transition process in separation bubbles induced geometrically where the separation point is fixed with a very short distance for the development of an attached boundary layer or no boundary layer development before the separation point at all.

2. Transition in separation bubbles induced by an adverse pressure gradient

An attached laminar boundary layer may separate due to the presence of an adverse pressure gradient and transition could occur in the separated shear layer, which reattaches to form a turbulent layer. This can be found in external flows such as flows over wind turbines and aircraft wings, and in internal flows such as gas turbine engine flows. Generally speaking for wind turbines and flight applications the free-stream turbulence intensity is relatively low (<5%) while it is high for turbomachinery flows at about 5 to 10% in compressor/turbine regions and can be as high as 20% in the wakes [2, 24].

2.1. Transition process under low free-stream turbulence

Under low levels of free-stream turbulence it has been clearly demonstrated by many numerical and experimental studies [25 – 32] that the transition process starts in the separated shear layer above the wall due to an inviscid instability mechanism - the Kelvin-Helmholtz (KH) instability. These initial 2D instability waves grow downstream with an amplification rate usually larger than that of TS waves. 3D motions develop further downstream via a secondary instability mechanism associated with distortion of coherent 2D spanwise vortices called the KH rolls. Streamwise vorticity forms as a results of those distorted KH rolls. Those large scale coherent structures breakdown to small scale structures, leading eventually to turbulence around the mean reattachment point. It is worth noting that although the KH instability usually plays a dominant role in the separated boundary layer transition process the TS instability may still be present, interacting with the KH instability and in some cases the TS instability mechanism may play a significant role in the breakdown to turbulence [33 – 37].

Even at low free-stream turbulence our understanding of the transition process in a separation bubble is relatively very limited compared with that for an attached boundary layer, and in the transition process described above only the first stage - the primary instability stare is well understood. The secondary instability mechanisms are reasonably well understood for attached boundary layer transition, such as K-type secondary instability, H-type secondary instability or O-type secondary instability but for separated flow transition there is no general consensus regarding the secondary instabilities at work despite many studies in the past two decades [27, 38 – 42] and much more investigation is needed in this area.

2.2. Transition process under elevated free-stream turbulence

Many experimental and numerical studies have shown that free-stream turbulence can have a big impact on separation bubbles, e.g., increasing the shear-layer entrainment rates, decreasing the mean reattachment length and resulting in earlier transition to turbulence. Haggmark [43] carried out an experimental study of a separation bubble developing on a flat plate under a grid generated turbulence intensity of 1.5%, and low-frequency, large-amplitude boundary layer streaks were observed in the boundary layer and in the separated shear layer. In addition, there was no evidence of two-dimensional waves from the flow visualization in the experiment.

McAuliffe and Yaras [28] studied transition mechanisms in separation bubbles formed over a flat plate due to an adverse pressure gradient under low (0.1% at separation) and elevated (1.45% at separation) free-stream turbulence using DNS. Their main findings are that under low free-stream turbulence transition occurs through receptivity of the laminar separated shear layer to small disturbances via the KH instability mechanism but at elevated free-stream turbulence the receptivity mechanism leading to shear layer roll-up is bypassed as a result of the boundary layer streaks formed upstream due to elevated free-stream turbulence interacting with the shear layer. Turbulent spots are generated through the interactions of the shear layer with the streaks via a localized secondary instability, and the Strouhal number (based on local conditions) associated with this instability closely matches that of the KH instability.

Balzer and Fasel [24] employed DNS to investigate the effect of free-stream turbulence on laminar boundary layer separation. One case without free-stream turbulence (unforced separation bubble) and three cases with different free-stream turbulence intensities: 0.05%, 0.5%, 2.5%, were studied and the elongated streamwise streaks were found in the laminar boundary layer even at the lowest free-stream turbulence intensity of 0.05%. The amplitude of these streaks was significantly larger at higher levels of free-stream turbulence. They also found that for all three cases with free-stream turbulence the observed dominant frequency is very close to the shedding frequency of the unforced separation bubble. This indicates that the inviscid shear-layer instability mechanism must still be present in all cases, which was confirmed by their linear stability analysis that even for the highest free-stream turbulence intensity case (2.5%) the linear shear layer instability mechanism (KH instability) is not completely bypassed, consistent with the results of a recent numerical study by Li and Yang [44] on a separated boundary layer transition on a flat plate with 3% free-stream turbulence intensity. It was found in the study by Li and Yang [44] that the boundary layer streaks (Klebanoff distortions or modes) were formed upstream the separation location, similar to the previous studies just discussed above. Nevertheless the flow visualization reveals the existence of distorted KH rolls, indicating that the KH instability is still present. As a result of the interactions between the distorted KH rolls and the streaks, portion of the KH roll merges with the streaks and develop into chaotic 3D structures rapidly downstream. Their further stability analysis confirmed the existence of the KH instability.

The influence of free-stream turbulence on transition in a compressor cascade was carefully studied by Zaki et al. [45] and five cases were considered, one without turbulence and four with different turbulence intensities at inlet: 3.25%, 6.5%, 8.0% and 10%. The transition process found on the pressure surface is very different from that on the suction surface as separation only occurs for the case without turbulence at inlet and for all other cases flow remains attached. This is because under those free-stream turbulence levels the boundary layer transitions to turbulence upstream of the laminar separation location, ensuring that the flow remains attached. Other studies have also demonstrated that separation could be prevented completely or suppressed periodically because wake initiated transition before the boundary layer could separate [46, 47]. Zaki et al. [45] showed that streaks were formed and amplified upstream of transition at the inlet turbulence intensity of 3.25% (decaying to about 2.5% at the blade leading edge). They found, however, that the breakdown of those streaks did not follow the conventional bypass mechanism as an inner instability was observed similar to those found in the secondary instability of classical TS waves. Nevertheless they further demonstrated that at higher inlet turbulence intensities bypass transition via the secondary instability of streaks became dominant. However, On the suction surface laminar separation persists and is modulated by the boundary layer streaks formed upstream of the separation location at the inlet turbulence intensity of 3.25%. The KH instability is still present as their flow visualization shows that once the KH rolls are formed, they are quickly destabilized and breakdown to turbulence. It is also noted that those KH rolls are not 2D but highly distorted in the span, very similar to the findings by Li and Yang [44]. At the next higher level of inlet turbulence intensity of 6.5% (decaying to about 4% at the blade leading edge) their averaged results indicate laminar separation and subsequent turbulent reattachment. However, they pointed out that this was misleading as the instantaneous flow fields showed the formation of turbulence spots in some regions where the boundary layer remained attached. When the inlet turbulence intensity was further increased to 8% and 10% (decaying to about 5.5% and 6.3% at the blade leading edge) they showed that a combination of mean flow distortion and transition to turbulence caused the boundary layer to remain attached, and the transition was dominated by the bypass mechanism of an attached boundary layer.

Previous studies have demonstrated that under elevated free-stream turbulence transition is more rapid and a kind of "bypass transition" has been mentioned in a few studies. However, "bypass transition" here means that the receptivity stage of disturbances enter the separated shear layer, leading to the shear layer roll-up is bypassed [28]. Whereas bypass transition in an attached boundary means that the dominant linear instability mechanism, TS Waves, is by passed. There is no evidence so far for the separated boundary layer transition under elevated free-stream turbulence that the linear shear layer instability mechanism, the KH instability, is bypassed. Several studies have confirmed the existence of the KH instability up to 3% free-stream turbulence intensity and a few studies demonstrated that separation is suppressed at much higher free-stream turbulence intensities (>5%).

3. Transition in separation bubbles induced geometrically

This section focuses on transition process in separation bubbles induced geometrically. The main distinct feature of those separation bubbles is that the separation point is usually fixed with a very short distance for the development of an attached boundary layer or no boundary layer development before the separation point at all, e.g., separation bubbles on a flat plate with a blunt/rounded leading edge [48 - 51]. As a result of this transition can only occur in the separated shear layer. Under low free-stream turbulence it has been demonstrated in many studies [52 – 60] that the transition process is initiated via the KH instability mechanism, more or less the same as in the cases discussed in the previous section. However, the transition process could be quite different under elevated free-stream turbulence as there is virtually no attached boundary layer developing before separation.

The literature on the transition process in separation bubbles induced geometrically under elevated free-stream turbulence is scarce. Experiments were carried out for a transitional separation bubble on a flat plat with a semi-circular leading edge with different flow conditions under different free-stream turbulence levels, denoted as the T3L test case of the ERCOFTAC Special Interest Group on transition [48, 61] but unfortunately few detailed numerical simulations have been performed on this test case.

A transitional separated–attached flow over a flat plate with a blunt leading edge under 2% free-stream turbulence intensity was studied numerically using the Large Eddy Simulation (LES) by Yang and Abdalla [62, 63]. They found that the mean bubble length was reduced by about 14% compared with the case without free-stream turbulence [56]. The free-stream disturbances produced more chaotic motion in the separated free shear layer, resulting in an early breakdown of the boundary layer as can be seen in Figure 1, showing a snapshot of instantaneous spanwise vorticity for the case without free-stream turbulence and the 2% free-stream turbulence intensity case. Nevertheless their flow visualization showed that the KH rolls were still visible, indicating the presence of the KH instability. This was further confirmed by the existence of the characteristic peak in the spectra as shown in Figure 2, equivalent to the characteristic KH value identified in the case without free-stream turbulence [56].

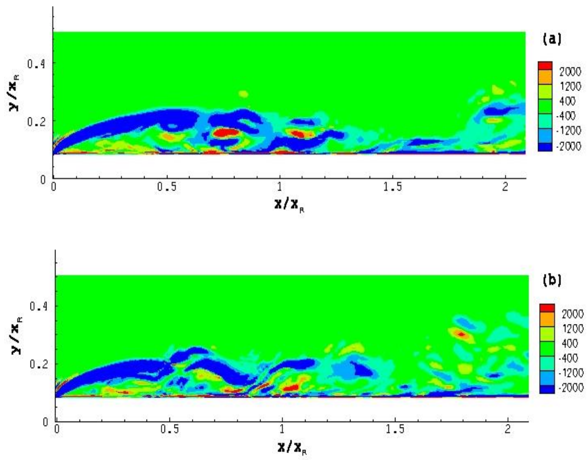

Figure 1 Instantaneous spanwise vorticity: (a) zero free-stream turbulence case; (b) 2% free-stream turbulence intensity case [62].

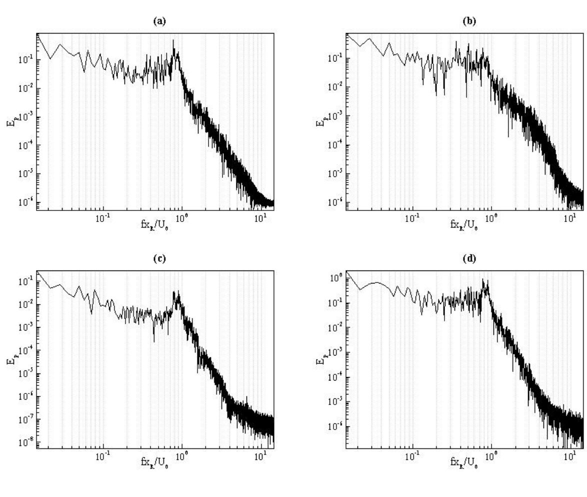

Figure 2 The pressure spectra at $x/x_R = 0.75$ and at $y/x_R = 0.01$ (a), $y/x_R = 0.05$ (b), $y/x_R = 0.13$ (c), $y/x_R = 0.2$ (d) [63].

Langari and Yang [64] carried out a detailed LES study of a transitional separated boundary layer over a flat plate with a semi-circular leading edge under two free-stream turbulence levels (0.2% and 5.6% above the leading edge). They demonstrated that for the low free-stream turbulence case the free shear layer formed in the separation bubble was inviscidly unstable via the Kelvin-Helmholtz instability mechanism, consistent with many previous studies discussed above.

For the higher free-stream turbulence case their results clearly demonstrate that the attached thin boundary layer, formed from the leading edge and developed over a very short distance before it reaches the separation point, is receptive to the free-stream turbulence disturbances and a small amount of turbulent kinetic energy is generated in the boundary layer which initially decays due to the acceleration of flow along the semi-circular surface from leading edge point to the separation location. However, after the separation at $x/D = 0.5$ (where D is the flat plate thickness, x is measured from the leading edge) turbulent kinetic energy is generated very rapidly for the elevated free-stream turbulence case, reaching the peak value at about $x/D = 1$ while for the low free-stream turbulence case the peak value is located at about $x/D = 3.25$ as shown in Figure 3, which presents the growth of maximum turbulent kinetic energy (the spanwise averaged peak value of k profile along the wall normal direction in the boundary layer and the separated free shear layer). The rapid generation of turbulent kinetic energy after the separation leads to earlier transition and breakdown to turbulent flow as can be seen in Figure 4, which shows isosurfaces of instantaneous spanwise vorticity for both the very low and elevated free-stream turbulence cases.

Their instability analysis shows that the criterion for the KH instability to occur is not satisfied anymore, which strongly suggests that the KH instability is bypassed. This is further confirmed by their flow visualization as shown in Figure 5 that the early stage of transition process is very different for the elevated free-stream turbulence case (5.6%) compared against the low free-stream turbulence case (0.2%). For the low free-stream turbulence case the spanwise oriented 2D KH rolls are clearly visible at the early stage of the bubble and become distorted/deformed downstream due to 3D motion setting in as a result of a possible secondary instability. However, for the elevated free-stream turbulence case those spanwise oriented 2D KH rolls are not visible anymore and spanwise irregularity appears at the early stage of the bubble in the separated shear layer leading to the formation 3D structures very rapidly, bypassing the 2D KH rolls stage, leading to a much earlier breakdown to turbulence. They conclude, hence, that a “bypass transition” occurs as the KH instability stage is bypassed under the free-stream turbulence intensity of 5.6%, similar to the “bypass transition” process in attached boundary layers where TS instability stage is bypassed.

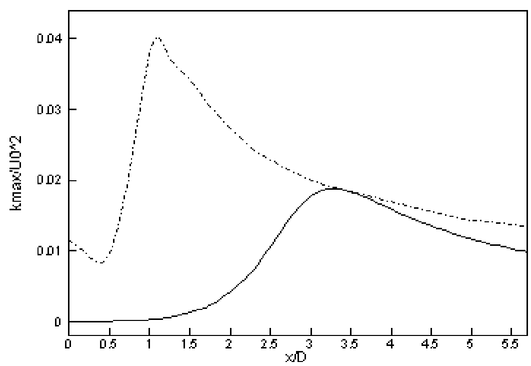

Figure 3 Development of the maximum turbulent kinetic energy: low free-stream turbulence case (solid line), elevated free-stream turbulence case (dashed line) [64].

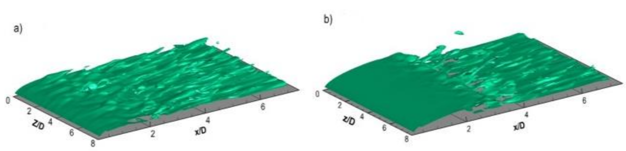

Figure 4 Isosurfaces of instantaneous spanwise vorticity: a) elevated free-stream turbulence case, b) low free-stream turbulence case.

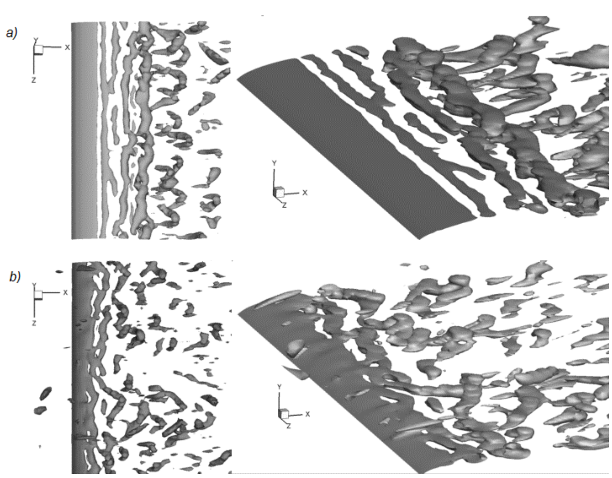

Figure 5 Top and perspective views of the Q-criterion isosurfaces: (a) low free-stream turbulence case, (b) elevated free-stream turbulence case [64].

4. Conclusions

This paper presents a very brief overview of laminar-to-turbulence transition which has been conventionally classified into three main categories: natural transition, bypass transition and separated-flow transition. Our current understanding of those three main categories of transition is briefly summarized and separated-flow boundary transition is the least understood in comparison with natural transition and bypass transition.

Separated-flow transition has been classified further into two sub-groups in this paper: separation induced by an adverse pressure gradient and separation induced geometrically. For the first sub-group an attached boundary layer develops over a certain distance before it separates whereas there is hardly any distance for an attached boundary to develop before separation for the second sub-group. It has been demonstrated that for the first sub-group under low free-stream turbulence the dominant primary instability is the KH instability but the TS instability may be present too, interacting with the KH instability. Under elevated free-stream turbulence a kind of “bypass transition” occurs but “bypass” here does not mean that the KH instability stage is bypassed as the KH instability is still present under free-stream turbulence intensity of 3%. Nevertheless, one study clearly shows when the free-stream turbulence intensity is further increased to about 5.5% at a compressor blade leading edge the separation on the suction surface is suppressed and the transition is dominated by the bypass mechanism of an attached boundary layer. For the second sub-group under low free-stream turbulence many studies have clearly demonstrated that the KH instability is the dominant mechanism. Furthermore, there is strong evidence showing that the KH instability stage is bypassed under a free-stream turbulence intensity of 5.6%. Therefore bypass transition does occur for the second sub-group when the free-stream turbulence intensity is sufficiently high, which is fundamentally different from the situation in the first sub-group as the separation is completely eliminated under sufficiently high free-stream turbulence intensity.

Acknowledgements

The author gratefully acknowledges that the Figures presented in this paper are from the Ph.D studies by by Drs I.E. Abdalla and M. Langrai under the author’s supervision.

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