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A mechanical model to investigate Aedesaegypti mosquito bite using new techniques and its applications

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Abstract. Mosquitoes are extraordinary in their ability to penetrate the epidermis layer into human skin with a natural ultimate microneedle without pain, named mosquito's fascicle. The mosquito usages a very small force to pierce into the skin. This force is at least four or three orders of magnitude smaller than the insertion force for a synthetic microneedle with an ultra-sharp tip to penetrate into the layer of human skin. In order to comprehend the piercing mechanism of the mosquito's fascicle into the human skin tissue, using new techniques as the variational iteration method. to analysis of elastic stability for mosquito's fascicle with the elastic foundation is conducted. Solutions for these types of problems are not a simple procedure since the equations of stability criteria are highly nonlinear. This study presents the application of the variational iteration method for obtaining the solutions for restrained mosquito's fascicle. The study proves that the variational iteration method is a very efficient and promising approach in the elastic stability analysis of specified problems. A good agreement occurs between the present results and the experimental measurements.

Keywords: mosquito mouthparts; variational iteration method; instability analysis; microneedle; penetration

1. Introduction

The aim of the present work is motivated by the desire to produce medical microneedles from the polymer material. Polymer microneedles will support new types of advanced medical treatments and increase the quality of present treatments. However, there are major challenges with use polymer microneedles: The stiffness stately as Young's modulus is for utmost polymers are about a factor 100 lower than the steel. This provides problems when injecting needles. A long slender needle buckles simply and the needle tip curve or flattens which the increases tip area and hence the required pierce force. The authors previously fabricated a micro jagged hollow needle that is similar to the proboscis of the mosquito by silicon micromachining (Oka *et al*. 2002, Lerche *et al*. 2015).

Later those needles were constructed from the silicon materials, because of the probability that the needle could be broken it was not safe for usage in humans. Since the safety to the human body, the researchers have fabricated a solid needle made of biodegradable polymer and development of a micro lancet needle (Aoyagi *et al*. 2005 and 2006, Izumi *et al*. 2006). This needle is formed by wet-etching a groove on a silicon die, molding polymer into this groove, and releasing it. Biodegradable polymer needle with different tip angles and influence of vibration and surface tension on easy insertion is investigated (Aoyagi *et al*. 2007).

The present work pays consideration to the way of insertion since comparison of vibration waveform and frequency implementation to decrease the needle piercing force (Saito *et al*. 2003), and no reports about microneedles. A mosquito drives the maxillas with vibration at numerous Hz on some literature; on the other hand, there is no statement to examine this motion in detail. The experimental system; Aoyagi *et al*. (2008) is shown in Fig. 1(a).

The mosquitoes gather to the body of human by detecting his temperature and sensing CO2 gas from the human. An illustration scene during penetration is shown in Fig. 1(b). The following facts are definitely by the observation: (1) the labium bends itself as the pierce progress. (2) The tip of labium make supports the bundle of further parts, which are the mandibles, the labrum, the pharynx, and the maxillas. (3) The tip of the labium opens or closes on the object surface synchronously to the bundle's vibration, which looks to provide tension to the surface for relaxed penetration. (4) The bundle is moved frontward regularly with vibration. These explained facts schematically displayed in Fig. 1(c).

The insertion mechanism progresses of the mosquito's fascicle is studied by Aoyagi *et al*. (2008), as shown in Fig.2, that is as the following: (1) The tip of the labium is opened, which provides the surface tension to the object. Then the maxilla's inserted. In this penetration, the surface tension has the influence for increasing the degree of the

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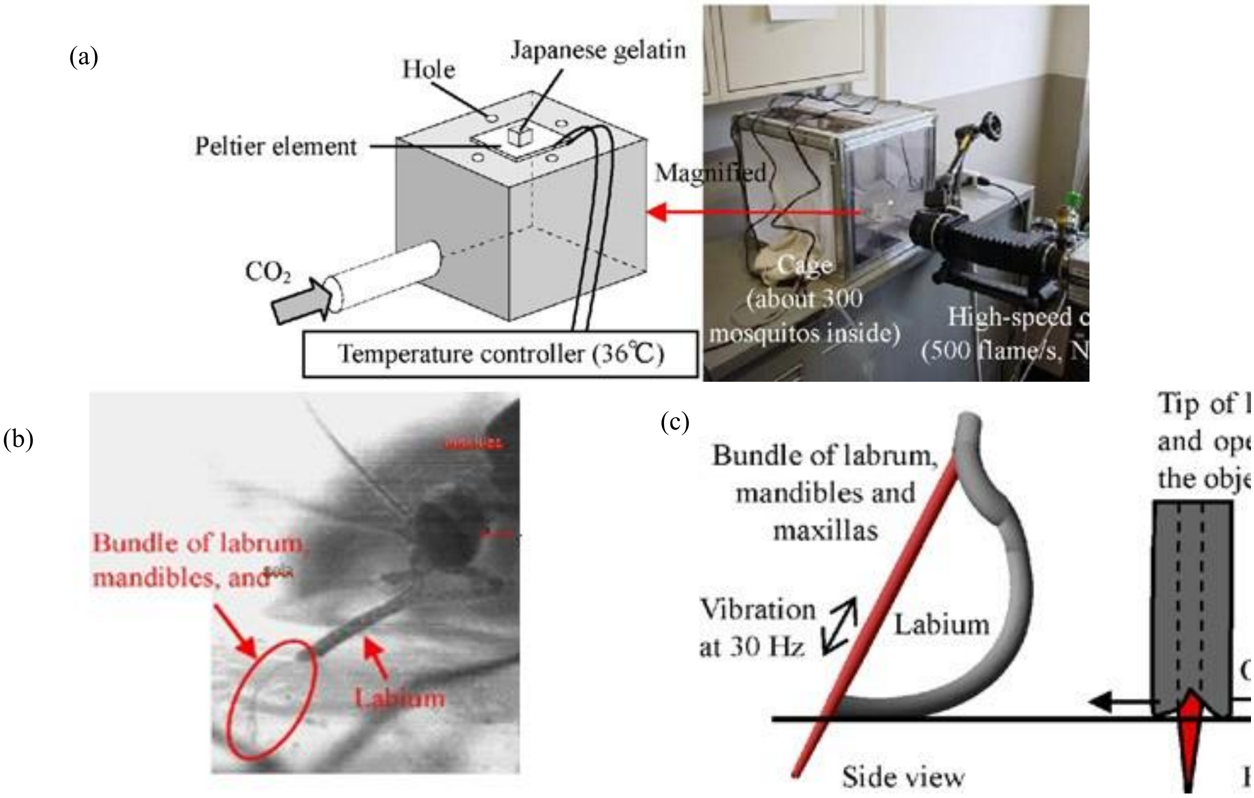

Fig. 1. Showed penetrating motion of mosquito's fascicle (Aoyagi *et al*. 2008). (a) Experimental system for showing penetration of mosquito's fascicle. (b) Example scene during penetration. (c) Schematic insertion motion

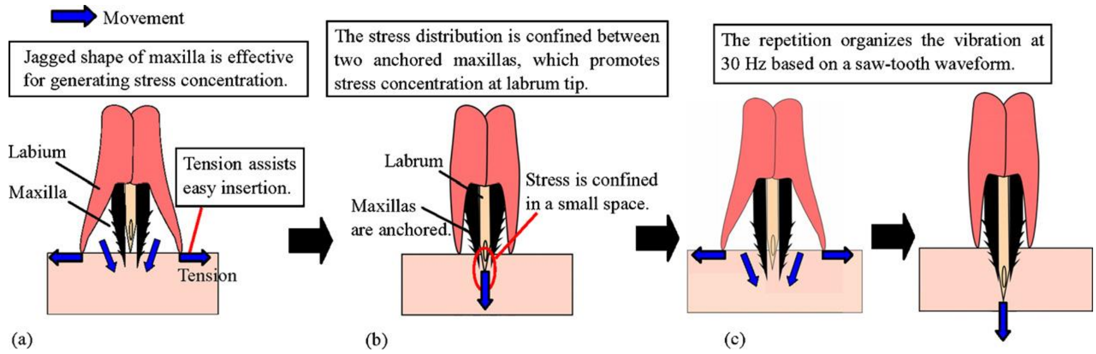

Fig. 2. Consideration on penetration mechanism of mosquito's fascicle (Aoyagi *et al*. 2008): (a) Tip of the labium is opened, and the maxillas are inserted. (b) Tip of the labium is closed, and the labrum is inserted. (c) The procedures of (a) and (b) are recurring, while the proboscis progresses increase the deep

stress act at tip area of two maxilla's and at the tip areas of the jagged protrusions (Fig. 2(a)). (2) The tip of the labium is closed.

The labrum is inserted while the two maxilla's are anchored to the epidermis layer in human skin organism (Fig. 2(b)). The stress distribution limited in the space between the maxilla's, which growths the degree of the stress at tip of labrum. (3) The previous procedures of (1) and (2) recurring at about 30Hz, while the mosquito's fascicle progresses deeper inside the object. The repetition arranges the vibration based on a saw-tooth the wave form.

Many revisions of microneedles have addressed the concern to the methods of the fabrication and the drug delivery abilities (Lin and Pisano 1999, Hashmi *et al*. 1995, Stoeber and Liepmann 2000). Artificial microneedles are now mainly fabricated with silicon, polymer and metal (Griss and Stemme 2003, Kuo and Chou2004, Park *et al*. 2005). Gordon and Lumsden (1939) detected the behavior of the mosquito's fascicle when taking up blood from a frog web. They presented A study of the behavior of the mosquito's fascicle when taking up blood from tissue together with some comments on the ingestion of microfilariae. Anne (1970) considered the penetration mosquito's fascicle of three types of mosquitoes using a Scanning Electron Microscope, provide a detailed report on the morphological structure of the mosquito's fascicle. Jones (1978) investigated the feeding behavior of female mosquitoes, as well as the anatomy of the mosquito's fascicle and alimentary canal.

The aim of the present paper is to understand the penetrating behavior of the mosquito's fascicle and to understand the penetrating mechanics while mosquito's fascicle penetrates the epidermis layer into human skin. For describe how a mosquito's fascicle acts on the human skin. Finally, numerical results are executed to analyze the penetrating process of the mosquito's fascicletip into the epidermis layer in human skin using variational iteration method.

2. Problem definition

For the uniform homogeneous mosquito's fascicle with the flexural rigidity EI, the length l is studied. The mosquito's fascicle is supposed as restrained along the length. The restraint is uniformly distributed lateral, stiffness k per unit length. Such a model is called an elastic foundation. A mosquito applies a compressive load $P_0 + P_t\cos\theta t$ on mosquito's fascicle, P_0 is static compressive load applied, and $P_t\cos\theta t$ is the fluctuating part of load applied at frequency θ. *Pt*is the maximum amplitude of time-varying load applied. The labium sheath exerts distributed lateral force βy on mosquito's fascicle, here $(\beta_0\cos\theta t)$is the modulus of the foundation. The equation of equilibrium of mosquito's fascicle resting on elastic foundation under axial compressive forces can be written as (Timoshenko and Gere 1964, Bolotin 1964)

$$EI\frac{\partial^4 y}{\partial x^4} + (P_0 + P_t\cos\theta t)\frac{\partial^2 y}{\partial x^2} + (\beta_0\cos\theta t)y + m0\frac{\partial^2 y}{\partial t^2} = 0 \quad (1)$$

The associated boundary conditions are

$$y(0,t) = 0;\quad y''(0,t) = 0;\ y(l,t) = 0;\quad y''(l,t) = 0 \quad 2)$$

As the time-varying load $P_t$is applied, the transverse vibrations are generated in the mosquito's fascicle and this leads to the development of the inertial forces, E is the elasticity modulus, I is the area moment of the inertia of the mosquito's fascicle, and *m0* is the mass per unit length of the mosquito's fascicle.

3. Solution methodology

The mosquito's fascicle subjected to simply supported, axial compressive loading and vibrations have to be dynamically stable for applied force and frequency. Study of the instability of such mechanical member achieved to get the parametric resonance critical buckling load and frequencies. The plot shows regions of stability and regions of instability between certain dimensionless parameters. These regions determine whether the mosquito's fascicle will fail with increasing amplitude of vibrations or will be dynamically stable (Timoshenko and Gere 1964, Bolotin 1964). The solution for the Eq. (1) can be written as

$$y(x,t) = F_n(t)\sin\frac{n\pi x}{l}, \qquad (k = 1,2,3,\ldots\ldots) \quad (3)$$

Where n is the order of harmonics of the vibration and $F_n(t)$ is an unknown function of time. From Eqs. (1)-(3) and the necessary and sufficient condition, we have

$$\left[m0\frac{\mathrm{d}^2 F_n}{\mathrm{d}t^2} + (\beta_0\cos\theta t)f_n + EI\frac{n^4\pi^4 F_n}{l^4} - (P_0 + P_1\cos\theta t)\frac{n^2\pi^2 F_n}{l^2}\right] = 0, \quad (4)$$

for any value of t. In other words, $F_k(t)$ must satisfy the following differential equations

$$\frac{\mathrm{d}^2 F_n}{\mathrm{d}t^2} + \mathrm{v}_n^2(1 - 2K_n\cos ft)F_n = 0, \quad (5a)$$

Eq. (5) is the well-known Mathieu Hill equation. These solutions appear in regions of dynamic instability and such regions exist in the plane of the two parameters $K$and v.

$$\mathrm{v}_n = \omega_n\sqrt{1 - \frac{P_0}{P_n}.}\ ;\quad K_n = \frac{P_t}{2(P_0 - P_n)}\ ;\ \omega_n^2 = \frac{1}{m0}\left(\frac{n^4\pi^4 EI}{l^4} + \beta_0\cos\theta t\right); \quad (5b)$$

$$P_n = \frac{n^2\pi^2 EI}{l^2} + \frac{l^2\beta_0\cos\theta t}{n^2\pi^2},$$

Eq. (5) has the coefficients that are periodic with the period $T = \frac{2\pi}{f}$, and the Floquet solutions, either periodic in period $2T$ *or* period T separate the regions of stability and regions of instability (Bolotin 1964, Ruby 1996, Arfken *et al.* 2012). Where P_n is the buckling of Euler load for the nth node, ω_n is the nth vibration frequency of unloaded rod, and $v_n$is the free vibration frequency when loaded with the constant load P_0 where K_n is the excitation parameter. Agreeing with the variational iteration method, a nonlinear differential equation may possibly be considered as the following:

$$L(F_n) + N(F_n) = g(t) \quad (6)$$

Where N is the nonlinear operator, and g(t) is the nonhomogeneous term and L is the linear operator. Based on the variational iteration method, a correct function can be constructed as follows:

$$(F_n)_{m+1} = (F_n)_m + \int_0^x \lambda(\xi)\{L(F_n)_m(\xi) + N(\widetilde{F_n})_m(\xi) - g(\xi)\}d\xi \quad (7)$$

Where the general Lagrangian multiplier λ, can be identified optimally via the variational theory, $\overline{(F_n)}$ is considered as a restricted variation i.e. $\delta\overline{(F_n)} = 0$, the subscript n denotes the nth order approximation. By solving the differential equation for λ obtained for Eq. (7) in view of $\delta\overline{(F_n)} = 0$ with respect to the boundary conditions, the Lagrangian multiplier $\lambda(\xi)$, is get as the following (Richards 1983, Momani and Abuasad 2006, Abulwafa *et al.* 2007, Sweilan and Khader 2007, Xu 2007, He *et al.* 2007, Xu *et al.* 2007):

$$\lambda(\xi) = \xi - \mathrm{t} \quad (8)$$

If the above the variational iteration method formulation is applied to Eq. (1), the following iteration formula is able to achieved accordingly:

$$(F_n)_{m+1}(t) = (F_n)_m(t) + \int_0^t \lambda(\xi)\left\{\frac{d^2F_n}{dt^2} + v_n^2(1 - 2K_n\cos\theta t)F_n\right\}d\xi. \quad (9)$$

In the variational iteration method analyses, a polynomial may be chosen as an initial approximation which is given below.

$$\overline{(F_n)}_0 = C\bar{x} + D. \quad (10)$$

The computations are conducted up to m=10 and four end boundary conditions such as pinned (simply supported),for each mosquito's fascicle are written by using the last iteration. Hence equations can be interpreted as a matrix equation which defines an eigenvalue problem as follows:

$$[M(\alpha)]\{A\} = \{0\} \quad (11)$$

where $\{A\} = (CD)^T$. The determinant of the matrix of coefficients yields the characteristic equation in the terms of α and the smallest positive real root of this characteristic equation is the normalized critical buckling load for the case considered. For a nontrivial solution, determinant of the matrix of coefficients must be zero.

4. Results and discussion

To illustrate the proficiency of the variational iteration method to investigate critical buckling loads, a considerable number of analyses have executed for $0 < \beta < 90$. After that, these numerical results are illustrated in figures with analytical solutions of continuously restrained mosquito's fascicle. The variational iteration method effectively handles the trouble of finding the smallest root of stability criteria and gives nearly exact results in the case studied. From the figures (3-6), it is able to see how end conditions such as pinned (simply supported), effect the critical loads required for the buckling of restrained mosquito's fascicle.

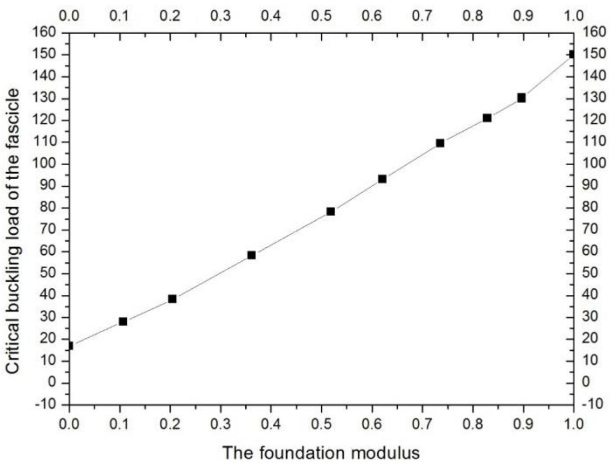

Fig. 3 Effect of foundation modulus on the critical buckling load

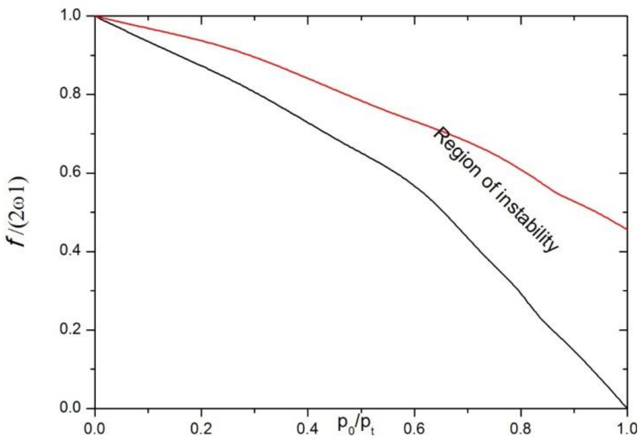

Fig. 4 Principal region of instability, β_0= 0 N·mm^{-2}

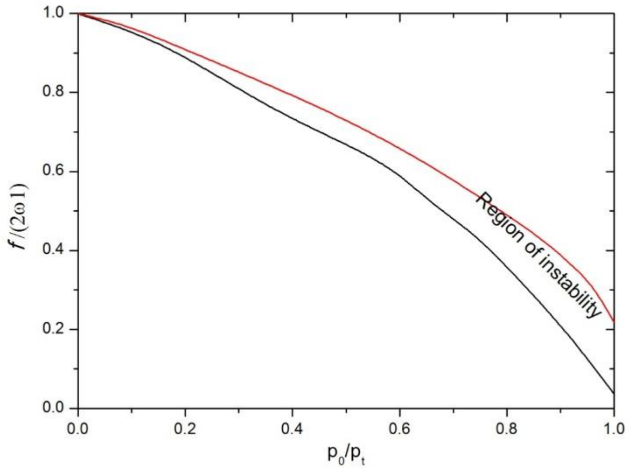

Fig. 5 Principal region of instability, β_0= 0.10 N·mm^{-2}.

For β = 0.25 N·mm^{-2} and declared dimensions and mosquito's fascicle properties, the vibration frequency of unloaded mosquito's fascicle, calculated from Eq. (5b). The reported frequency applied by mosquito's fascicle is around 17 Hz, the stability region for the mosquito's fascicle exists between frequencies ω_1 and zero, and the region of the instability exists in the middle of the two boundaries of ω1. As the applied frequency, f is smaller than ω1.The principal region boundaries of instability for Figs. 4-6 computed using the first approximation as the following:

$$f = 2v\sqrt{1 \pm K}$$

Figs. 4 and 5 illustrate the impact of the amplitude of vibration P_t on the instability of the principal region, as the foundation modulus β_0 = 0.25 N·mm^{-2} is constant. For P_t = 0.32 P_0, the instability region is greater as compared to P_t= 0.11P_0. The region of the instability shrinks in size as P_t declines, i.e. for applied frequency f, the mosquito's fascicle is able to withstand more load beforehand it enters the region of the instability.

Analogous results were perceived when the amplitude of periodic load is constant value at P_t= 26mN in Fig. 6 and. The only difference is the instability region boundaries as shown in Figs. 6 is the graphs with

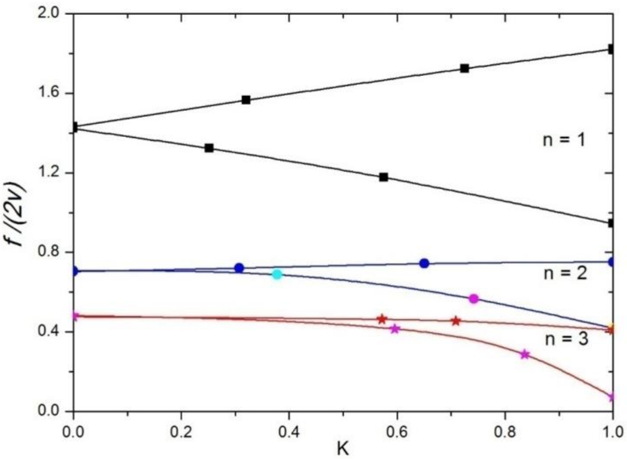

Fig. 6 Regions of instability on f/2*v*, *K* plane for *n* = 1, 2, and 3

variation in β_0, for $P_t = 0.33P_0$. The nature of the curve may possibly analogous, but the place of points will change as the modulus of foundation acting important role in critical load and frequency calculation. The natural frequency of vibration of mosquito's fascicle ω_1, and Euler buckling load P_t for the mosquito's fascicle for n = 1 depends on the foundation modulus β_0. The value of foundation modulus is varied from 0 $N \cdot mm^{-2}$ to 0.25 $N \cdot mm^{-2}$. The buckling of Euler load growths linearly with reference to the foundation modulus β_0, from 5.5mN to 107mN. For the similar range of the foundation modulus β_0, the natural frequency of mosquito's fascicle with no load growths from 3.67 kHz to 17.1 kHz, though the growth noted is nonlinear in nature.

5. Conclusion

In this study, biomechanical model to study the behavior of Aedesaegypti mosquito such as the stability and the instability happened in mosquito's fascicle in try to pierce human skin, as the epidermis layers, has been investigated using the variational iteration method. The impulsive forces applied by mosquito to penetrate the epidermis layer create dynamic buckling in the mosquito's fascicle. The buckling load of mosquito's fascicle is estimated and the vibration frequency of unloaded mosquito's fascicle and foundation modulus of labium sheath are considered. However, the bio-mathematical model developing aids to know the instability in the mosquito's fascicle to a fair extent. The forces of reaction exerted by the labium sheath at buckled condition progress the stability of the mosquito's fascicle. Increase in frequency of free vibration and the critical buckling load of the mosquito's fascicle is considered for increment in values of modulus of the foundation. The results of the analysis using the variational iteration method as analytical based method are in good agreement with analytical results. Moreover, the comparisons with those experimental results pointed out that the variational iteration method is very efficient and powerful in the analysis of buckling problems of restrained mosquito's fascicle. Finally, the results have been applied to set design strategies for the advance of dynamically stable vibration aided microneedle as a medical application. Other works can be considered in future by introducing other models with shear deformation effect (Panda and Singh 2009, 2010 and 2013, Panda and Katariya 2015, Kumar *et al*. 2016abc, Kar and Panda 2016, Lata *et al*. 2016, Katariya and Panda 2016, 2018 and 2020, Kar *et al*. 2017, Katariya *et al*. 2017ab and 2018, Mehar and Panda 2018 and 2019, Panjehpour *et al*. 2018, Mehar *et al*. 2018, 2019 and 2020ab, Avcar 2015 and 2019, Chaabane *et al*. 2019, Ahmed *et al*. 2019, Katariya and Panda 2019, Gupta and Anandkumar 2019, Hussain and Naeem 2019, Abualnour *et al*. 2019, Alimirzaei *et al*. 2019, Chikh 2019 and 2020, Belbachir *et al*. 2019, Sahla *et al*. 2019, Al-Furjan *et al*. 2020abcd, Asghar *et al*. 2020, Boussoula *et al*. 2020, Hussain *et al*. 2020, Kaddari *et al*. 2020, Tounsi *et al*. 2020, Kim *et al*. 2020, Ramady *et al*. 2020, Bekkaye *et al*. 2020, Khadimallah *et al*. 2020, Al-Furjan *et al*. 2021ab).

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